ICEFA 2011

9th INTERNATIONAL CONFERENCE ON ELECTRICAL FUSES AND THEIR APPLICATIONS

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PROCEEDINGS

CONGRESS CENTRE HABAKUK
MARIBOR, SLOVENIA

12th-14th September, 2011

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General sponsor of the conference:
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Conference:	9th INTERNATIONAL CONFERENCE ON ELECTRICAL FUSES AND THEIR APPLICATIONS
Organized by:	University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17, SI-2000 Maribor ICEM-TC, Gosposvetska cesta 84, SI-2000 Maribor
With co-operation of:	Fuse Club
General chair of the conference:	prof. dr. Jože Pihler, University of Maribor
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Chief editor:	prof. dr. Jože Pihler, University of Maribor
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Design:	Navdih.net
Edition:	100

Maribor, Slovenia
September, 2011

CIP - Kataložni zapis o publikaciji
Univerzitetna knjižnica Maribor

539.42(082)

INTERNATIONAL Conference on Electrical Fuses and their Applications (9 ; 2011 ; Maribor)
Proceedings [Elektronski vir] / ICEFA 2011 - 9th International Conference on Electrical Fuses and their Applications, Maribor, Slovenia, 12th - 14th September, 2011 ; [organized by University of Maribor, Faculty of Electrical Engineering and Computer Science with cooperaton of Fuse Club ; chief editor Jože Pihler]. - El. zbornik. - Maribor : Faculty of Electrical Engineering and Computer Science, 2011

ISBN 978-961-248-297-8

1. Pihler, Jože, 1955- 2. Faculty of Electrical Engineering and Computer Science (Maribor) 3. Fuse Club

COBISS.SI-ID 67648769

FOREWORD

The 9th International Conference on Electric Fuses and their Applications is being organized by the University of Maribor, Faculty of Electrical Engineering and Computer Sciences – Power Engineering Laboratory and ICEM-TC. The Faculty of Electrical Engineering and Computer Science is a scientific institution of explicitly regional, national, and international significance. Its regional significance is reflected in its close co-operation with industry within and around the city of Maribor. Its international significance is reflected in the faculty's participation in international research activities covering numerous projects, exchanges of students and professors, publications in respected scientific magazines, participation at international conferences. ICEM-TC is an independent institute, which was founded in 2001 with the help of the Faculty, ETI, and other industrial companies. The Institute's activities are covering of an applicative, research, development, consultation, educational, and informative nature - documentation, publication, promotional work, testing and measurements in the fields of energy industries, telecommunication, measurement and switching technology.

The ETI Elektroelement d.d. company plays an active part and closely collaborates within the framework of the Organizing Committee and also as a General Sponsor.

Following the previous eight conferences, this conference is being organized in close collaboration with the FUSE CLUB, founded several years ago to increase and exchange knowledge about fuses.

The International Scientific Committee is composed of eminent experts from companies that produce and research fuses, plus some academic representatives. They have done an important work, reviewing abstracts and papers, for which we sincerely thank them.

We would also like to express our gratitude to the Organization Committee, especially Dr. Lech and Dr. Wilkins, who have helped us with their immense experience.

We would like to give preferences to the articles connected with practical industrial work, standardization, and testing. We hope that the authors have been successful in their work.

The Conference Organizers and the entire Conference Team wish you a pleasant and rewarding time at this conference set in the beautiful surroundings of Maribor.

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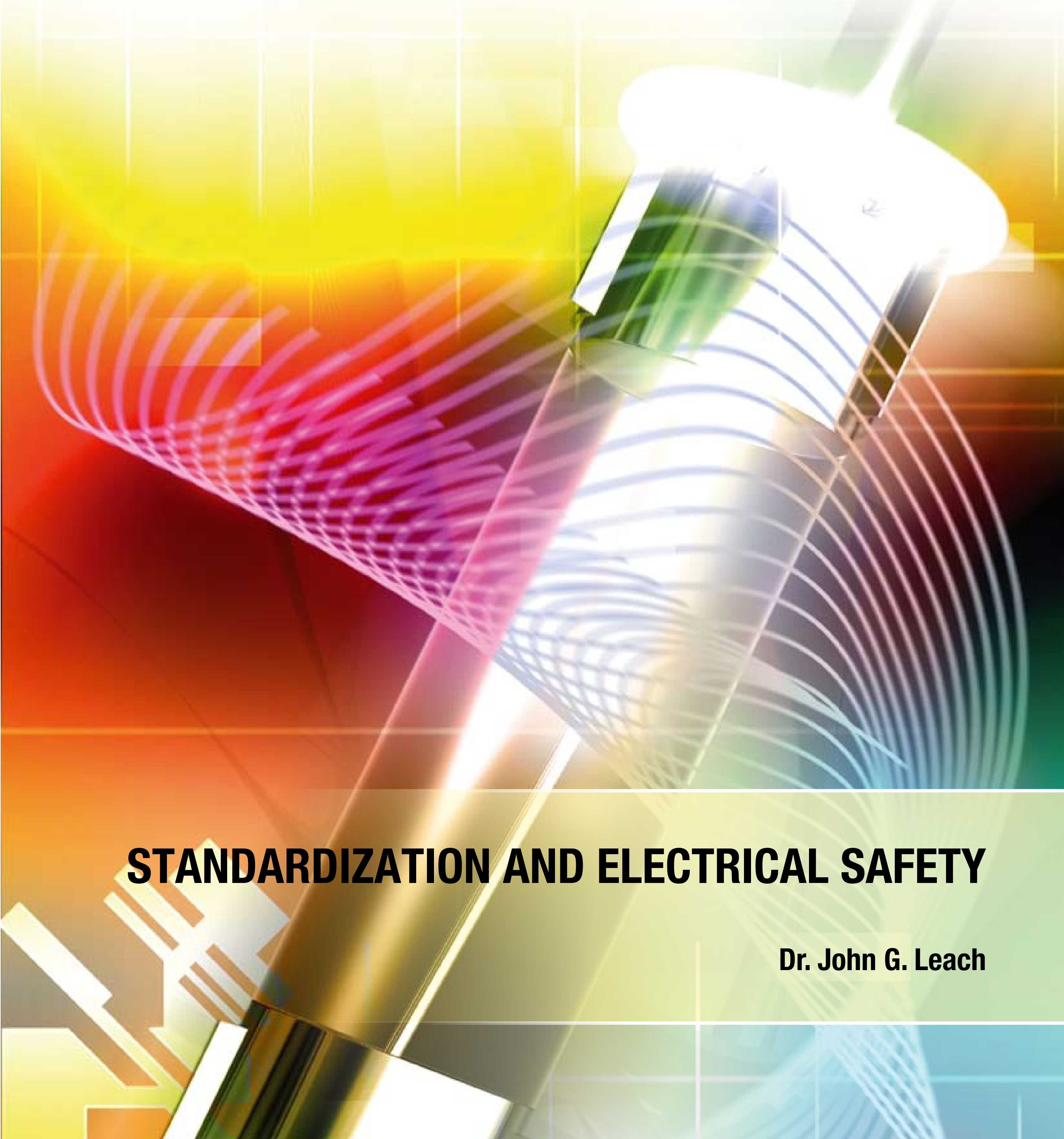

STANDARDIZATION AND ELECTRICAL SAFETY

Dr. John G. Leach

OPENING LECTURE

Standardization and Electrical Safety

Dr. John G. Leach

Consultant – Hi-Tech Fuses, Hickory, NC, USA, j.g.leach@ieee,org

Abstract

This is the opening day lecture at ICEFA 2011 on the subject of "Standardization and Electrical Safety". After a general introduction, on the purposes of standards and the author's background, a brief review of "safety" as it relates to fuses is attempted. This is followed by a discussion of the standards process, and some examples are given of current standards development that are intended to improve the application of fuses.

Keywords: e.g. electric fuse, fuse standards, fuse application.

1. Introduction

Electrical standards, related to fuses, have existed since the earliest days of fuse use. Standards are developed primarily for the direct benefit of two groups, manufactures and users (users being considered as those who purchase fuses, or who purchase equipment that includes fuses). However when the issue of "safety" is considered there is a much larger group that benefits, and that is everyone who uses electricity or is ever near electrical equipment. Few people do not fall into this category!

Fuse standards are written primarily by representatives of fuse manufacturers, with input from users. This is because, in general, the work is done by "volunteers", often persons supported by their employers or by manufacturer's organizations. Since manufacturers have the most to gain financially from the existence of standards, and manufacturers are generally the most knowledgeable concerning the practical aspects of fuse design and development, it is no surprise that they are the ones to primarily support standards making.

At the most basic level, a standard lays down the rules that apply to all products of a particular type - that is standardizing both testing and the product itself. An old myth is that standards inhibit innovation and restrain trade. In fact the opposite is true; without at least certain standards there would be chaos. The fact that standards change as often as they do is testament to the progress that occurs because of, rather than in spite of, standards. For fuses, in addition to the obvious advantages of standardizing such things as voltage and current ratings (and in some cases physical dimensions), the manufacturer also gains by having standards set some limits to the amount and types of testing required; without a standard, a user could specify any tests they wanted, whether or not relevant, which would make testing completely open ended. The user gains from fuse standards since they can be sure that any given product has received testing at least equal to that deemed necessary by a consensus of the most knowledgeable people in the field. Since few uses are sufficiently skilled to specify their own testing requirements, it relieves them of this burden. Perhaps somewhat surprisingly, it can be argued that limiting the scope of testing is actually beneficial to the user, since with no potential limit on testing, new products could be too expensive to develop; no manufacturer would undertake a development without a reasonably firm estimate of the testing costs, since they can be so high. This is particularly true in the case of high current interruption tests, where short-circuit testing can cost the equivalent of between about 5 000 to 50 000 US dollars a shift, depending on location and power requirements.

When issues of "safety" are considered, three general areas are relevant, and standards have a bearing on all three. The first is that the correct types of fuses should be chosen to provide appropriate protection when electrical failures occur, in order to minimize risk to life and property, and minimize the extent of the loss of electrical power. Standards can help here through application information of an "educational", or tutorial, type. The second area is that is that fuses must work correctly within their ratings, so that they do not add to the problems present when faults occur, or even worse cause a failure. Here standards help by providing standardized testing requirements that assist in ensuring a product has been designed to work properly in service. Thirdly, even a fuse that has been designed and tested correctly cannot provide protection if it has not been applied correctly (i.e. if it is the wrong type of fuse for the task, or the correct type but with the wrong ratings). Again standards can provide application information to educate the user in the correct choice of a fuse. Most fuse "failures" are as a result of misapplication.

Because the potential scope of the lecture's title is so large, of necessity coverage of only certain aspects of standards development and their significance will be attempted. However coverage will include discussion of standards development at both the National and International level, and some of the current developments taking place in International Electrotechnical Commission (IEC) High-Voltage (HV) fuse standards, all aimed at making the (electrical) world a safer place.

2. Background

The author's background is in the design and application of fuses of many types; initially experience centred on low-voltage fuses (that is with fuses having a voltage rating up to 1000 V ac and 1500 V dc) to be followed, for the last 33 years, by high-voltage fuses (over 1000 V ac). Consequently most of the comments in the lecture will relate directly to HV fuses. However many of the more general comments will relate to the other primary areas of fuse standards: low-voltage fuses and miniature fuses.

There is, perhaps, a general impression that a product that has been in widespread use for well over a hundred years (some would claim almost 150 years, or even 230 years![1]) is so mature, there should be little reason to change a fuse standard. In fact it is a cause of concern to some manufacturers and users that standards do change, often more frequently than they would like, and an attempt will be made to explain why this is so.

3. Standards and "safety"

Fuses are protective devices and, like all protection, their primary function is to act in the case of "something going wrong". Some failures may be caused by human error (e.g. it is virtually impossible to make all insulation so perfect that it will last forever) while others are the result of "natural" phenomena such as lightning, storms and earthquakes. Therefore, it is inevitable that some failures will occur. Many fuses are therefore designed to operate when all else has failed, and we seek to make them as well and reliable as possible. No manufacturer wants to create a product that will not work properly. However, a fundamental question is "how does one design testing to find out what might not work correctly in a product, if one does not know in advance what might not work correctly?" Fortunately with fuses we have over a hundred years of commercial (and standards) experience to head manufacturers in the right direction. Standards represent the collective wisdom of our fuse community. As particular applications became common, experience (sometimes a bad experience of course!) suggested areas that needed to be addressed in terms of standardized testing. This is testing required for a new design for a recognized application. For new applications, the situation is more complex, as appropriate testing may not be available in standards. This issue is somewhat addressed in the paper by Leach [2] at ICEFA 2003. New test requirements typically appear first in "regional" standards and only later find their way into IEC standards. More on this later.

A fundamental principle applied to most fuses is that of "type testing". The testing that may be conducted on every manufactured fuse is somewhat limited. The most important tests (interrupting tests) leaves the fuse unusable, so the method used is to thoroughly test a new design and then not deviate in any way from that design in manufacture. Any manufacturing changes that could affect a fuse's performance must then be addressed with additional testing.

System safety is therefore dependant on the correct testing of a fuse design followed by correct manufacturing of the device. The final aspect that is vital to "safety", however, is in the correct application of fuses. Demonstrating that a fuse will work perfectly under the conditions for which it was designed and tested certainly does not mean it will work correctly if it is subjected to conditions for which it was not intended!

Despite being a device intended to enhance the "safety" and functionality of power systems and equipment, it is unlikely that, today, there will be any reference to "safety" in the fuse standards and application guides. While "safe" has a variety of meanings, one of them is the protection of persons from harm. When the IEC HV fuse tutorial and application guide IEC 62655 [3] (see 6.) was first being written, suggested wording included such phrases as "safely interrupt". By this the writer meant interrupting current with the fuse intact and doing its job as was intended. However it is impossible for any HV fuse to "safely interrupt", if by "safely" we mean no one will suffer any harm. If the fault were caused by someone coming into contact with a live conductor for example, even a successful fuse operation is very unlikely to occur with no harm to the person being electrocuted. The phrase in the above example therefore ultimately became "correctly interrupt". Much care is now being exercised in writing standards to avoid any issues of liability, so safety aspects may be down-played to some extent (e.g. "the tests assist in ensuring that..." rather than "the tests ensure that..." We have to face the fact that excess electrical current through the human body is damaging, and this is the price we pay for a technology that enhances and improves our life in so many ways. However it cannot be argued that the general "safety" of our electrical systems is not enhanced by the correct use of fuses that have been tested to appropriate National and International standards. I use the term "correct use" advisedly, since, again, only when correctly used can fuses work successfully in a system. Therefore, better application advice is the next major step forward in IEC standards (see 6). Before discussing this important aspect of "safety", however, some general information on standards bodies and the standards process is in order.

4. Standards bodies and the standards process

Most countries have some form of standards body or bodies, responsible for writing or approving electrical standards. The way in which such standards are written, approved and enforced (or in many cases not enforced, since often standard compliance is voluntary) varies from country to country and even between fuse types in a given country. The subject is therefore too large and complex to be addressed in a brief lecture. Since specific examples will be given between IEC and IEEE HV fuse standards, a brief description of these two bodies and their process for developing and maintaining fuse standards will be given. The Institution of Electrical and Electronic Engineers (IEEE) is "the world's largest professional association for the advancement of technology" with over 400 000 members from more than 160 countries (with over 45% from outside the USA). The IEEE has a "Standards Association" (SA) within its structure and members pay a fee to belong to this group. HV fuse standards are developed within a subcommittee of the Power and Energy Society (PES) Switchgear Committee. The HV Fuses subcommittee and its working groups write and maintain HV fuse standards, primarily addressing North American practice (though it should be pointed out that "North American Practice" – a phrase also recognized in IEC standards – extends well beyond North America and in fact is common around the world, except in Europe). Standards developed by IEEE and other bodies are also recognized as "American National Standards" by the American National Standards Institute (ANSI).

IEC is also a world organization, but its "members" are individual country's National Committees. The National Committee for the USA, for example, is ANSI. The IEC Technical Committee (TC) for fuses is TC 32. It is divided into three subcommittees SC32A (high-voltage), SC32B (low-voltage) and SC32C (miniature). The TC rarely meets, while the subcommittees meet periodically (every few years) usually at main IEC plenary meetings. At such meetings, attendees represent their countries (one voting member per country). The actual work of writing and maintaining IEC standards is done primarily in Working Groups (WG) or Project Teams for new documents, and Maintenance Teams (MT) for existing documents. Members of these groups work as individuals (rather than as representatives of their countries), although such "experts" have to be nominated by their National Committees. After the WG/MT develop a document (a "Committee Draft" or CD) the document is circulated for comments from the National Committees. If there are many significant comments, additional CDs may be produced. When the document is essentially finished, at the "enquiry stage" a Committee Draft for Vote (CDV) is issued, and countries have to vote on the document. Providing sufficient affirmative votes are received (2/3), the document is essentially complete, although minor changes before a final vote (in the case of a standard) occurs with the circulation for vote of a Final Draft International Standard (FDIS). IEEE standards have a similar process, except that all document circulations outside the WG is in the form of a ballot. Here the balloting group is made up of interested parties. Anyone, anywhere in the world, who is an IEEE SA member can join a balloting group in which they have an interest, and any comments made to a ballot must be addressed. Even if the WG disagrees with a comment and rejects it, they must give a reason and recirculate the ballot and reason so that everyone can have the opportunity to change their vote. Only when this process is complete, and an affirmative vote of at least 75% has been achieved, can a standard be submitted to the IEEE Standards Board for approval.

There is a special relationship between the IEEE and IEC. Some IEEE documents are adopted by IEC and some are jointly developed. Such standards are termed "dual logo" standards. In addition, many IEEE and IEC working groups have members in common, so that coordination and cooperation is achieved. The author is one such person.

5. Standards development

The main problem for standards makers is to decide what applications have enough interest to enough people to warrant inclusion in a particular standard. As stated earlier, there is a natural disinclination to change standards more often than is absolutely necessary. However, while the pace of new fuse product introductions has inevitably slowed, as the field of fuse technology becomes more mature, new materials and new applications constantly demand that changes to standards be considered.

The process of introducing new requirement into existing standards is not an exact science. For example, there have been some devices that have appeared in the marketplace, and subsequently disappeared, without ever having testing specific to their requirements being included in any standard. Of course, there have also been other devices, at one time popular and included in, at least regional, standards that have declined and become obsolete and had their testing requirements removed (e.g. oil-fuse cutouts). The SF_6 fuse is a case of the former type of device. Similar in concept to the vacuum fuse, this used a short element between two massive contacts in a very small enclosure filled with SF_6 gas. It was similar to an expulsion fuse in performance, but more compact and with the advantage of no expulsion products. Although it was useful as a high current rating fuse suitable for encapsulation and use in insulated conductor systems, its cost and difficulty of manufacture led to its demise. While the expulsion fuse standard IEC 60282-2 [4] states that it can be used for any non-current limiting fuse (so that would include SF_6 and vacuum fuses), both devices remained as possible work items (PWI) with the IEC HV fuses subcommittee until relatively recently. Believing both devices to be no longer made (they are no longer made in Europe or North America), at the 2009 IEC SC32A meeting they were dropped as possible subjects for inclusion in IEC standards.

The question is therefore, “what is required for a new device or application (that requires additional testing) to be included in IEC standards?” Usually, the first requirement is that there be more than one manufacturer of the device. “Standardization” implies that several different devices should have common requirements. Secondly, sufficiently widespread use is needed to gain support from a number of countries’ National Committees. Finally, sufficient “experts” willing to work on creating the necessary testing requirements need to be found. This is why there is more variety of device and testing requirements in National or regional standards where agreement for change is likely to be easier to get. For example, because of the concern with starting brush fires, Australia has the most comprehensive testing requirements for the exhaust products of a distribution fuse-cutout (expulsion fuse), while IEEE has testing requirements for liquid-submerged expulsion fuses, because they are widely used in North American practice.

National standards existed before IEC, and IEC represented a attempt to draw these national requirements into a common format and with common requirements. Obviously this is of particular use to developing countries who did not have their own standards prior to IEC. However, Leach [2] discusses in some detail the difficulties of getting agreement as to what should appear in an IEC standard. It was explained that international participation in IEC HV fuse activity is relatively weak and dominated by a few countries. While fuses are used in probably every country of the world, only 21 countries are “P” (participating) members, and 19 are “O” (observing) members of the IEC SC32A. Even worse, however, less than ten countries are regularly represented at IEC meetings at this time. IEC standards therefore tend to represent the “lowest common denominator”, that is fuse types, applications, and their associated testing that the majority present at meetings can agree need to be addressed. This means that even quite widespread applications, that are not common in the majority of the relatively few countries represented in meetings, may not appear in IEC standards. In [2] there are some details of the attempts made to draw IEC and IEEE HV fuse standards closer together. It explains that great care must be exercised if fuses and techniques developed using a particular philosophy (e.g. North American methods that use fuses tested to IEEE) are employed in another country that has IEC standards as their norm, if the IEC standard does not recognize the additional testing required for such a fuse type and application.

Because of the limitations inherent in trying to write a “one size fits all” approach to standards, many countries adopt IEC standards but add their own “in country” requirements. In some cases this may be no more than a Annex giving additional relatively minor additional requirements (e.g. specifying some preferred time-current characteristics – of which there is little in IEC HV fuse standards). At the other extreme we find IEEE standards, which while following most of the IEC fuse requirements, uses a somewhat different format and includes special testing for several types of fuse not addressed in IEC standards (e.g. open-link, liquid-immersed, and enclosed cutouts). Despite these differences, IEEE are constantly trying to line up better with IEC, and the IEEE Fuse Subcommittee has a project in hand with this aim in mind. The special relationship between IEEE and IEC has been mentioned (4.). One area where the cooperation is somewhat less “official”, but very real, is the development in SC 32A WG6 of a fuse tutorial and application guide [3]. Some details of this project will be given, because it illustrates a very positive direction both for IEEE and IEC cooperation and an important step forwards for HV fuse standards in general.

6. Development of IEC 62655 TR

IEC HV fuse standards presently have five active documents. Four of these (current-limiting fuses, expulsion fuses, motor circuit fuses and capacitor fuses) contain testing requirements and some application information. A fifth document, a technical report, contains application information for the selection of HV current-limiting fuses for transformer circuits. No single document contains application information for HV fuses, unlike the situation with LV fuses, which has IEC TR 61818 Application Guide for low-voltage fuses [5]. In addition to the lack of convenience of having a single reference document for applications, concern had been expressed in view of the gradual loss of expertise among users. This has occurred as economic conditions have forced fewer engineers to take responsibility for larger numbers of devices after the retirement of engineers whose primary responsibility had been fusing. Although some manufacturers produce their own application guides, the desire was expressed for an “official” guide that customers would know was unbiased and represented the consensus of fuse experts throughout the world.

About 20 years ago the necessity arose to introduce definitions and testing for “Full-Range” current-limiting fuses in both IEEE and IEC HV fuse standards. Unlike with IEC standards, all of the application information in IEEE fuse standards was gathered into one document, IEEE Std™ C37.48 [6]. An IEEE survey of fuse users at the time disclosed widespread confusion concerning the different types of HV fuse, and so in addition to introducing special Full-Range fuse testing, a tutorial was written to explain the basic construction, operation, classification and application of current-limiting fuses of all types. This document, IEEE Std™ C37.48.1 [7] included an extensive section on common applications and went well beyond the constraints of C37.48 (although there was some duplication of information).

In standards development of a few decades ago, writers were discouraged (by older participants) against making statements in standards that were “tutorial” in nature. The old way of writing standards was to give no more information than was absolutely necessary. Now while a precise and unambiguous style is vital for a good standard, minimizing commentary and explanations of why a test is being done does not guarantee clarity, but often has the reverse affect. Even today, it is not uncommon to discover testing requirements in standards written many years ago that are somewhat ambiguous. If the reader does not already know what was intended requirements may be difficult to understand (for obviously those who wrote them knew exactly what was intended, but often failed to convey such information in an unambiguous manner). There has therefore been a gradual recognition that our documents need to be made more “user friendly” (although some of the “old thinking” still exists and not necessarily from elderly engineers!)

With some inspiration from IEEE Std C37.48,1, and in a spirit of helping the user, it was decided by the IEC HV Fuses subcommittee SC 32A to embark on the production of a tutorial and application guide IEC 62655 TR. It was to go well beyond what we had done in IEEE, and was truly grand in its scope. It is instructive to read the “mandate” given to the Working Group 6 responsible for its production:

"Given the general decline in the number of engineers having knowledge of fuses and their applications, the following goals have been identified:

- to help prospective users and protection engineers understand the basics of fuse technology and applications involving fuses, and to enhance the usage of such fuses;

- to illustrate the particular and unique advantages of fuse protection for most service applications;

- to minimise possible misapplications of fuses which could lead to problems in the field;

- to list and describe the many types of fuse in use today and the International standards and test procedures that apply to them;

- to consolidate and enhance existing knowledge of fuse application."

The Working Group has therefore gathered all of the published HV fuses application information available including both IEC and IEEE standards and has produced a document in broadly two parts, the first covering more “tutorial aspects” – that is how both current-limiting and expulsion fuses work and their ratings and characteristics, and a second part – covering application details. In the second part, in addition to application considerations common to most if not all applications (e.g. current and voltage selection) there are separate sections for the most common applications (e.g. overhead lines, transformers, motors, capacitors, wind power generation, etc.). Since installation, operation, maintenance, replacement, and recycling are also addressed, this is a very comprehensive document (presently having about 120 pages). With the decision to cover many more applications than were covered in existing IEC documents the Report should have wide application (e.g. for transformer protection, the typically North American practice of combining expulsion and Back-Up fuses is covered in addition to the typically European practice of striker tripped switches and Back-Up fuses). It is hoped that this document, with relatively minor changes can be adopted as an IEEE/ANSI standard (primarily requiring changes in nomenclature – “melting” versus “pre-arcing” for example).

7. Other activities in IEC standards

In addition to the Tutorial/Application Guide, presently close to having a second Committee Draft (CD) issued, work is also occurring in MT7 on a revision of the standard “HV fuses for external protection of shunt capacitors”, IEC 60549. The level of interest in capacitor fuses can be gauged by the fact that this standard was written in 1976 and has not been changed since. Although of limited interest, capacitor fuses are in quite widespread use and so it was felt by SC32A that a revision of this very old document was necessary. The first CD stage should be complete by the time of ICEFA and it will be interesting to see whether this draft revision has generated any significant comment.

MT3 continues to address issues with HV current-limiting fuses as they arise. The common North American practice of including current-limiting fuses in transformers is now spreading to Europe. In [2], there was discussion concerning the challenges that this can provide certain fuse designs, and the testing included in IEEE standards to address this. Some of this additional testing is now included in IEC, although with rather “weaker” requirements. For this application, however, all fuse designs need a more rigorous thermal cycling test to demonstrate the suitability of their sealing system for the higher temperatures to which they are exposed in transformers, compared to the typical European practice of fuses in oil-filled switchgear. Plans are therefore underway to include testing that is modelled on IEEE thermal cycling requirements for transformer applications. This testing has been in use for more than 30 years in the USA, and has produced excellent application experience.

Another area of interest to standards makers is non-ceramic insulators. There is a growing trend of polymer insulators being used for distribution fuse-cutouts. While standards have been established for composite line post insulators and suspension insulators, there are somewhat different conditions imposed on cutout insulators. Therefore for this application, IEC 60282-2 presently only requires that testing of composite insulators be by agreement between users and manufacturers. Work in the USA and Canada is seeking to redress this situation, but proposals for test methods have not been without controversy. When agreed test methods have finally been established in IEEE standards, it is likely that there will be interest in using them in IEC 60282-2.

8. Conclusions

The subject of standardization is vast; the issues involving safety are endless. But in summary, three things are needed to maximize “safety” when fuses are used as part of an overall protective scheme, all of which are addressed to a greater or lesser extent in fuse standards:

1) Firstly, an individual device needs to be designed and tested in a manner that demonstrates its ability to perform a particular function. Our fuse standards, both National and International, are a good starting point, but as pointed out in [2], no standard is a substitute for a knowledgeable manufacturer with integrity. Our standards have even begun to specifically acknowledge this. For example, if one looks at the “crossover testing” required for HV Full-Range fuses that use “dual elements”, IEC 60282-1 recognizes that only the fuse manufacturer can specify the test currents needed to show that the fuse meets the “spirit” of the standard.
2) Secondly, a fuse must be used for an application for which it is suited and applied following the necessary application guidelines. While this might seem obvious, the IEEE survey discussed earlier showed that some users thought a Back-Up fuse can clear any current that causes it to melt! Misapplication of a Back-Up fuse could, potentially, be worse than no fuse at all (in an oil tank for example). It is primarily to address this second point that the project to produce the HV fuse Tutorial/Application Guide was launched.
3) Thirdly, the user must treat a fuse with appropriate care. In the IEC application information for high-voltage fuse-links, it is advised that fuse-links should be handled with at least the same degree of care as any other precision-made item of equipment (such as a relay). Careless handling, especially of CL fuses, can result in damage that may prevent a fuse from working properly and in particular from interrupting fault current correctly.

The large number of people who are engaged in the writing of standards should be commended. While in some ways a tedious and thankless task, our industry could not exist without carefully written standards. One area where the standard process could be improved is by having more participation from the users of our fuses. Attending standards meetings is both an excellent education, and also gives one the opportunity to help steer standards to be of more relevance to the product user. A large part of the actual work of writing standards is done by volunteers who are retired (as they tend to have enough time to do the work) or by working engineers but in their "spare" time. A debt of gratitude goes out to them all.

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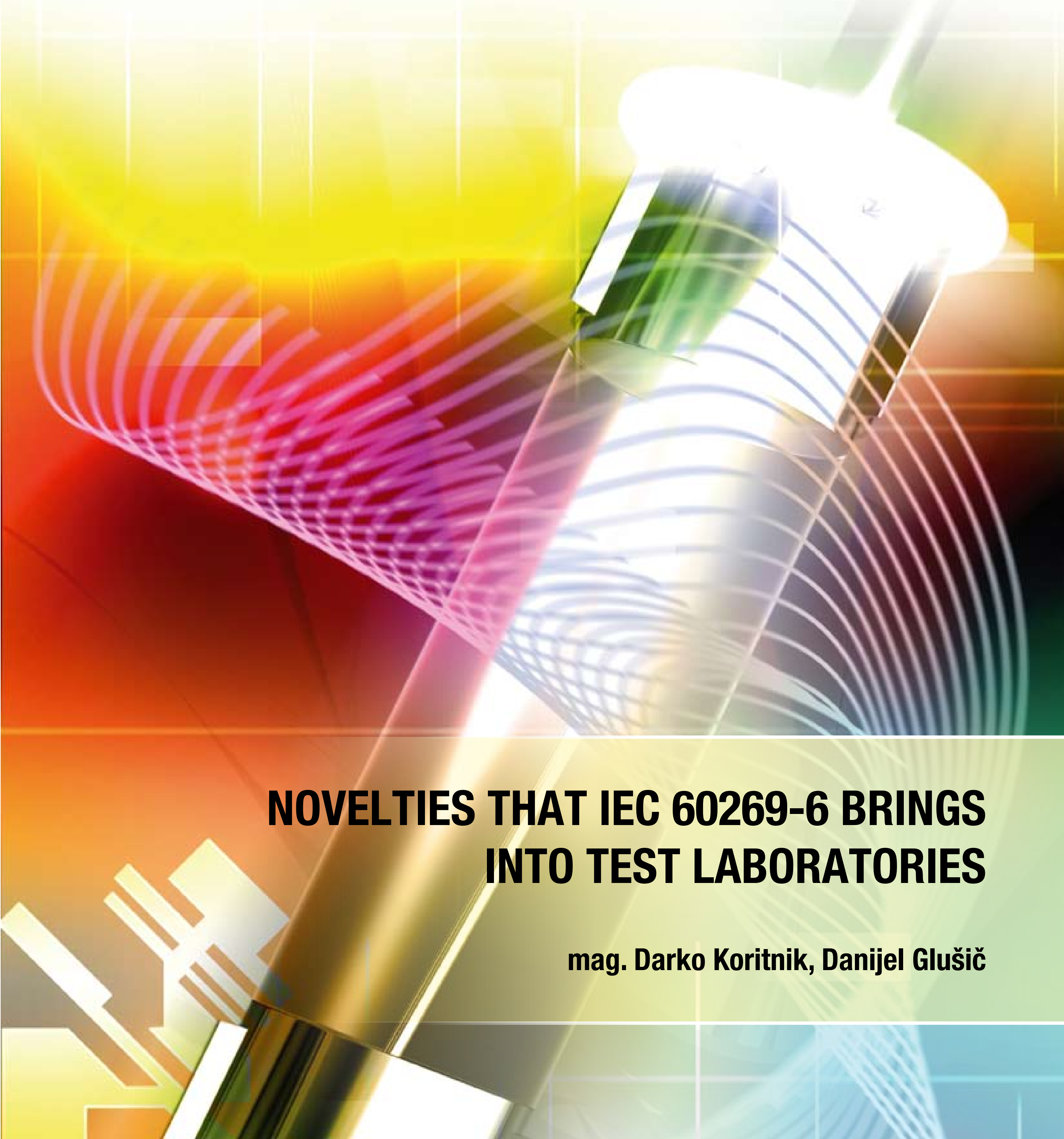

NOVELTIES THAT IEC 60269-6 BRINGS INTO TEST LABORATORIES

mag. Darko Koritnik, Danijel Glušič

Novelties that IEC 60269-6 brings into test laboratories

Darko Koritnik, Danijel Glušič

ICEM-TC, Gosposvetska cesta 84; 2000 Maribor; Slovenia, darko.koritnik@icem-tc.si, danijel.glusic@icem-tc.si

Abstract

The IEC 60269-6 standard on Low-voltage fuses – Part 6 Supplementary requirements for fuse-links for the protection of solar photovoltaic energy system was published in September of 2010. With such, a period of uncertainty has ended when we did not know how to test fuses for photovoltaic systems. Before such standard was accepted, the manufacturers and test laboratories only had guessed how to test PV fuses. Through acceptance of new standard IEC 60269-6, there is a uniform document for serves as a guide for what we do.

Every new standard introduces some novelties and so it does IEC 60269-6, which requires some changes and completions of test laboratories. For past several years, we have been preparing for those changes in test laboratories. Equipment and measuring procedures have been further completed in relation to the information that has been received from clients and members of TC, who have prepared the standard. However, in ICEM-TC we did not go into large investments, until we were absolutely certain what would be final requirements of the standard. In our laboratory, such uncertain transitional period has been surmounting with improvised solutions that enable tests in accordance with standard requirements and did not require large financial investments. However, those solutions have been useful but time-consuming.

Presented in this paper, are solutions with which, in ICEM-TC, test laboratories have been adjusted for testing according to IEC 60269-6 standard. Temporary solutions, which are currently being used, are described as well as permanent solutions that are mostly still in the making.

Keywords: PV electric fuse, testing, laboratories.

1. Introduction

Testing laboratory in ICEM-TC is mainly intended for developmental tests. These tests are conducted on the basis of standards or in relation to the particular client requirements. Tests demands can be altered in regards to a type of test objects: Fuses, protective switches, overvoltage protection...and in relation to test parameters: AC, DC, current, voltage, cosϕ, time constant... All this is feasible rather quickly and simply if the required parameters are inside the boundaries of a test laboratory capabilities. With appearance of photovoltaics, those parameters have exceeded our capacities. Large inquiry and solutions that had looked simple at the first sight convinced us to reorganize and complete the test laboratory so all requirements of the IEC 60269-6 standard have been taken into consideration. Due to the already mentioned financial sources and time restrictions, we have utilized various improvizations and unusual approaches. We have reached our goal at its core and prepared the laboratory for realization of tests according to the IEC 60269-6, while on the other hand, a number of errors on the existing equipment has drastically increased.

2. History and the purpose of a test laboratory at ICEM-TC

For a long time, there has been a plan for a laboratory for high power tests in Slovenia (making and breaking capacity during normal and short circuit operating conditions). First attempts to build a laboratory have been at Dogoše transformer distribution station and afterwards in the central valley of Sava River, although everything has been left in the planning stage. In mid 90's, we have been preparing first devices and equipment high power tests. A huge step was made in 2001 when the ICEM-TC institute had been founded. Short after the founding, we have installed used equipment from the EPM München in one of the abandoned transformer station at the hydro power plant of Mariborski Otok. Later on, the equipment was completed, changed and renewed. We have replaced copper-wire controls with a programmable digital controller, which enables fast and easier adjustment to changes in the test laboratory. Majority of measuring converters are replaced with the newer ones (high-voltage differential probes, Hall probes...) and gathering of data is regulated with the help of a digital transient recorder. From older equipment, only the larger parts remained (transformers, loads, thyristor switch, and rectifier). Most of the mentioned equipment will be replaced soon with the new one. Loads are also restored and reorganized, so they entirely suit to our needs.

In ten years of work, we have learned something indeed. We notice that the initial arrangement of the equipment has not been optimal, gathering and transfer of measuring signals has not been the best, and we mainly must replace few key elements (transformer, thyristor switch, rectifier...). Because of such, in 2011 a complete renovation of the test laboratory is underway.

3. Testing according to IEC 60269-6:2010

IEC 60269-6 is based on IEC 60269-1:2006. From the aspect of testing, there are very little news and even those tests are seemed to be simplified. Test laboratories that covered requirements of the part one of the standard have simply adjusted to the new requirements. Theoretically, that is true, although there are a number of test laboratories that covered only a portion of tests from the part one of the standard. We have been in a similar situation at ICEM-TC, where we have been limited by test voltages, as in most of the test laboratories.

4. Test laboratory equipment

Standard Low voltage has already been limited before PV occurred to 1000V AC and 1500V DC, although tests with DC voltage above 600 V have been very rare. Majority of test laboratories have been adapted to those requirements. The test voltage has also been limited at ICEM-TC to 550V AC and 600V DC. With appearance of a PV program, the inquiry has raised up to 1000V DC and more. Due to such a number of problems have occurred:

4.1 Ensuring the correspondingly high AC voltage

To the existing transformer TR1, we have added two more transformers TR2 and TR3 (figure 2). Primary winding is connected parallely and the secondary winding series or parallely (figure 2). In such way, maximal voltage rate is expanded to 1000V AC with a step of around 10V. Then, the maximum prospective current decreases to app. 30kA, which is still enough for DC PV majority of tests.

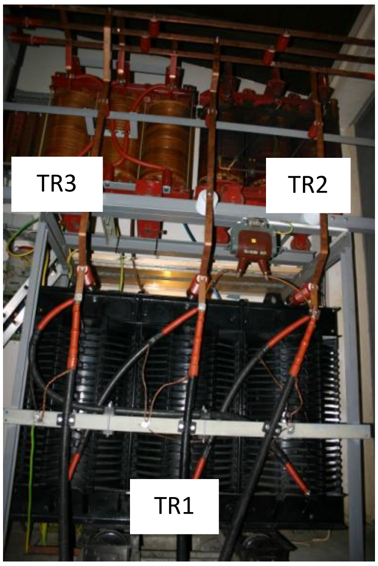

Fig 1: Setting of transformers

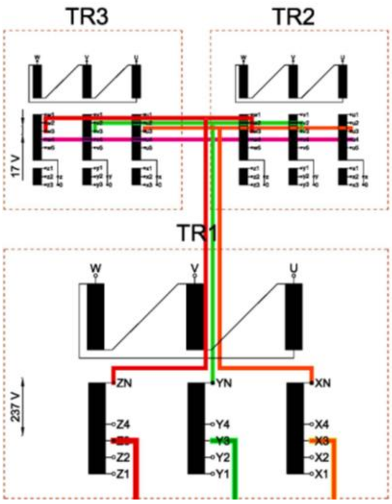

Fig 2: Example of transformers connection

4.2 The preparation of the corresponding rectifier

The existing rectifier (figure 3) is not designed for voltages over 600V DC and for the requirements of the PV tests, it is practically not applicable. The problem will be solved in two steps.

Short term provisional solution is a rectifier from aluminum factory TALUM. At TALUM, we have temporarily borrowed and partially reconstructed a diode rectifier (figure 4). That rectifier is originally intended for continuous operating at constant current of up to 10kA. During the tests, it is also often loaded with a current that is a few times the nominal, although only shortly. Because of such, the rectifier is not constructed optimally, although it serves its purpose. Turn on and turn off of the circuit is conducted with the existing thyristor switch on the alternating side. Long term solution will be a thyristor rectifier which would unite a rectifier and a switch in one device.

Fig 3: The existing rectifier

Fig 4: Temporary rectifier from TALUM

4.3 Checking and reconstruction of switches and other elements

Switches, busbars, insulators, loads and other elements in the circuit are checked and evaluated so the equipment could also withstand voltages of up to 1500V DC. Practically, smaller and larger faults (figure 5) have occurred, although they have been successfully resolved.

Fig 5: Examples of damages and faults on equipment

4.4 Measuring equipment

4.4.1 Measuring of voltage

Increase of test voltage and increased arc voltage has required a new voltage measuring converter. Among various possibilities, we have decided for high frequency differential probes. Their characteristics are not the best. However they are sufficient enough to meet the standards and the measuring procedure and they have a user-friendly concept, hence they galvanically separate measuring point from a transient recorder.

4.4.2 Gathering of data

Gathering, analysis and storing of data has already been conducted before with National instruments PXI measuring system. The system is based on flexibility and enables an easy adaptation to new requirements; however for testing of new PV fuse, we have had to introduce only a few software changes.

5. Measuring procedures and practical solutions

Most of the measuring procedures for tests, according to IEC 60269-6, can be thoughtfully assumed according to already fleeting procedures for other parts of IEC 60269 standard. Particular specifics do come up in relation to the characteristics of testing laboratory and physical phenomena.

5.1 Calibration with reduced voltage

Before the realization of short circuit tests as well as prior to other current tests it is necessary to calibrate the measuring circuit. With such key parameters are verified: Prospective current, power factor or a time constant and recovery voltage. Calibration, from the view point of a test laboratory is often more problematic than the test itself and because of such, the test laboratories use different procedures with the intention to decrease the number of calibration strikes and their negative effects. Computer application to determine necessary settings (figure 6) has already been used at ICEM-TC. On the basis of that calculation, the necessary settings are theoretically determined. It has been shown in practice that the calculated and measured values vary for app. 10% max. That application is not meant as a substitute for calibration but only as a guide for staff.

Calibration is always conducted with the measurements. We calibrate only up to 20kA under the full voltage because of mechanical and thermal limitations of equipment. In that example the effective current flows and parameters are determined with the help of a direct measurement (figure 7).

For current higher than 20kA, we have introduced calibration with reduced voltage. Primary winding of the test transformer is supplied with 400V only instead of 10 000V (figure 8). With such, both current and voltage theoretically decrease by the factor of 20. Practically, particular deviations appear which are dependent on the current. Due to such, we have conducted a series of calibration tests and prepared correctional diagrams.

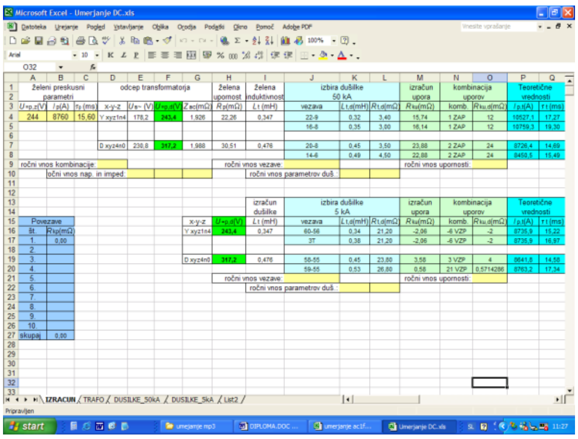

Fig 6: Computer application for calculation of necessary settings of transformers and loads

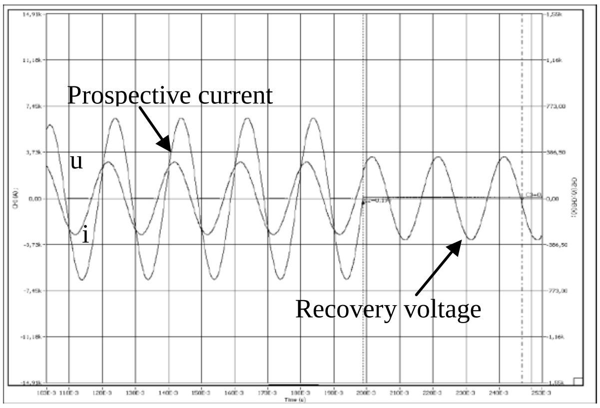

Fig 7: Example of calibration parameters

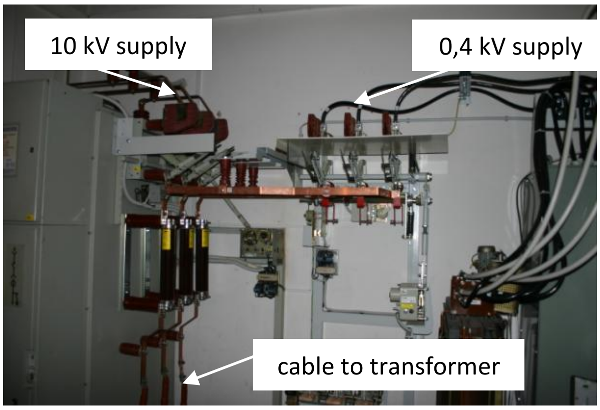

Fig 8: Arrangement for calibration with a reduced voltage

Calibration with reduced voltage provides us only basic values. Even tough, at the beginning, we have doubted the adequateness of the method, with the help of our own calibration measurements and inter-laboratory comparison we have determined that this method completely satisfies the requirements of developing tests.

5.2 Determining the time constant

Determining of the time constant is given in IEC 60269-1 standard (figure 9).

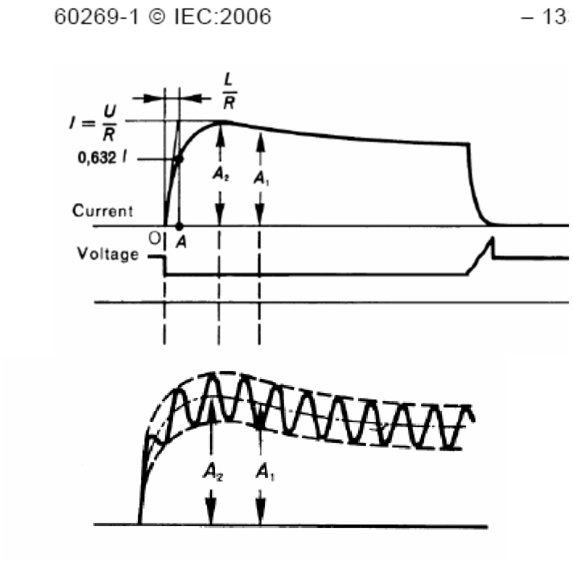

Fig 9: Instructions for determining the time constant in IEC 60269-1 standard

Theoretically it is clear how to determine time constant in cases of a completely smooth as well as ripple voltage. In case of the ripple voltage, practical problems appear which the consequence of voltage rectifying is. Standard IEC 60269-1 determines time constants between 15 and 20 ms. In that case, it is quite easier to determine effective value of maximal current I and time when that current reaches 0,632·I. The problem tough appears in IEC 60269-6 standard when the time constant is decreased from 1 up to 3 ms. In that case, the increase of the current is so fast that it is not possible to determine the course of the effective value. Under the identical settings of the circuit, the slope and the current waveform are mostly affected by the particular moment when the turn on is conducted respectively start angle on the alternating side of the rectifier.

We have searched for different possibilities of a more precise, simpler and faster determining of time constant, tough we have not found an appropriate solution. Because of such, we have analyzed the influence of start angle with the measured value of time constant.

Presented in Table 1 is a characteristic example (730V, 490A, 2ms). Parameters of the test circuit have been completely identical. We have only changed the moment, respectively the moment of start on the alternating side. We have observed one

3,33ms (60˚) ripple and divided it into 20 equal parts, each being 3˚.

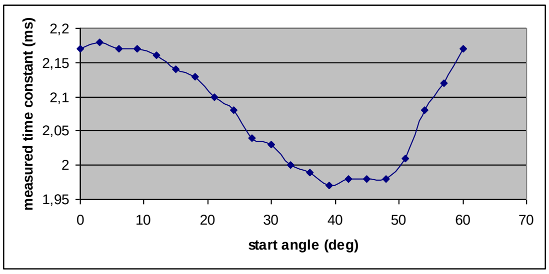

Fig 10: Comparison of measured values of time constant in relation to the start angle on AC side

Table 1: Comparison on measured values of time constant in relation to the start angle on AC side.

Start angle (˚)	Time constant (ms)		Start angle (˚)	Time constant (ms)
0	2,17			
3	2,18		33	2
6	2,17		36	1,99
9	2,17		39	1,97
12	2,16		42	1,98
15	2,14		45	1,98
18	2,13		48	1,98
21	2,1		51	2,01
24	2,08		54	2,08
27	2,04		57	2,12
30	2,03		60	2,17

The comparison of calculated values has shown expected deviations in the range of ± 0,10 ms. Required time constants are between 1 and 3 ms, and if we take into consideration reading errors, uncertainty of measuring instruments and even add some reserves, the boundaries can be narrowed to 1,5 – 2,5 ms. In such way, the corresponding values of time constants are reached without any complicated and time-consuming analyses of the current waveform. That approach is simple, fast and reliable, although it requires loads, which enable to set time constant within the narrowed range.

6. Standard tests and measurements

As we have previously stated, the biggest problem presents DC voltage of up to 1500V, which is nothing new from the viewpoint of the standard. IEC 60269-6 standard still introduces some novelties in the field of testing as well. For a better overview, we have created a comparison of test requirements between IEC 60269-6 and IEC 60269-1. We have followed chapter 8 and its subchapters.

Subchapter: 8.1 – General – Mentions some changes in organization, preparation of tests and set of required tests. From the viewpoint of tests themselves, there are not any significant changes except for few exceptions, which are described in the continuation.

8.2 – Verification of the insulation properties and of the suitability for isolation – without changes

8.3 – Verification of temperature rise and power dissipation

PV Fuses of lower nominal currents are often installed in fuse disconnectors, which disable access to a fuse during operation. We have encountered that very problem with other fuses in closed enclosures.

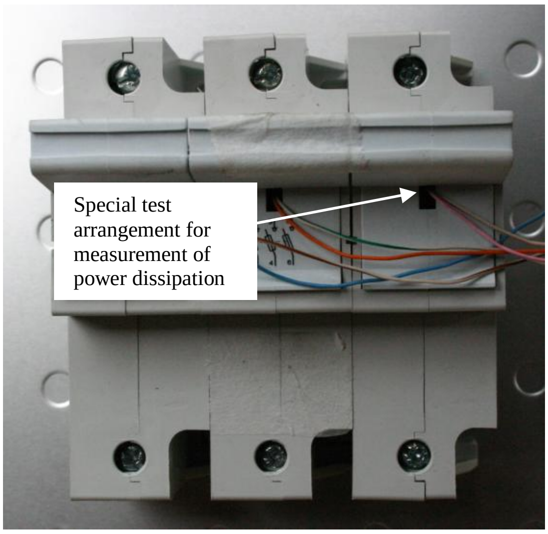

Fig 11: Example of reorganization of fuse-holder for the purpose of power dissipation measurements.

8.4 – Verification of operation

Verification of conventional non-fusing and fusing current

Test arrangement and measuring devices stay the same as before and small novelties are only in the fields for required test parameters.

Verification of rated current

New requirements that require additional preparations appeared in this field. Different approaches are possible. We have used switches that start or shut off loads for higher currents, and for lower currents the adjustable resistors. Operation of indicating devices and strikers, if any

Simplified method and evaluation that is possible to realize during the test of breaking capacity (I5), during the preparations and at lower voltage of 50V.

8.5 Verification of breaking capacity

This subchapter, from the viewpoint of test laboratories, is the most problematic, although in the sixth chapter of the standard, it is significantly simplified in regards to other chapters of IEC 60269.

I1 – 1500V, 30 kA, 1-3ms are uppermost required boundaries. With above described resolutions, we have almost reached those values at ICEM-TC. Upon the reconstruction of the test laboratory, all the required parameters will be attained.

I2 –If the laboratory is qualified to carry out I1, it also requires just the appropriate loads and with ease covers those tests as well.

I3 –crossed out

I4 –crossed out

I5 –Preparation of this test is significantly simplified and the inductance is determined and not the time constant. Inductance of a circuit is only limited to downwards (≥100µH), and there is not a limitation for the upwards direction. During the carrying out of tests, we have noticed that a significant increase of inductance (1000 µH and more) negatively affects the results. To conduct development tests, the missing uppermost boundary is rather distracting since we do not know which parameters would be used during certification.

8.6 Verification of the cut-off current characteristics

No changes

8.7 Verification of I^2t characteristics and overcurrent discrimination

No changes

8.8 Verification of the degree of protection of enclosures

No changes

8.9 Verification of resistance to heat

No changes

8.10 Verification of non-deterioration of contacts

No changes

8.11 Mechanical and miscellaneous tests

Added to an entire clause 8.11 is another clause that is simple at first look, although during practical tests some unclear details appear which quite powerfully impact on results.

8.11.2.5 Verification of functionality at temperature extremes

A simple concept: the test object is heated to a certain temperature (50˚C) with a tolerance ± 5˚C, which does not require any special temperature chambers. Further on those test objects are loaded with a particular current and the time of circuit break as well as an overall condition of a test object is observed. Basically, these tests are rather simple, although in practice a lot of unclear details emerge. In the standard itself, it is not defined what is the surrounding temperature during the current test. Are current tests carried out at room temperature (20˚C) or in a chamber at 50˚C or even at an increased temperature caused by the heating of a test object? Different ambient temperatures in some of the cases strongly impact on test results.

7. CONCLUSION

At ICEM-TC, we test for different manufacturers who all carry out test according to the same standards; however for the needs of development, they utilize different adjusted procedures. We are quite used to such deviations and individual wishes that our clients have. In spite of that, the period before the approval of IEC 60269-6 standard has been rather uncertain and difficult. Everyone tried to convince us that we have to adjust to test PV fuses although no one exactly knew what would be the final requirements. As standard has been developing, we have been receiving more reliable information. Upon the acceptance of the standard, we have already had a qualified laboratory for almost all key tests. The emphasis has been and is still on the Verification of breaking capacity, where we have from the pre-existing and upgraded equipment achieved practically impossible and reached almost all the standard requirements (1450V, 30 kA DC). The use of devices at the limits of their capabilities or even over their limits has caused a number of faults. Most of them have been quickly and effectively fixed, except for one related to the transformers and because of such faults, the available current decreased to a half (15kA). In relation to the condition of our devices, current and the arriving standards and experiences that we gained, we have decided to completely reconstruct and renovate overall test laboratory. At the beginning of next year, we expect to open the renovated test laboratory where it would be possible to carry out all high power tests on PV fuses (up to 30 kA) and other similar devices.

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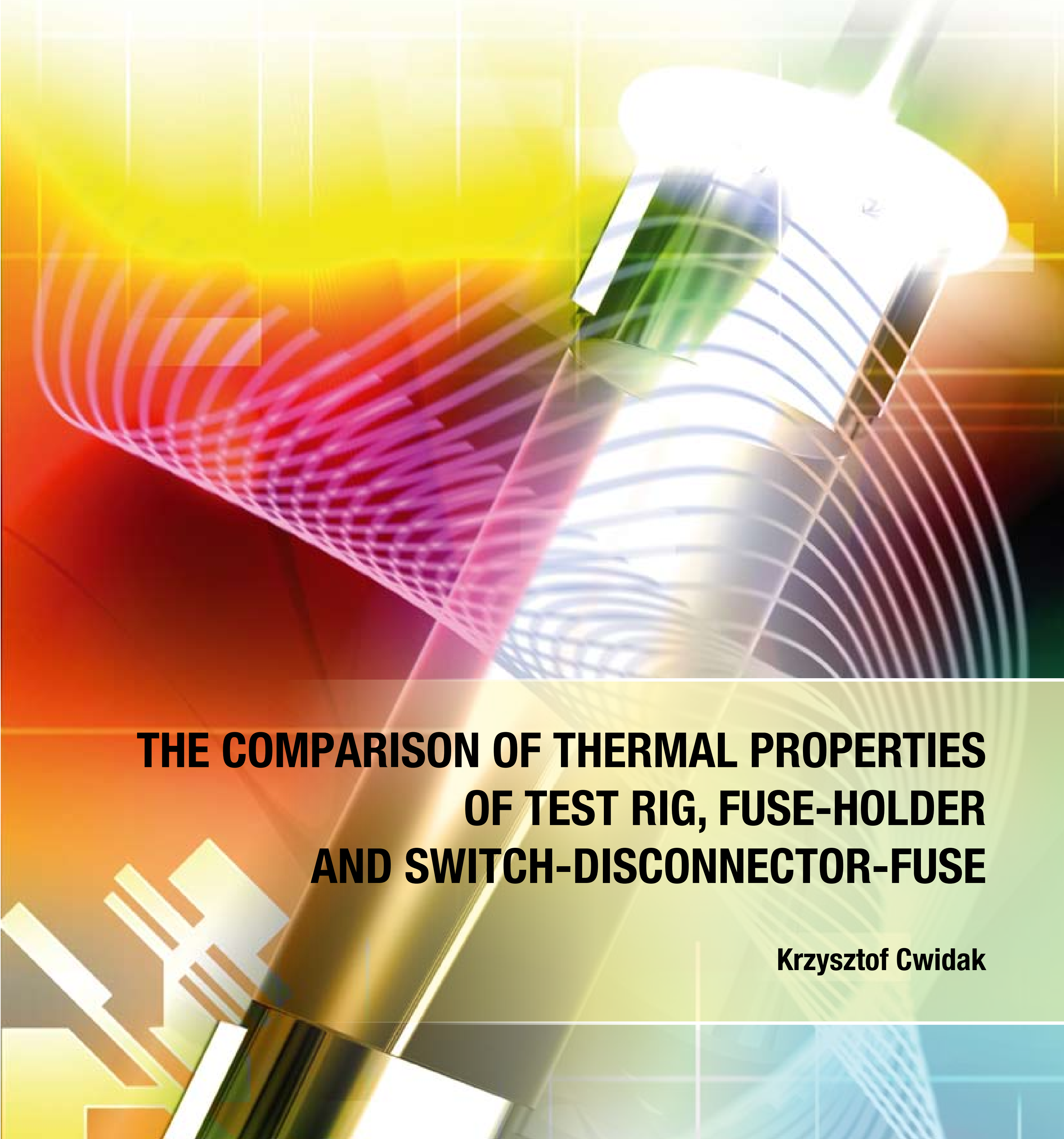

THE COMPARISON OF THERMAL PROPERTIES OF TEST RIG, FUSE-HOLDER AND SWITCH-DISCONNECTOR-FUSE

Krzysztof Cwidak

The comparison of thermal properties of test rig, fuse-holder and switch-disconnector-fuse

Krzysztof Cwidak

Electrotechnical Institute Gdansk Branch, Narwicka 1, 80-557 Gdansk, Poland, krzysztof.cwidak@iel.gda.pl

Abstract

The paper presents results of verification of conventional non-fusing current and fusing current performed with the usage of the test rig according to IEC 60269-3, fuse-bases with fuse-carriers and switch-disconnector-fuse. The results show that the test rig according to IEC 60269-3 is not a thermal equivalent apparatus to the fuse-holders. Furthermore, the switch-disconnector-fuse has even worse cooling conditions of the fuse-link than fuse-holders.

Keywords: fuse-link test, D-type fuse-link, test rig, conventional time, conventional current.

1. Introduction

The inspiration to start with a comparative tests were negative results of size D fuse-links tested in testing laboratory at conventional fusing current (I_f) in the test rig according to IEC 60269-3 [1]. The fuse-links tested did not operate within conventional time. It can be assumed from this results that the differences in fuse-link cooling between test rig and fuse-holders have an influence on the results of the tests i.e. operate time at conventional fusing current.

According to the IEC 60269-3 standard the verification of conventional non-fusing (I_{nf}) and fusing (I_f) currents of D and DO type fuse-links shall be performed with the usage of the special test rig while in earlier CEE 16 [2] and IEC 60269-3A:1978 [3] standards this tests were performed with the usage of typical fuse-holders consisting of fuse-base and fuse-carrier. The reason for introduction of this test rig to the IEC 60269-3-1 [4] in 1994 was to eliminate the influence of fuse-base and fuse-carrier types on test results. However, the construction of this test rig is an "open" construction while the fuse-holder (fuse-base with fuse-carrier) is a "closed" construction. This change caused a better fuse-link cooling in the case of test in the test rig than in the case of test in the fuse-holder. Also in the last years the disconnector-fuses and switch-disconnector-fuses are becoming popular. These apparatus have even worse cooling conditions than fuse-holders.

That is why the comparative tests of verification of conventional non-fusing current and fusing current were performed with the usage of the test rig according to IEC 60269-3, fuse-holders (fuse-bases with fuse-carriers) and switch-disconnector-fuse.

2. The objects to be tested

- Test rig according to Fig. 105 and 106 of IEC 60269-3. Test rig is presented on Fig. 1. The contact force was adjusted to 80 N.

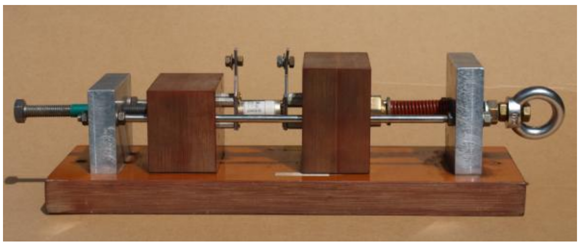

Fig. 1: Test rig according to Fig. 105 of IEC 60269-3.

- Typical size D02 fuse-holders consist of fuse-bases and fuse-carriers. The fuse-holder is presented on Fig. 2.

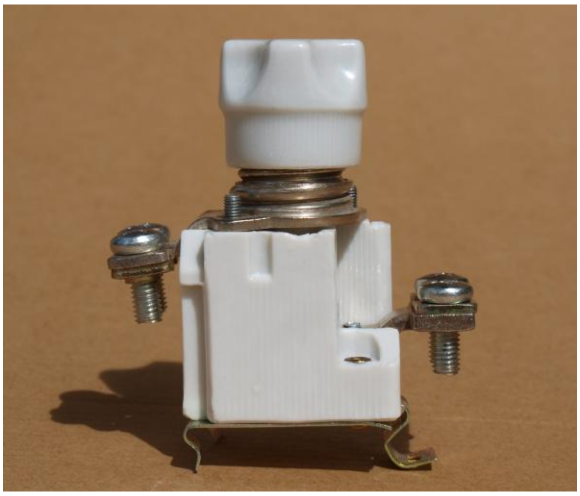

Fig. 2: Size D02 fuse-holder used in tests.

- 1-pole switch-disconnector-fuse type STV D02-1 for rated current of 63 A and rated voltage of 400 V AC made by ETI. This apparatus is presented on Fig. 3.
- Typical size D02 gG fuse-links for rated current of 63 A and rated voltage of 400 V AC. The fuse-links tested belong to the same manufacturing batch.

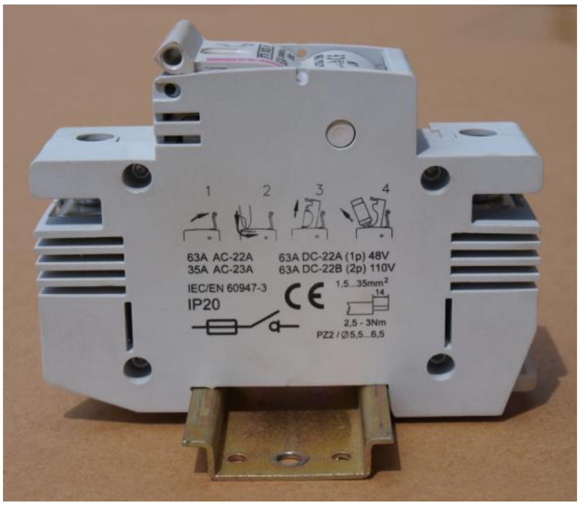

Fig. 3: Switch-disconnector-fuse type STV D02-1.

3. Preliminary tests of the fuse-links

Before the tests at I_{nf} and I_f currents the internal resistance of 15 fuse-links tested were measured with a measuring current of 6 A. The resistance of fuse-links varied from 0,872 Ω to 0,937 Ω. After this the fuse-links were divided into three groups of similar distribution of resistance.

The next test is verification of temperature rise and power dissipation of all fuse-links that performed in fuse-holders. The temperature rise not exceed 50,1 K and the power dissipation of fuse-links varied from 4,60 W to 4,93 W.

4. Comparative tests and test results analysis

According to IEC 60269-1 [5] the tests at non-fusing and fusing currents should be performed on the same fuse-links. Each of the groups of fuse-links were tested in one type of apparatus. The cross-section area of copper conductors was 16 mm^2. The conductors were insulated with PVC. The ambient air temperature during the tests was between 23,5°C and 26,5°C. After the tests at non-fusing current the fuse-links and tested apparatus were cooled down to ambient air temperature. No one of the tested fuse-links operated within 1 h conventional time. The times measured at fusing current are presented in Table 1. One of the fuse-link tested in test rig operated in time which exceed the conventional time. Also in Table 1 the results of statistical analysis are presented.

Small significance level of 0,0002 indicate that averages of times for test rig, fuse-holders and switch-disconnector-fuse differ significantly. In other words, a significant difference exists among the averages for test rig, fuse-holders and switch-disconnector-fuse. This mean that the test rig isn't thermal equivalent to fuse-holders and switch-disconnector-fuses.

Table 1: Comparative test results and statistical analysis.

	Test rig	**Fuse-holder**	**Switch-disconnector-fuse**
Times at I_f [s]	1897 1915 2625 2836 3934	1030 1061 1176 1288 1721	640 662 679 855 913
Average [s]	2641	1255	750
Standard deviation [s]	835	280	125
Variance	697685	78187	15619

5. Conclusions

- The tests results show that the test rig according to IEC 60269-3 is not a thermal equivalent apparatus to the fuse-holders. This cause the differences in the operate times of the fuse-links tested in test rig and fuse-holder. In extreme cases fuse-links tested at fusing current in the test rig may have fusing times exceeding conventional time (negative result) while tested in the fuse-holder have fusing times not exceeding conventional time (positive result). That's why the construction of the test rig according to IEC 60269-3 should be modified. The second way is resignation from the test rig and test the fuse-links in typical fuse-holders.
- The switch-disconnector-fuse have even worse cooling conditions of the fuse-link than fuse-holders and test rig. This means that the fuse-links used in switch-disconnector-fuse have very short operate times. It was confirmed during the tests.

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CUMULATIVE-AGEING APPROACH FOR DETERMINATION OF THE LIFE-DURATION OF FUSES IN CASE OF MULTI-LEVELS CYCLES

Jean-Louis Gelet, Tadahiro Hayashi

Cumulative-ageing approach for determination of the life-duration of fuses in case of multi-levels cycles

Jean-Louis Gelet(1), Tadahiro Hayashi(2)

(1) MERSEN SB sas, Rue Vaucanson, 69720 Saint-Bonnet de Mure– France, jean.louis.gelet@mersen.com
(2,) MERSEN JAPAN KK, Shinjuku Dai-ichi Seimei Bldg 3F P.o. Box 5059 2-7-1 Nishi-Shinjuku Shinjuku-ku, 163-0703 Tokyo, Japan

Abstract

Fuses-manufacturers carry out many tests in order to evaluate the life-duration of their products, but tests cannot match exactly actual conditions in the field. Then, they have to extrapolate test-results for estimating life-duration in operation. MERSEN drew out a method based on determination of coefficients applied to the fuse-rating for withstanding the required life-duration.

But, fuses are often submitted to complex conducting-cycles, combining short and long periods, with more or less high current-values, even with off-times. The common and simple approach is to calculate coefficients corresponding to each stress and to combine them by multiplication.

This can lead to excessive restriction of the current in the fuse, or reversely to large fuse-ratings, increasing I^2t and reducing the short-circuit-protection. In this paper, MERSEN will propose an improved method using accumulative-effect approach. This method will help the application-engineers to better choose the fuse and improve the quality of the equipments.

Keywords: electric fuse.

1. Fatigue ageing of ultra-fast fuses

Protection of power-semiconductors needs to develop specific ultra-fast fuses, according to IEC standard 60269-4. Indeed a very fast operation of the fuses is required in order to save semi-conductors in case of short circuits in the field. In other words, for a given rated-current, fuses will have to present a minimal conducting area ; or, on another hand, for a given I^2t, they will be able to carry a maximal current.

Unfortunately, carrying a large current doesn't go without any risks. The biggest of them is the occurrence of some metallurgical fatigue phenomenon. Let us introduce briefly what happens. Due to Joule-effect, the current-conduction induces a heating of the conductors, specially at the notches of fuse-elements. Then, the temperature would causes some dilatation of the metal. But, as this dilatation is interfered with sand around the notches, stresses are developed. Note that stresses are generated all along the element, but they are amplified on the restrictions of the necks.

When fuses are used in a cyclic way, the alternation of stressed and relaxed states leads to ageing by fatigue phenomenon. This phenomenon is well known by metallurgist-engineers. For instance in bridges-building, in automotive-engines, in aerospace-industry, people take big care of it. Nevertheless, in case of power-semi-conductor-fuses, the problem becomes more difficult because the metal mechanical properties actually change during the cycle, due to change of temperature. In a previous paper presented at ICEFA-2003[1], we showed that ageing was probably due to a combination of fatigue and creep. As a matter of fact, it is still difficult to calculate by analytical or numerical methods what will be the ageing of fuses.

Another question is the large discrepancy going together with fatigue.

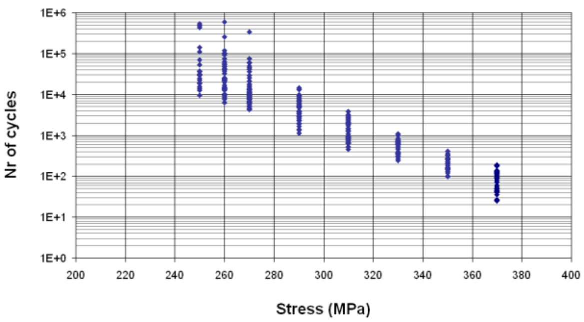

Fig. 1: Rotative-bending fatigue-tests on XC10-steel[2]

Under a characteristic value of the stress, the material will not be subjected to fatigue. But beyond this value, fatigue will occur. As soon as 1870, Wöhler studied fatigue of railways-axles and proposed his law, which is available when fatigue happens, but doesn't take into account any transition to the area where material sustains infinite number of cycles :

$$\log(N) = a - bS \qquad (1)$$

Fig. 1 shows that in words of numbers of cycles N, the discrepancy runs from 1 to more than 10 at a level of stress S. For example, for S = 290 MPa, N ranges from 1150 to 14500.

mean value is mean(N) = 5208 cycles (2a)
standard deviation is σ(N) = 3550 cycles (2b)

and ratio $\frac{\sigma(N)}{\mathrm{mean}(N)} = 0.68$ (2c)

This is a traumatic and inexact reading of Wöhler's law. It will be more precise to consider that log(N) runs from 3.061 to 4.161.

mean value would be mean(logN) = 3.620 (3a)
standard deviation would be σ(logN) = 0.298 (3b)

and ratio $\frac{\sigma(\log N)}{mean(\log N)} = 0.082$ (3c)

This way of considering the Wöhler's law doesn't only make sense from a mathematical point of view. Also from the physical point of view, it is legible. Indeed, it is now a common knowledge that the fracture-mechanism of fatigue is based on the opening of a crack due to application of cyclic stresses. The increment of the crack is called the C.O.D. (Crack Opening Displacement). And what is interesting is that C.O.D. doesn't occur at each cycle, but corresponds to a block of several cycles.

2. MERSEN's methodology for fuse-determination

For a long time, MERSEN's engineers are aware of this phenomenon and thanks to many tests, could develop a method allowing to correctly choose a fuse. Nowadays requirements from customers concern figures for very long life-durations, up to thirty years, and statistical considerations giving evaluation of tolerances around mean values.

Because of the complexity of calculations based on theory of fatigue, MERSEN's engineers have given priority to statistical analyzes of numerous tests-results. Basically, from their observations, engineers have been brought to consider two tendencies[3].

The first of these tendencies involves cases where it is possible to consider that heating concerns the whole fuse. The current-conduction period is long enough to reach a quasi stabilized field of temperature within the fuse. It is what occurs when the equipment is running during the day and stopped during the night. The stabilized temperature comes when the conduction period is less than about three times the thermal time-constant of the fuse. For most of fuses, stabilisation is got after one hour. Then tests one hour on / one hour off are characteristic of this first approach. The RMS-value of the current is the decisive parameter.

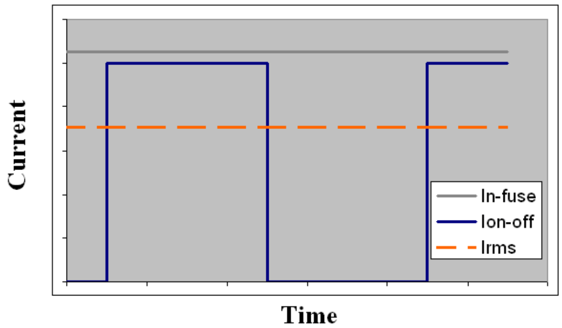

Fig.2: Example of a global heating of the whole fuse. RMS-current is to be taken into account.

MERSEN has introduced a coefficient A as the ratio:

$$A = \frac{I_{RMS}}{In} \,, \tag{4}$$

where I_{RMS} is the RMS-current of the cycle and In is the rated current of the fuse. MERSEN also defined A2 as the value of A for a life-duration of 30 years. Generally, for ultra-fast fuses, A2 is about 0.60.

A second tendency concerns cases where thermal stabilisation is not achieved, but where peaks of current may induce local heatings of the fuse-elements.

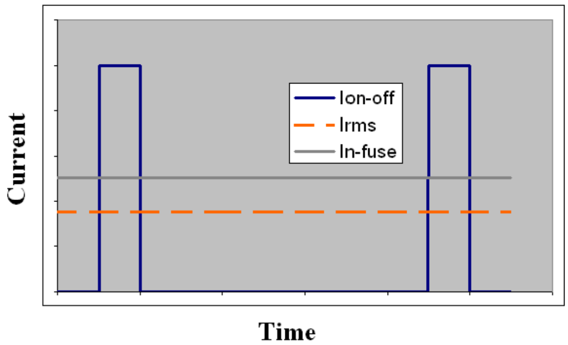

Fig.3: Example of a peak of current. How much is this peak close to the melting point?

Of course, melting temperature is not reached, but as more the local temperature becomes closer to the melting temperature, as more ageing is important.

The decisive issue will be how much the current I_{ON} during the conduction-period t_{ON} will be close to the current I_{melt} which will lead to melting for a conduction-time equal to t_{ON}.

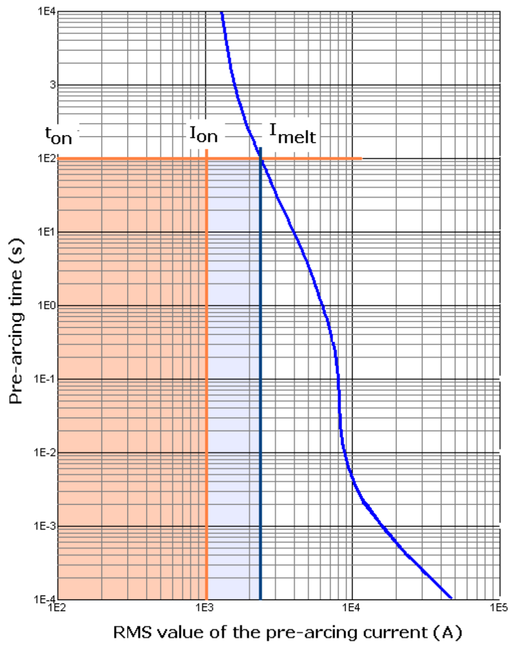

Fig.4: Prearcing-curve with t_{on}, I_{on} and I_{melt}.

MERSEN introduced a coefficient B as the ratio:

$$B = \frac{I_{ON}}{I_{melt}} \,. \tag{5}$$

As for A2, MERSEN also defined B2 as the value of B for a life-duration of 30 years. Generally, for ultra-fast fuses, B2 is about 0.60.

3. Complexity of the cycling-conditions

Pure rectangular cycles as shown on fig. 2 and 3 are very simple and also very rare. In addition, rated current In and the melting curve are defined under standard conditions that are not of common use.

Several practical parameters will interfere on the life-duration :

- A1 is to be used when the temperature inside the cubicle is above 30°C. This coefficient is calculated from the published coefficient a.
- C1 takes into account the size of the conductors connected to the fuse and the cooling of the terminals
- B_V takes into account the velocity of the air on the fuse. It is calculated from the published B1.
- C_{PE} is to be used when the current-frequency is higher than 100 Hz, because of proximity effect.
- and k is to be applied to A2 for calculating :

  $$A'2 = k.A2 \qquad (6)$$

  when conduction time and/or stop-time are shorter than one hour.

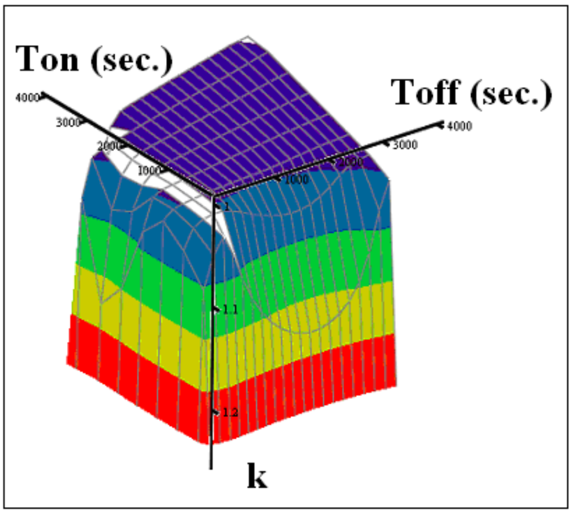

Fig. 5: Coefficient k to be applied to A2 vs t_{ON} and t_{OFF}.

Coefficient k supposes that the cycle presents a simple shape, with a conduction time t_{ON} at I_{ON} and stop-time t_{OFF}. Times t_{ON} and t_{OFF} as well as the value of the current I_{ON} may have different values.

4. Cumulative effects

Moreover than A2 and B2 coefficients which have been defined and determined in order to guarantee a life-duration of 30 years, MERSEN's engineers are able to draw out the ageing-law of the fuse: log(Nr)= f(□), where Nr is the number of cycles that the fuse will withstand before opening and □ is the stress it will have to support. The stress □ could be expressed according to different ways :

- current I_{ON} during t_{ON},
- Rms-current I_{RMS} of the cycle during $t_{ON} + t_{OFF}$,
- ration of the current I_{ON} to the rated current of the fuse : $\frac{I_{ON}}{In}$
- ratio A of the current I_{RMS} to the rated current I_n of the fuse : $A = \frac{I_{RMS}}{In}$
- ratio B of the current I_{ON} to the melting-current I_{melt} of the fuse : $B = \frac{I_{ON}}{I_{melt}}$

In the following developments of this paper, let us consider □ as A.

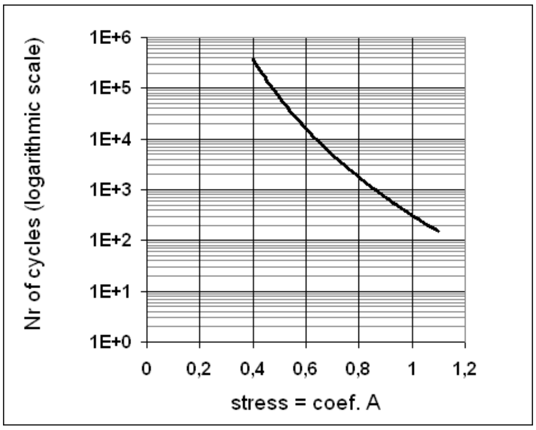

Fig. 6: typical ageing curve (available only for demonstration)

Miner[4] defined *damage* as the ratio at the time t, of the duration spent since time $t_0 = 0$ to the total expected duration :

$$\text{Damage}(t) = \frac{N(t)}{Nr} \qquad (7a)$$

damage also depends on the load :

$$\text{Damage}(t, A) = \frac{N(t, A)}{Nr(A)} \qquad (7b)$$

This definition of damage is equivalent to the ratio of total life. In fact more physical observations could be used for describing damage. For instance, a sample submitted to stresses will develop a crack; the depth of the crack can be used as a measure of damage. Another example is with ageing of fuses ; the value of the electrical resistance could be used as a measure of damage. In these two examples, damage is not linear with the ratio of total life.

Here-after, we shall consider damage as linear with the ratio of total life. This will help us for taking into account cumulative effect of several kinds of loads.

Let us suppose that the sample has to be stressed by two kinds of cyclic loads expressed as $A_{(1)}$ and $A_{(2)}$. How does each of them contribute to make damage on the sample and what will be their cumulative effects ?

$$\begin{aligned}&\text{Damage\_cumulative}(t, A_{(1)}, A_{(2)})\\&= f\left[\text{Damage}(t, A_{(1)}), \text{Damage}(t, A_{(2)})\right]\end{aligned} \tag{8}$$

Then, the question will be: what is the function **f**? Answer will be: it depends. And let us take an example.

Example :

The fuse is submitted to cyclic currents. Two kinds of cycles can occur :

- $t_{ON(1)}$ = 1 hour under current I_{ON} followed by $t_{OFF(1)}$ = 1 hour
- series of $t_{ON(2)}$ = 5 minutes under current I_{ON} followed by $t_{OFF(2)}$ = 5 minutes ; each series will count 30 repetitions of $t_{ON(2)} + t_{OFF(2)}$

In addition, long cycles, i.e. $t_{ON(1)} + t_{OFF(1)}$ will alternate with series of short cycles $t_{ON(2)} + t_{OFF(2)}$ as follows, in a ratio of 1 to 2, for instance :

- $t_{ON(1)} + t_{OFF(1)}$
- one series of 30 repetitions of $t_{ON(2)} + t_{OFF(2)}$
- $t_{OFF(1)}$
- a second series of 30 repetitions of $t_{ON(2)} + t_{OFF(2)}$
- $t_{OFF(1)}$
- and then, coming back at $t_{ON(1)} + t_{OFF(1)}$

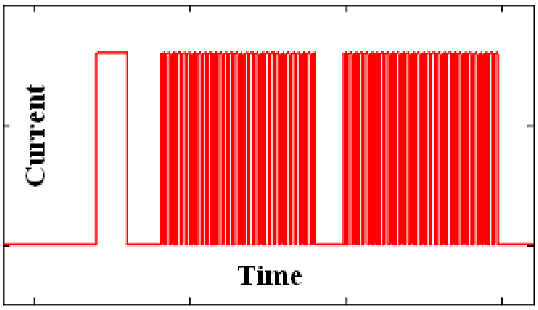

Fig. 7: long cycles and short cycles alternations

We can consider that if the heating of the fuse is the same after 1 hour than after 5 min. (and idem at cooling down), then from the point of view of damage, a long cycle $t_{ON(1)} + t_{OFF(1)}$ is equivalent to a short cycle $t_{ON(2)} + t_{OFF(2)}$.

Then:

$$\begin{aligned}&\text{Damage\_cumulative}(t, A_{(1)}, A_{(2)})\\&= \text{Damage}(t, A_{(1)}) + \text{Damage}(t, A_{(2)})\end{aligned} \tag{9}$$

and:

$$\text{" f " = " + "} \tag{10}$$

But if the heating of the fuse is different between long and short cycles, then, from the point of view of damage, a long cycle $t_{ON(1)} + t_{OFF(1)}$ is not equivalent to a short cycle $t_{ON(2)} + t_{OFF(2)}$. And the question will be how much each of them will contribute to the ageing of the fuse.

Because of long cycle $t_{ON(1)} + t_{OFF(1)}$, at the time t, the fuse will present the damage :

$$\text{Damage}(t, A_{(1)}) = \frac{N(t, A_{(1)})}{Nr(A_{(1)})} \tag{11}$$

and because of short cycle of $t_{ON(2)} + t_{OFF(2)}$, at the same time t, the fuse will present another damage :

$$\text{Damage}(t, A_{(2)}) = \frac{N(t, A_{(2)})}{Nr(A_{(2)})} \tag{12}$$

The actual life-duration t_{end} of the fuse will be reached when the summation of damages will be :

$$\begin{aligned}&\text{Damage}(t_{end}, A_{(1)}) + \text{Damage}(t_{end}, A_{(2)})\\&= \frac{N(t_{end}, A_{(1)})}{Nr(A_{(1)})} + \frac{N(t_{end}, A_{(2)})}{Nr(A_{(2)})} = 1\end{aligned} \tag{13}$$

If we draw the characteristic curve of $\text{Damage}(t, A_{(2)})$ vs. $\text{Damage}(t, A_{(1)})$:

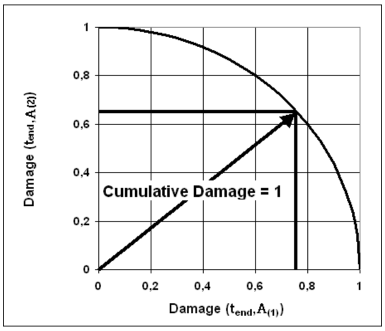

Fig. 8: Damage(t_{end} , ⍰$_{(2)}$) vs. Damage(t_{end} , ⍰$_{(1)}$)

we'll get the equation of a circle and global damage will be the result of a quadratic summation:

$$\begin{aligned}&\text{Damage\_cumulative}(t, A_{(1)}, A_{(2)})\\&= \sqrt{\text{Damage}^2(t, A_{(1)}) + \text{Damage}^2(t, A_{(2)})}\end{aligned} \tag{14}$$

and:

" **f** " = " **quadratic summation** "

This expression will be highly useful in any case of combination of independent (or non-linear) stresses. It will be used to calculate the life duration of a fuse from the stresses expressed as $A_{(1)}$ and $A_{(2)}$. Reversely, it will be used in order to determine the right fuse for supporting during 10 or 30 years a combination of stresses expressed as $I_{ON(1)}$, $t_{ON(1)} + t_{OFF(1)}$ and $I_{ON(2)}$, $t_{ON(2)} + t_{OFF(2)}$.

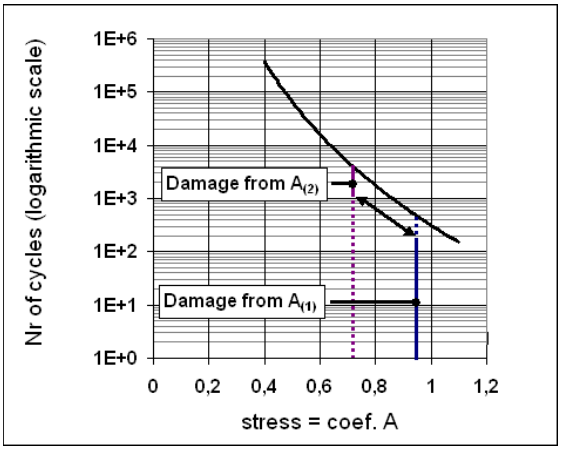

Fig. 9: in words of damage, Damage(t_{end} , □$_{(1)}$) is about 2/3rd and Damage(t_{end} , □$_{(2)}$)is about 1/3rd ; but in words of Nr of cycles, Nr(A(1)) is about 200 cycles and Nr(A(2)) is about 2400-1000=1400 cycles.

Before coming to conclusions, it is to be noticed that the quadratic summation is available when two or more independent cycles are combined and only in this case. By non-independent combinations we understand cycles showing for instance different conduction phases :

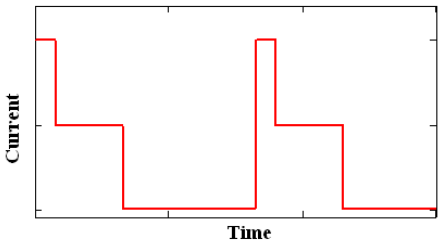

Fig.10: an example of combination of two conductive phases within a cycle. This combination does not allow to use the quadratic summation to evaluate the life-duration of the fuse.

In case of non-independent cycles, it should be advised to determine a more pessimistic cycle. The idea of cumulative damage is not available.

5. Conclusions

Even with many experiments, the calculation of the life-duration of ultra-fast fuses is always a demanding exercise. Many and many tests have been and are still run by manufacturers, but unfortunately, tests cannot cover the whole range of customers' applications. A strong difficulty is that customers intend to use fuses for many years when they are requiring for immediate answers. The authors hope that this paper will be an efficient contribution to the matter and will help engineers facing ageing of equipments.

In addition, we would like to underline some interesting points :

- first is that cumulative damage has been presented here-above, considering the coefficient $A = \frac{I_{RMS}}{In}$ used by MERSEN's engineers ; of course, same equivalent and appropriate demonstration could be done for any other parameters comparable to a stress ;
- damage has been defined by a linear law :

$$\text{Damage}(t) = \frac{N(t)}{Nr} \qquad (7a)$$

it should be interesting to study and compare this law with a logarithmic law :

$$\text{Damage}(t) = \frac{\log[N(t)]}{\log[Nr]} \qquad (16)$$

this is to be connected with the idea of C.O.D. presented in the first paragraph of this paper ;
- the quadratic summation can be extend to more than 2 independent cycles :

$$\text{Damage\_cumulative}(t, A_{(1)},..A_{(i)},..A_{(n)}) = \sqrt{\sum_{i=1}^{n} \text{Damage}^2(t, A_{(i)})} \qquad (17)$$

- the cumulative damage method has been presented considering the mean values of the life-duration ; extension to the Gaussian distribution around these mean values is also possible.

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ICEFA 2011

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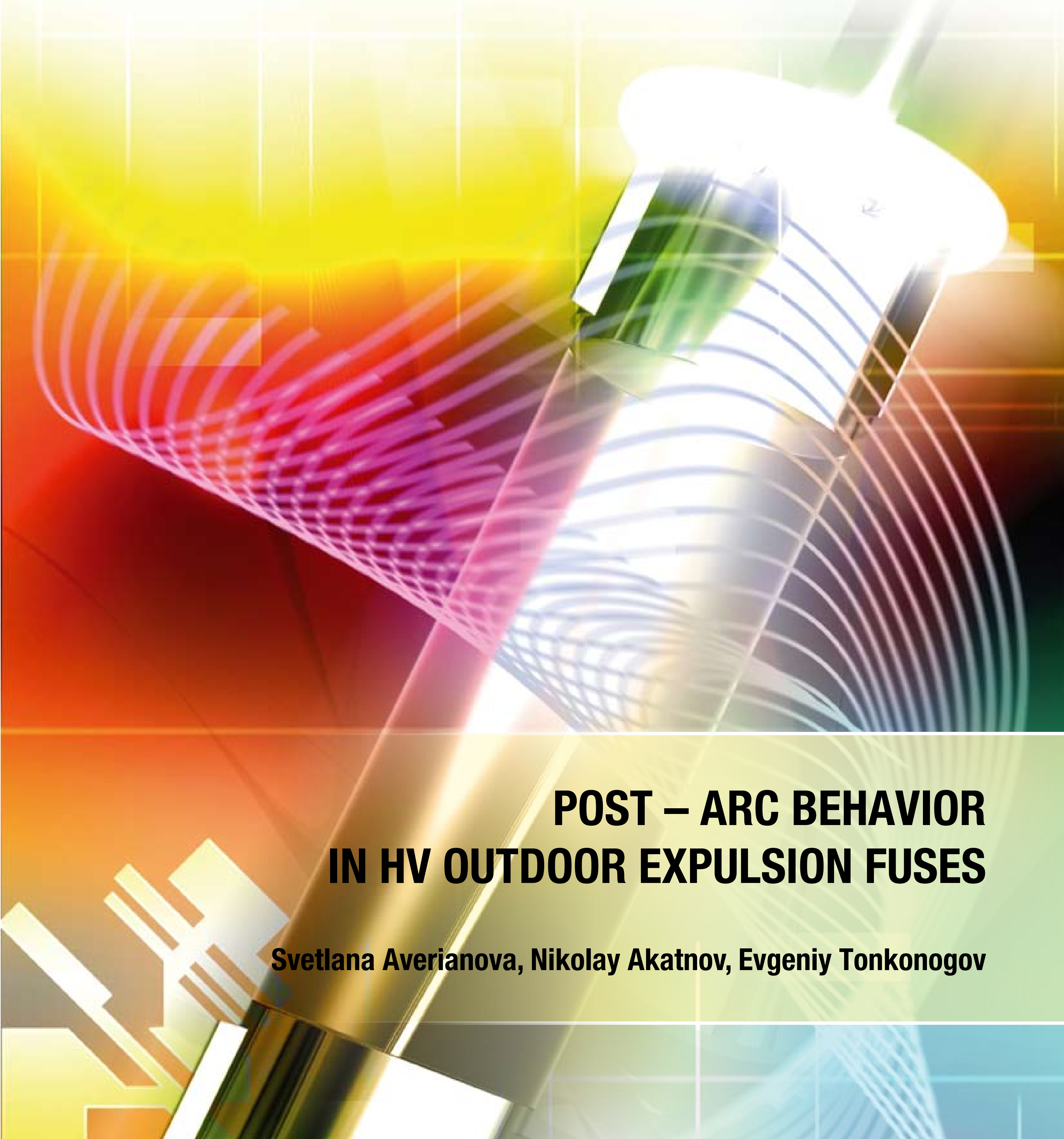

POST – ARC BEHAVIOR IN HV OUTDOOR EXPULSION FUSES

Svetlana Averianova, Nikolay Akatnov, Evgeniy Tonkonogov

Post – arc behavior in HV outdoor expulsion fuses

Svetlana Averianova[(1)], N. Akatnov[(2)], Evgeny Tonkonogov[(1)]

(1) Polytechnical University, Department of Electrical Apparatus, 29 Polytechnicheskaya st., St. Petersburg, 195251, Russia, averly@yandex.ru

(2) Polytechnical University, Department of Gas Dynamic, 29 Polytechnicheskaya st., St. Petersburg, 195251, Russia, akatnow@gmail.com

Abstract

HV outdoor expulsive fuses are popular and competitive switches for a protection against short-circuit in HV networks. Post-arc behavior is very important for breaking limits and the effects of turbulence plays one of the most important roles in the resistance restore. It is known that the turbulence plays the most important role in the arc decaying thanks to a high growth of the turbulent energy in the arc. We use the algebraic model of turbulent viscosity which is conceded this growth. In this paper results of the calculations, based on our theory, and comparison between theory and experimental data are presented.

Keywords: HV outdoor fuses, decaying arc, turbulence, turbulent viscosity.

1. Introduction

The high-voltage fuses are used for protection of power transformers, overhead and cable lines, and capacitors. For designing these fuses, it is necessary to solve a number of the interconnected tasks to support their reliable operation in various modes. One of these tasks is the optimization stream parameters extinguishing the arc. In the present paper, two aspects of the given tasks, namely, influence of the geometry of the channel and the turbulence of a flow for post-arc phenomena are considered.

Usually, on actuating the fuse, at burn-off of an insertion by fusion, the contact blade is released and, being thrown off under the influence of a spring, draws out behind itself a flexible tail. The arc elongates by the tail moves away and is extinguishing by the gas flow from the tube opening. The arc forming is axially blown by the quenching gas, which is forms during the burning-off of the burn-off element, and quenched. After the arc quenching the interval of gas providing the necessary isolation level formed.

As it has been told earlier, for designing the fuses, it is necessary to solve a number of the interconnected tasks. Experiments are very expensive, so we think that it would be good to have a model for calculating arc- and post-arc phenomenon, for predict breaking limit parameters in the new fuses design. In this paper we present such semi-empirical theoretical model that can be used for the task of optimization of the stream parameters extinguishing the arc is considered. One of the main parts of our model is the turbulence describing. As known, the interaction between the decaying arc and gas flow in the fuses plays the important role in increasing the arc resistance due to the axial convection and radial turbulent heat conduction. In addition, the turbulence in the post-arc mode intensifies heat transfer between the arc and the gas flow that accelerates temperature decrease and the resistance is quickly growing up. Experiments show that the turbulent energy in a volume unit of gas of the arc essentially increases in the vicinity of the current zero, and, hence, also the coefficient of the turbulent viscosity increases. Thus it is possible to show [1] that the latter increases to proportionally to the square root of the density growth in the arc, changing by tens times during the current decrease. In the present paper, the algebraic model of turbulence describing the process in the post-arc mode extinction taking into account this effect is offered. The model offered shows the good agreement between the calculated curves and experimental data, and can be applied in a wide range of initial and boundary conditions.

2. Model equations and boundary conditions

Calculations are based on the experimental data [2]. The turbulent arc in the stream formed by an axisymmetric supersonic nozzle is considered, thus the current in the arc changes in time under synthetic test. Interaction between the flow and the arc is described by the equations of Navie-Stokes added by continuity equation and balance of energy equation [1]. The Ohm’s law and models for the turbulent viscosity and for the radiation [1] add the system.

Model of the turbulent viscosity. The model of the turbulent viscosity describes two mechanisms of generation of turbulence in the flow: at the expense of shift stress and at the expense of the Rayleigh-Taylor instability. The coefficient of turbulent viscosity is given by:

$$\mu_t = (\rho\rho_e)^{0.5}\nu_t$$

$$\nu_t = \delta f_1 f \sqrt{\left[\left(C\delta\frac{\mathrm{v}_\Delta}{\Delta}\right)^2 + \left(C_1(u_\mathrm{m} - u_\Delta)\right)^2\right]} \quad (1),$$

where ρ_e – density of the gas; ρ- density of the gas in point; δ - middle by the coordinate x arc radius; Δ - value of *r* where $r=1.5\cdot r_{0.15}$; $\bar{u}_\Delta$, $\bar{v}_\Delta$ - value of velocity u and v in the point $r=\Delta$, u_m – axis value of velocity. Turbulent parameters using in model are $C=10^{-1}$; $C_1=4{,}9\cdot10^{-3}$; *f*, f_1 – empirical functions providing reduction of turbulent viscosity in the stream near the nozzle wall.

For stationary process we used model Eq.(1). Unsteady processed we calculated based on Weil test. Therefore, we used theory of “freezing” ν_t. It mean that in all moment of time ν_t is defined as constant and it is number value is equal to it stationary value, during current decreasing.

The radiation model is described in paper [4] explicitly.

At carrying out of calculations it is considered that the channel is axisymmetric; its walls are impenetrable and adiabatic. The left electrode is in the input section of the channel. The right electrode is carried out for the channel limits.

Breaking limit. It is known from experiments [2, 5] that after current zero appearance the part of post-arc where the temperature is falling down more quickly than in another it. Therefore, it was considered that breakdown ability of gas would start to recover if the temperature on the arc axis reaches values of 3000K in one point at least. This length was chosen because it defines main part of the resistance in the post-arc phase. It was assumed that electrical breakdown (U) is being proportional to a section length on the post-arc axis (L - breaking length) on which temperature is equal or less than 3000K because this part of gas is non-conductivity. In the first assumption for the analysis of the breaking limit can be used a simple expression:

$$U(t) = C \cdot L(t) \cdot \left(\frac{p}{p_0} \right)^n \cdot \frac{t}{t_0} \quad (2)$$

Where C is empirical factor; *L* - breaking length; *p* is the gas pressure on the length *L*; p_0=0,1MPa; *t* is the time last after the breaking length appearing; t_0 is equal $I_{max}/(dI/dt)$ to for the Wail test, I_{max} – maximum current value. We define numerical values of experimental constants as: $C = 3; \quad n = 0.5$.

4. Results and discussion

Note, that we are interesting in breaking limits parameters of fuses. Therefore, we design semi-empirical model and we have to determine the empirical coefficients of the model from the experiment and calculation data comparing. Unfortunately, there are not enough detail experimental data for fuses parameters in the arc- and post-arc period. We tested our model based on the experimental data [2]. The paper [2] is devoted to arc- and post-arc phenomena in the supersonic nozzle. We assumed that data [2] can be used for testing fuse describe model based on two moments. First, the experiments [6] show that in the limit regime the pressure in the arc chamber can be very high. Secondly, research [7] shows that fuse with nozzle chamber is very effectively and arc quenched rapidly in it. Authors in [7] used fuse with nozzle in high-voltage installations at nominal current of over 2 kA. In view of told all above we choose experimental data [2] for testing our model.

The geometry of the nozzle for analyzing the post-arc phenomenon in the nitrogen [2] is presented in the Fig. 1. The inlet pressure is equal to 23atm, the outlet one is equal to 1atm. The current is changing with time according to the Wail's test. We have stationary value I_{max}=2кA, dI/dt = -23,5A/μs [2]. The current reaches zero and stops.

Three possible various types of the flow were considered:

A. The turbulent arc in the stream formed by the supersonic nozzle.

B. The laminar arc in the stream formed by the supersonic nozzle.

C. The turbulent arc in the stream formed by the nozzle with a pipe as a diffusor.

The results of these calculations are presented in Fig. 2-4.

Fig.2 shows the calculated curve averaged by the length axial temperature of the arc depending on time in comparison with the experimental data [2]. Also, figure plots the current as the function of time. Obviously, the calculated curve is in a good agreement with the experimental data in a steady state and at low values of temperature. At median values of temperature (15000÷10000^{0}K), the calculations give the results underestimated in comparison with the experiments. We relate this result to the fact that the model of radiation gives the integral losses of heat on radiation, disregarding an additional thermal emission at a recombination in the specified range of temperatures. However, at values of the temperature of interest in the present work, (low values temperatures) the agreement between the calculated curve and experimental data is satisfactory.

Fig. 3 shows the curves of the increasing breaking length *L* for three variants of the flow conditions. Obviously, that under flow 'C' condition delay period (time lasts from the current zero to breaking length occurrence) (24μs) is more, than in case of 'A'. For the laminar post-arc mode (flow 'B' condition) delay period is almost by 7 times more than that for the turbulent one (58 and 8.2μs after current zero, respectively).

In Fig. 4, curves of the average pressure along the breaking length, *p*, related to the input pressure, p_{in}, as the function of time after current zero for all variants of the flow conditions are presented. As seen in the figure in cases 'A' and 'C', when the flow is turbulent, the average pressure slowly changes with time, and are not much dependent on the diffusor part of the channel geometry. Computing under flow 'B' condition, the pressure in the channel is noticeably higher, than in two other case and falls with time from 0.7 at the moment of the beginning of current drop to 0.6 in 40 μs after current zero. Therefore, in this case the pressure reduction amounts approximately 15 %.

Thus, it is possible to state that in case of a laminar arc the delay period is unacceptably great. In case of a turbulent arc, the delay period is minimum in case of the presence of the diffusor parts extending (8.2 μs), and for 3 times greater in case of a cylindrical diffusor parts (24 μs). Thus, it is necessary to recognize as the best result the calculation for flow 'A' condition.

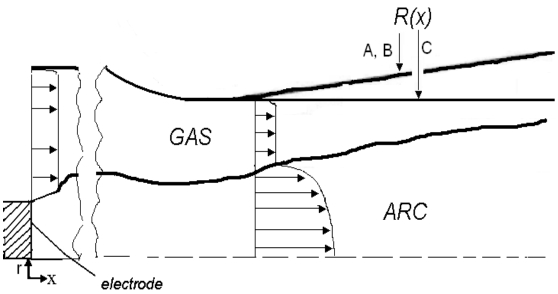

Fig. 1: Channel geometry.

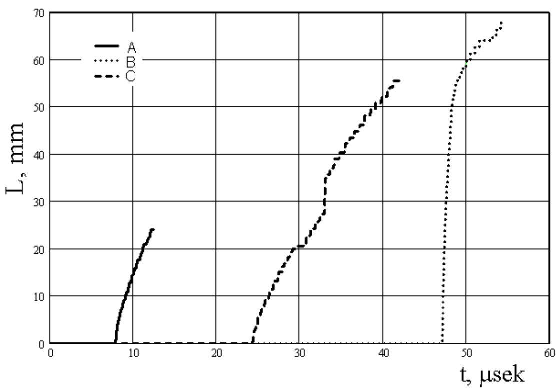

Fig. 2: Axial temperature as the function of the post-arc time.

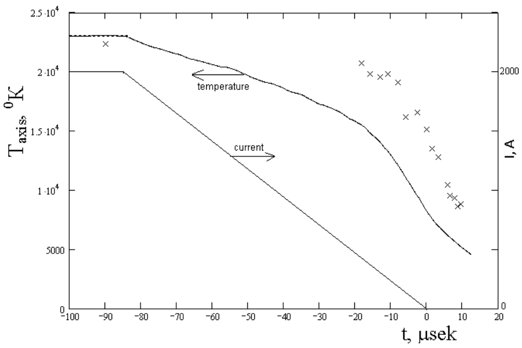

Fig.3: Break length *L* as the function of the post-arc time.

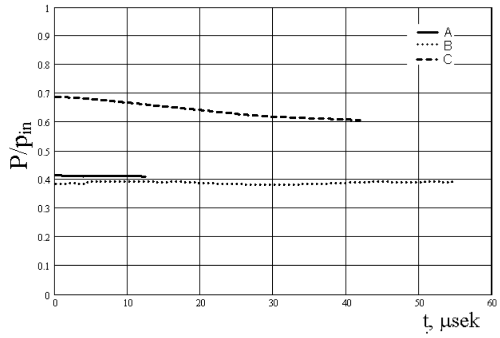

Fig.4: Relation p/p_{in} as the function of the post-arc time.

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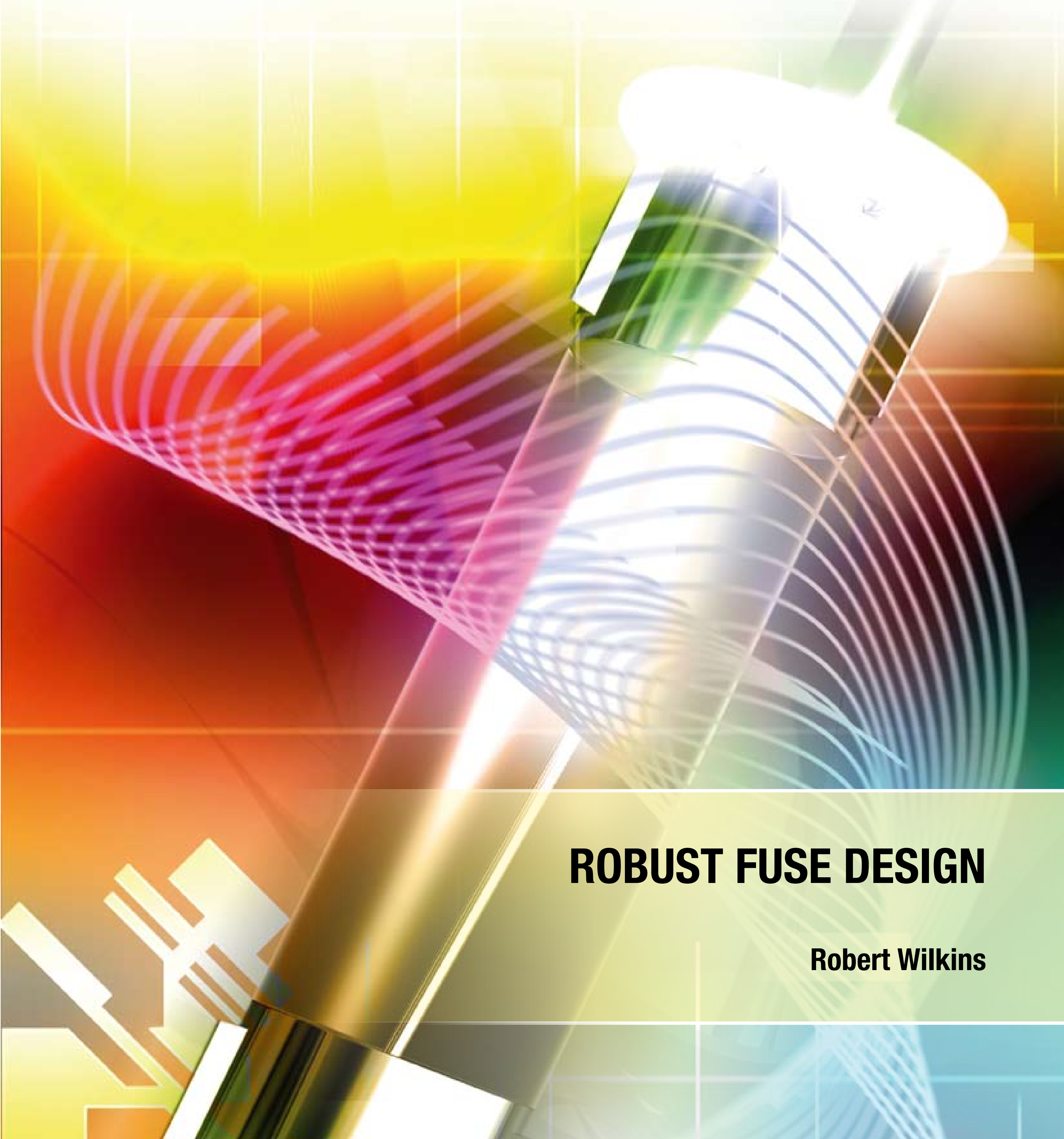

ROBUST FUSE DESIGN

Robert Wilkins

Robust fuse design

Robert Wilkins

Consultant, Overdee, Rocky Lane, Heswall, Wirral, CH60 0BZ, UK, bob@overdee.demon.co.uk

Abstract

The paper describes an approach to fuse design which is based on optimisation methods, where the performance requirements are represented as constraints on the values which the design variables are allowed to take. A solution space for any given design concept can be developed, but to do this, the prototype testing needs to be conducted in an unconventional way. When a feasible solution space has been obtained, the design can be finalised in a way which is robust and less sensitive to dimensional tolerances and other variations.

Keywords: electric fuse, design, optimization.

1. Introduction

Electric fuses are designed to meet a given set of performance requirements (which can be regarded as constraints on the design), usually those specified in the appropriate international standard. These requirements include, for example, the need to comply with specified set of limits on: temperature rises on the tube or the ends; fusing or non-fusing times; power loss; let-through currents, I^2t, and peak arc voltage.

Some of these constraints require testing at a fixed multiple of the rated current of the fuse, while others (such as the breaking capacity tests) require testing at a fixed prospective (available) current.

Often it is desired to develop a set of fuses (which may be part of a homogeneous series), with different current ratings, but within a given body (case) size.

The traditional approach is to choose a **design concept** (based on experience) and then build a prototype fuse and test it in accordance with the standard, to see whether it meets the performance requirements. If the design fails to meet the requirements in some way, it is then modified, re-tested, and the development continues iteratively until a satisfactory design is obtained.

Unfortunately many of the performance requirements conflict with each other. For example a low watt loss requires a fuse with a relatively low resistance, while a low I^2t requires a relatively high resistance, and often the requirements are not met, in which case the design concept needs to be changed.

In this paper, an alternative approach is described. The tests are carried out in a different way, which enables the limits on the design variables to be determined, and the constraints to be drawn in a **solution space** [1]. Sometimes a *feasible* solution space does not exist, in which case the design concept can be abandoned at an early stage.

However if such a space does exist, all the ratings in the series can be designed quickly, and they can be located within the space to give **robust** designs which are less sensitive to dimensional tolerances and other variations, and which can also be optimized as desired.

2. Typical constraints

The general approach described here can be used for any type of fuse, but it is illustrated by referring to a typical set of performance requirements (constraints) for a low-voltage power fuse.

2.1 Thermal limits

The most common thermal design constraint is that the steady-state temperature rise must not exceed a specified limit when carrying a specified value of test current. The limiting value may be on the fuse tube (body) or end terminal, or both.

A closely related requirement is often that the power loss under these conditions must not exceed a certain limit.

2.2 Time-current requirements

There are two types of constraints on the time current characteristic. A **fusing** requirement means that the fuse must melt within a specified time when tested at a specified multiple of the fuse current rating. A **nonfusing** requirement means that the fuse must **not** melt within a specified time when tested at a specified multiple of the fuse current rating. Time-current **gates**, through which the time-current curve must pass, can be regarded as two constraints, one fusing and one non-fusing.

2.3 Breaking test requirements

Assuming that the design can successfully interrupt the specified prospective short-circuit test current, there may be limits on the allowable I^2t, peak current, and peak arc voltage values.

3. Feasible solution spaces

As an example, consider the design of a homogeneous series of power fuses which by definition uses the same notching pattern for the fuse elements. The case (body) size is the same for all ratings in the series, and the key variable is the thickness of the fuse element (T). The designs can be characterised by a pair of values (T, In), where In is the rated current of the fuse, *and is treated as an unknown quantity at this stage*.

The first step in the process is to choose two values of fuse element thickness T_X and T_Y, which are believed will cover the expected range of thicknesses needed. T_X and T_Y can be selected by experience, rules-of thumb, or modelling, and T_Y needs to be roughly 3-5 times larger than T_X.

Two sets of model fuses are then built, one set with thickness T_X and the other with thickness T_Y.

3.1 Thermal limits

To determine the feasible solution space for a temperature rise constraint, tests are carried out to determine the temperature rise as a function of test current for the model fuses. (Note that this is quite different from the conventional procedure, which is to assume that the rated current is known, which then requires one set of tests for each prototype rating).

Typical results are illustrated in Fig.1. By careful selection of the test currents, the points at which the curves cross the specified temperature limit line can be determined. This gives two currents I_X and I_Y.

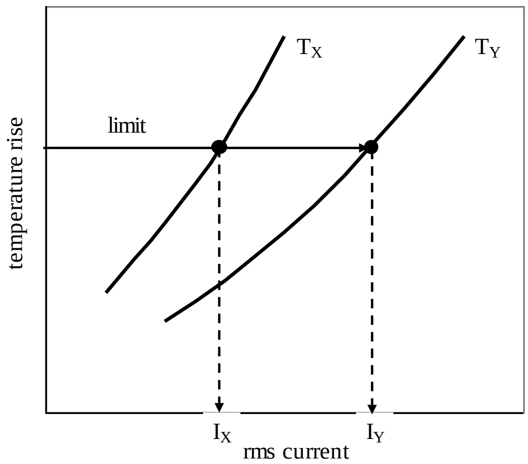

Fig. 1: Temperature rise versus test current for two different fuse element thicknesses.

In general the thermal constraint is that the temperature limit must not be exceeded when tested at k_1In. (k_1 is usually 1.0, but not always - see section 4).

At the limiting points $I_X = k_1In_X$ and $I_Y = k_1In_Y$, where In_X and In_Y are the maximum possible current ratings for fuses with element thicknesses T_X and T_Y. This gives $In_X = I_X / k_1$ and $In_Y = I_Y / k_1$. A pair of points (T_X, In_X) and (T_Y, In_Y) are then plotted in the (T, In) plane in Fig.2.

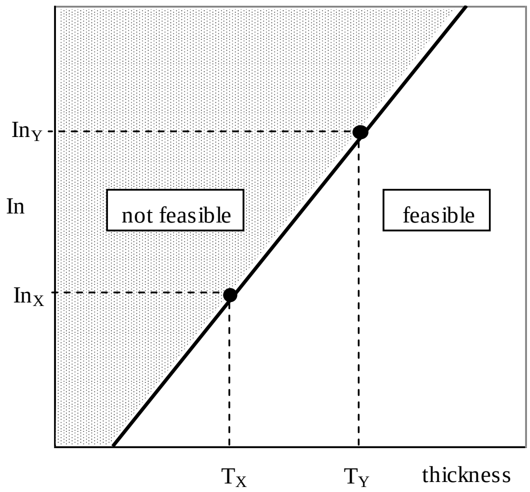

Fig. 2: Maximum possible current rating, based on a temperature-rise test limit.

Drawing a straight line through the two points divides the plane in Fig.2 into two regions. The upper (shaded) region represents designs which are not feasible - for any given rating the element thickness is too low, and the temperature rise limit would be exceeded. The lower (unshaded) region represents feasible designs. If the temperature-rise limit were the only constraint on the design, an arbitrarily large thickness could be used, which would ensure cool running.

Power-loss limits can be dealt in a similar way. However, as they are usually specified for each individual rating in a series, this results in a number of straight-lines sections in the (T, In) plane, rather than a single line.

Note that for Fig.2 and all subsequent diagrams, logarithmic scales are used on both axes. Since the range of thicknesses and the other variables in the region of the constraints is less than one decade, the test curves can be represented quite accurately by a power law, which results in a straight line when these points are transferred to the (T, In) plane.

3.2 Time-current requirements

For time-current constraints, tests are conducted to give time-current test points for times in the vicinity of the specified prearcing time t*. This is regardless of whether it is a fusing or a nonfusing requirement.

Typical results are shown in Fig.3. From these tests the rms currents which cause operation in the time t* can be determined, I_X for a thickness T_X and I_Y for a thickness T_Y.

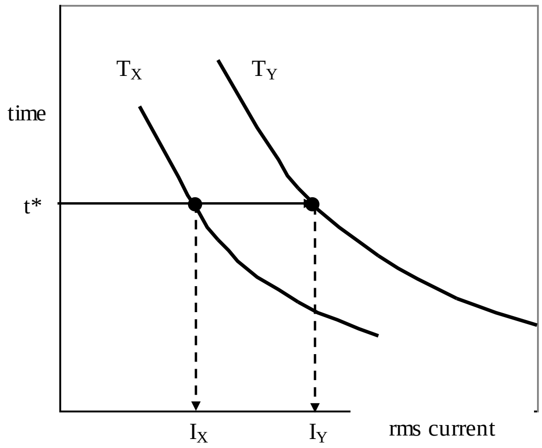

Fig. 3: Time-current test data in the vicinity of a specified fusing (or nonfusing) time for two different element thicknesses.

At the limiting points, $I_X = k_2In_X$ and $I_Y = k_2In_Y$, where k_2 is the specified multiple of the rated current.

For a **fusing** constraint,

$In > I_X / k_2$ for $T=T_X$ and $In > I_Y / k_2$ for $T=T_Y$

This generates the two points shown in Fig.4. A straight line through these points divides the plane into two regions. The upper (unshaded) region is feasible. In this region, for a given rated current, the fuse element thickness is less than the limiting value, and the fuse will operate within the specified time, which is the requirement.

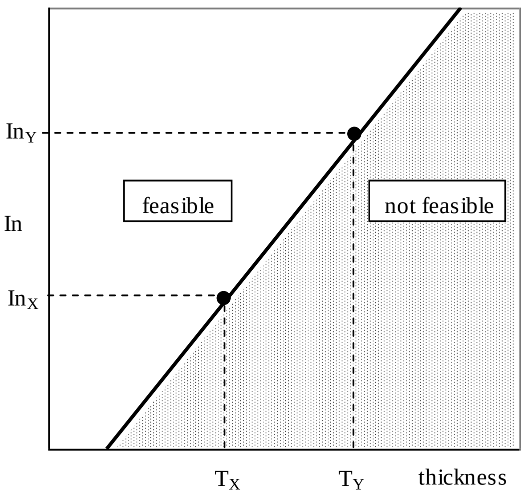

Fig. 4: Minimum current rating to meet a specified fusing requirement.

For a **nonfusing** constraint, the reverse is true.

$In < I_X / k_2$ for $T=T_X$ and $In < I_Y / k_2$ for $T=T_Y$

The result is shown in Fig.5. The upper (shaded) region is not feasible. In this region, for a given rated current, the fuse element thickness is less than the limiting value, and the fuse will operate within the specified time, which violates the requirement.

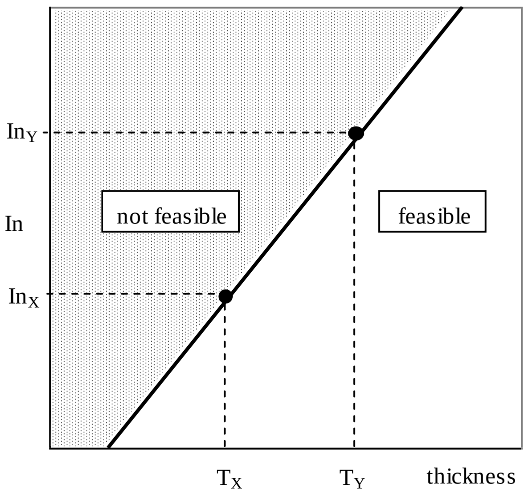

Fig. 5: Maximum current rating to meet a specified nonfusing requirement.

3.3 Breaking test requirements

Assuming that the design is capable of successfully interrupting the specified prospective short-circuit test current, then tests on model fuses will give I^2t or peak current increasing as a function of element thickness, as shown in Fig.6.

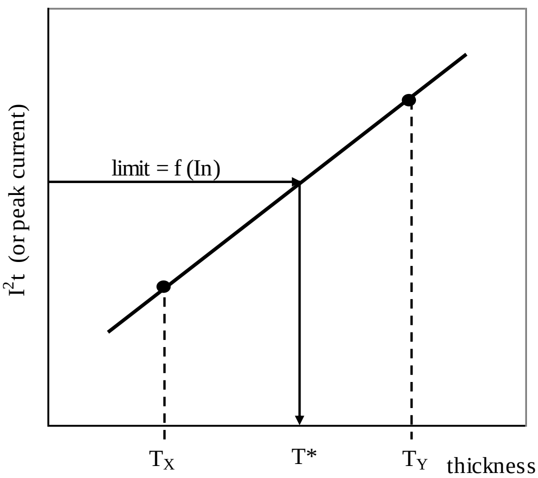

Fig. 6: I^2t or i_{peak} test data for two different fuse element thicknesses at a specified prospective current.

For a each rating the I^2t or peak current limit is given, and so the maximum permissible element thickness T* can be found. This corresponds to a single point in the (T, In) plane.

Fig.7 shows two such points plotted for two adjacent current ratings in the homogeneous series. It is convenient to join these with a straight line and shade the region to the right hand side as not feasible.

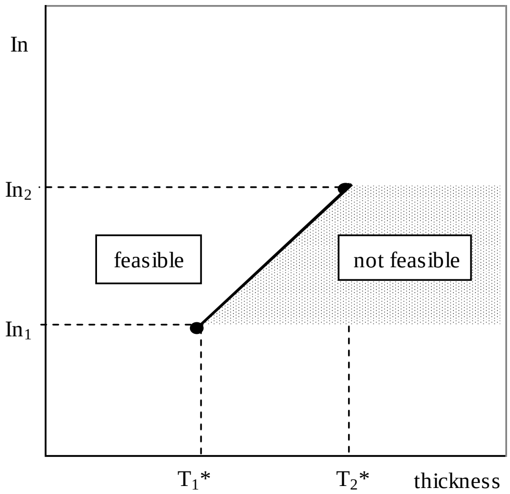

Fig. 7: Minimum possible current rating, based on I^2t or i_{peak} requirements.

For a homogeneous series with a table of I^2t or peak current limits for each rating, Fig.7 can be developed into a series of points joined by straight lines.

A similar procedure can be used for peak arc voltage limits if these are specified.

3.4 Physical limits

In addition to the thermal and electrical constraints there are physical limits to the value of element thickness which can be used. These limits are determined by the manufacturing processes used in the fuse construction, and are very simply added to the (T, In) plane as shown in Fig.8.

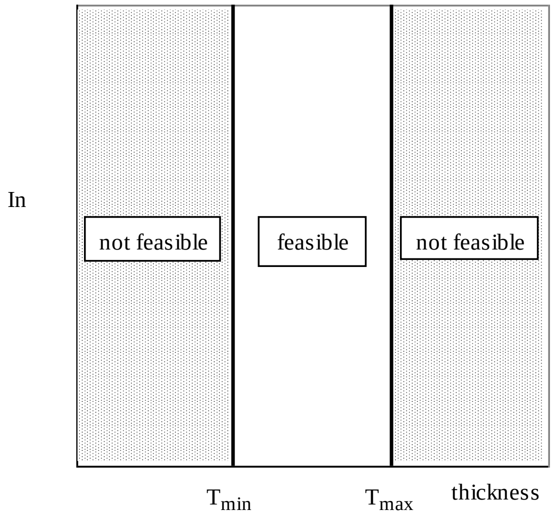

Fig. 8: Feasible fuse element thicknesses.

4. Typical example

When all the performance requirements are plotted on the (T, In) plane a complete picture of the design concept emerges.

As an example consider the performance requirements for a 600V class J fast-acting power fuse in the 200A case size. This size includes current ratings of 110A, 125A, 150A, 175A and 200A. The performance requirements are:

Thermal requirements

(a) Tube rise must not exceed 85 degC at 1.1 In
(b) Blade rise must not exceed 60 degC at 1.1 In

(i.e. k_1 = 1.1)

Fusing requirements

(a) fuse must operate within 2 hours at 1.35 In
(b) fuse must operate within 480s at 2 In

(As this is a "fast-acting" fuse there are no nonfusing requirements).

I^2t and peak current limits

At the 100kA and 50kA test levels, the I^2t, peak current and peak arc voltage must not exceed the values specified in Tables 1 and 2.

Table 1: Performance requirements at 100kA

In (A)	I^2t (kA^2s)	ipeak (kA)	Varc (kV)
110	100	14.5	3
125	150	15.5	3
150	175	17	3
175	225	18.5	3
200	300	20	3

Table 2: Performance requirements at 50kA

In (A)	I^2t (kA^2s)	ipeak (kA)	Varc (kV)
110	200	16	3
125	200	16	3
150	200	16	3
175	200	16	3
200	200	16	3

At the 50kA level the limits are the same for all current ratings.

Based on test data derived from tests conducted using the methods described in section 3, the (T, In) plane is shown in Fig.9, with all the above constraints applied. A final feasible solution space is seen to exist, the rest of the plane being shaded because one or more of the constraints are violated. (The peak arc voltage requirement was easily met, and is not shown).

The presentation of Fig.9 gives a complete picture of how the design concept meets the various performance requirements, on a single sheet of paper.

For the 110A, 125A and 150A ratings, the feasible solution space is bounded by the constraints imposed by the tube temperature rise limit and the requirement for operation within 2h at 1.35 In. The first of these requires a relatively low element resistance, while the second requires a relatively high resistance. However, for this design concept, a band exists where both conditions can be met, and a convenient available thickness can be selected near the middle of this band, which will give a robust design, so that dimensional tolerances do not cause the design to fail to comply with the requirements.

For the 175A and 200A ratings, the peak current limit becomes more important than the 1.35 In fusing requirement, and for the 200A rating the width of the range of feasible thicknesses becomes rather small. For the 200A fuse, the design is less robust, and Fig.9 shows exactly why this is so.

If the width of the feasible band is reasonably large, it is possible to choose a thickness which will optimize the design, according to some desired criterion. For example if it is desired to have a low watt loss, the actual design point can be chosen to be near to the right-hand side of the feasible solution space. If it is desired to lower the peak current and I^2t, a point nearer to the left-hand side can be chosen.

5. Conclusion

The method described differs from conventional design methods in that the current rating of prototype fuse designs is treated as an unknown quantity until the very end of the procedure. This requires a different approach to testing, but with careful planning the number of test samples needed can be minimised.

The reward is that when the design of a homogeneous series is completed, the resulting plot, equivalent to Fig.9, gives much more valuable information than a set of tables of test results.

In the example given, element thickness was chosen as the key variable, as it usually is. However the method can be applied equally well if other variables are chosen.

6. References

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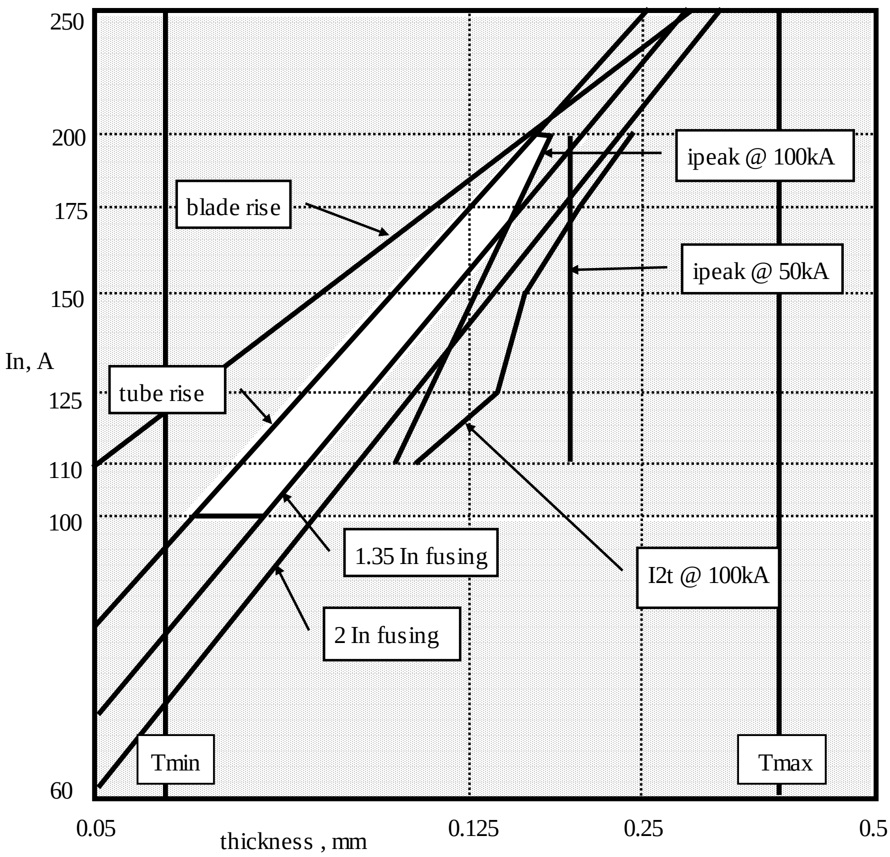

Fig. 9: Example showing all constraints and feasible solution space for a fast-acting class J fuse.

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FUSE RECYCLING IN GERMANY SUPPORTS RESEARCH AND EDUCATION IN THE FIELD OF ELECTRICAL POWER DISTRIBUTION

Volker Seefeld, Peter Brogl

Fuse Recycling in Germany supports research and education in the field of electrical power distribution

Volker Seefeld[1], Peter Brogl[2]

[1] SIEMENS AG, Siemensstraße 10, D-93055 Regensburg, volker.seefeld@siemens.com

[2] Mersen Deutschland Eggolsheim GmbH, In der Büg 12, D-91330 Eggolsheim, peter.brogl@mersen.com

Abstract

Verein zur Förderung des umweltgerechten Recycling von abgeschalteten NH/HH-Sicherungseinsätzen e.V. (Association for the promotion of environmentally-compatible recycling of disused LV HRC/HV HRC fuse-links)

The association is officially accredited as a non-profit association. It was founded in 1995 and since then the association is busy with the recycling of LV and HV HRC fuse-links in Germany and that on a non-profit basis. The association was founded by fuse manufacturers with the aim to return utilizable raw materials from LV and HV fuse links to the cycle of resources again. In addition the target is, that only those fuses will be produced in future, which can be recycled without any problems.

LV and HV HRC fuses are collected in Euro grid box pallets (GBP) and smelted down in a copper converter. Compared with disassembling or shredding of fuses, the smelting procedure offers the most environment-friendly way of recycling. Material, which could cause troubles, for example like asbestos, are gathered in the slag.

The system has proved itself for more than 15 years and is running in German utilities and big industrial companies.

From the start of the association till today around 410 tons of copper and around 5 tons of silver had been recycled. As a result, it was possible to save approximately more than 43.000 tons crude ore. And we disburdened the world by tons of CO2.

Our recycling system is user-friendly as well as free of charge. The recycling system and the logistics are financed by the sales of copper and silver.

Surplus is sponsored for the engineering research in the field of fuse links carried out at universities and colleges. So there will be different topics presented at ICEFA 2011 have been sponsored and supported by our association, such as:

- Theoretical and experimental investigation of fault currents to be interrupted by PV fuses
- The influence of fuses on arcing fault energy and personnel protective clothing required
- The influence of current frequencies up to 1.000 Hz on power dissipation and time-current-characteristics of NH fuse-links

Additionally and as a new and future aim of our association universities and colleges will be sponsored encouraging the education of electrical engineers in Germany. Those engineers are the future guarantors for save and efficient power distribution systems including high-sophisticated modules as photovoltaic and wind power plants, smart grips, DC-networks and so on. Those engineers will safe the future application of fuses in a wide range of applications.

We want to close the gap of missing engineers in the field of electrical power distribution and we improve the general conditions by financial and professional support.

The adoption of the European Directive and Environment Regulations such as WEEE, ROHS and EuP have effects on the fuse-link industry. Our association offers the most practicable and efficient return system of the world.

Keywords: NH-HRC-Fuses, HH-HRC-Fuses, Low Voltage and high Voltage Fuses Recycling, NH/HH-Recycling, European Directive, WEEE, ROHS, EuP, Association for the promotion of environmentally-compatible recycling of disused LV HRC/HV HRC fuse-links, Application of Fuses.

The association NH-HH-Recycling e.V. is officially accredited as a non-profit association. It was founded in 1995 and since then the association is busy with the recycling of LV and HV HRC fuse-links in Germany and that on a non-profit basis.

The association was founded by German fuse manufacturers with the aim to return utilizable raw materials from LV and HV fuse links to the cycle of resources again.

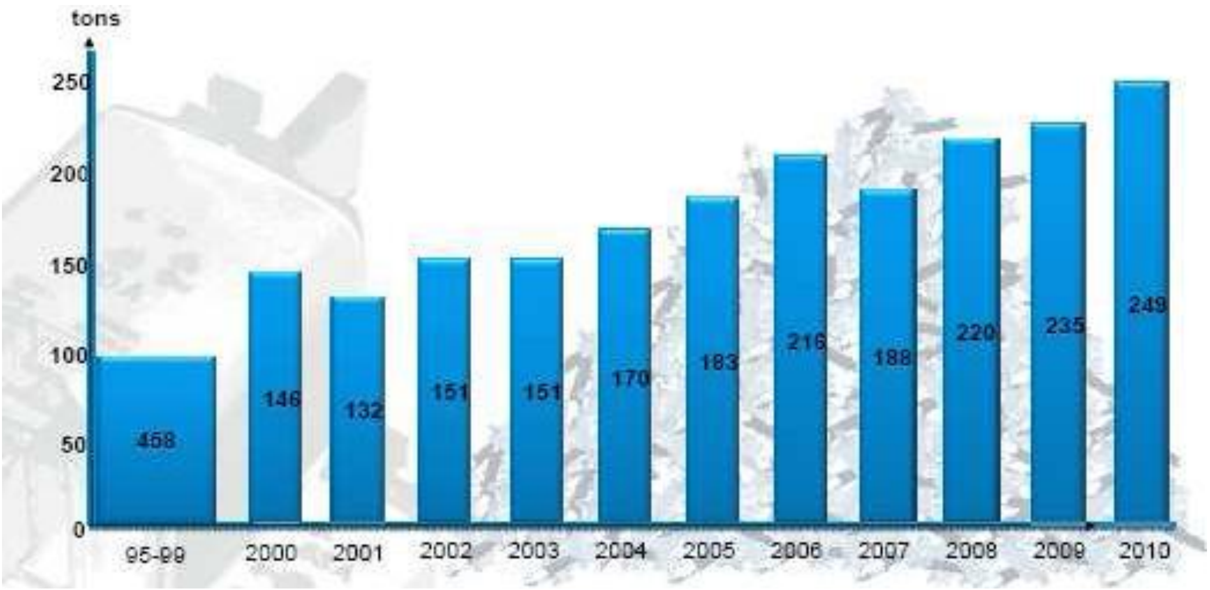
In addition, the target is that only those fuses will be produced in future, which can be recycled without any problems.

Surplus is sponsored for the engineering research in the field of fuse links and their application carried out at universities and colleges.

The task of the Verein zur Förderung des umweltgerechten Recycling von abgeschalteten NH/HH-Sicherungseinsätzen e.V. is to process the various materials of which fuse links are made so that they can be returned to the cycle of manufacture for further use. Those materials are much too valuable for putting into normal waste. In 2010, for example, our association collected and recycled 249 tons of fuses.

From the start of the association till today around 410 tons of copper and around 5 tons of silver had been recycled. As a result, it was possible to save approximately more than 43.000 tons crude ore. And we disburdened the world by tons of CO2.

Next figure shows the collected tons of LV and HV fuses over the years. It illustrates the steady increasing acceptance of our recycling system.



Fuses include valuable materials

Fig. 1 shows a cross section through an LV HRC fuse link and lists the other materials used in its construction; similarly Fig. 2 illustrates an HV HRC fuse link.

Structure of an HV HCR fuse link

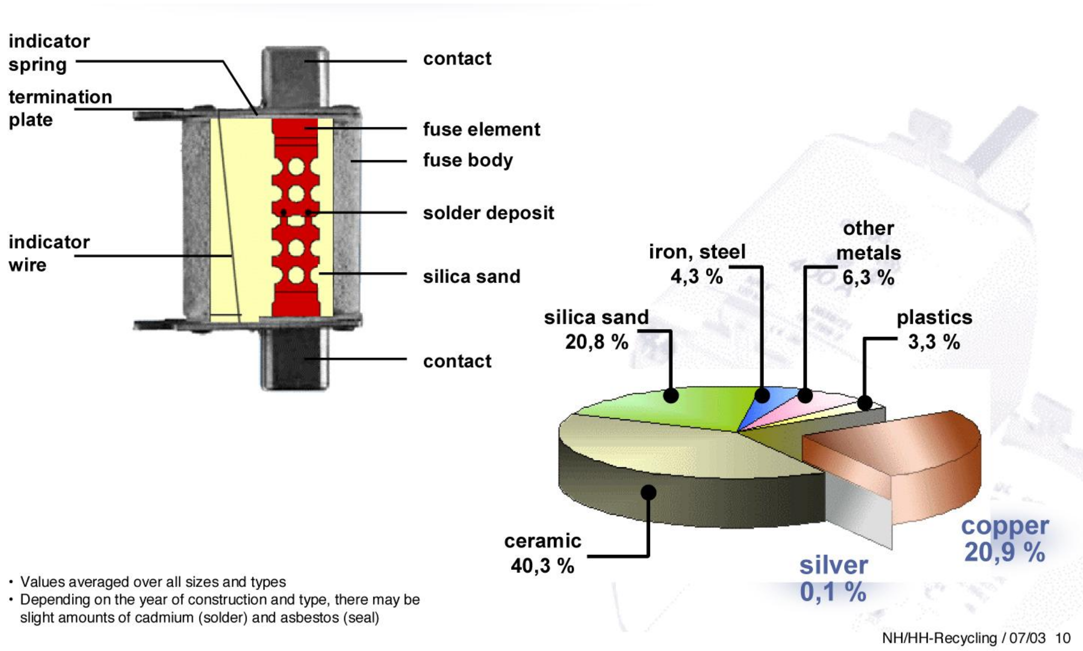


Fig. 1

Structure of an LV HRC fuse link

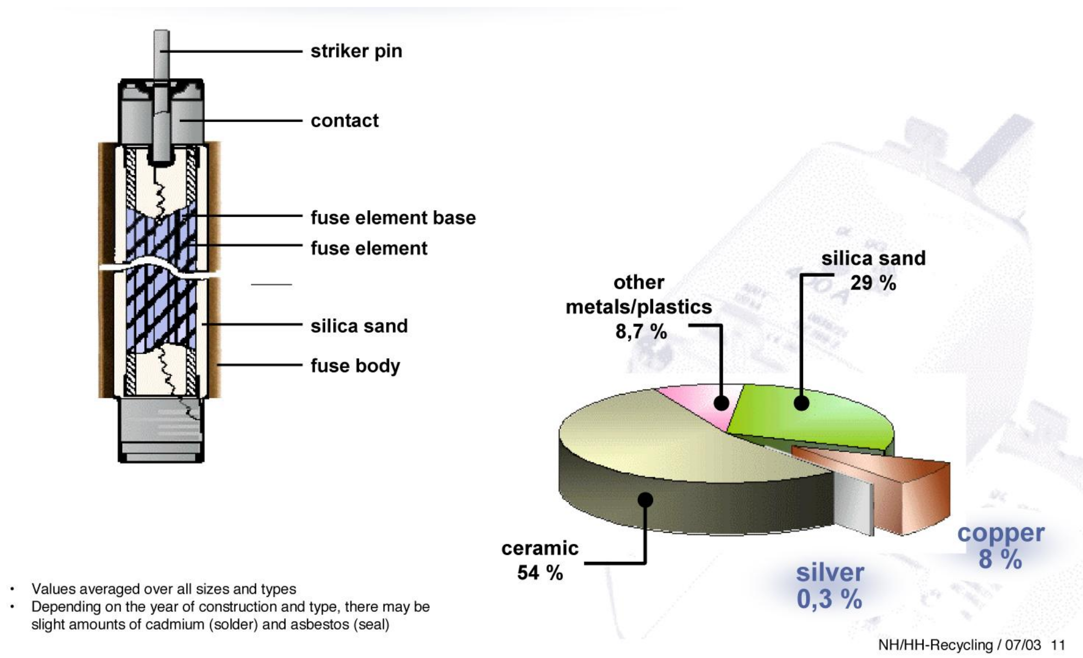


Fig. 2

Our successful fuse recycling system is user-friendly and free of charge

LV and HV HRC fuses are collected in Euro grid box pallets (GBP) and transported to a collection place (buffer store) organized by our association. The collecting customer has to send a telefax or an e-mail to our office. That's all. The rest is organized by our logistic partner. He picks up the box pallets with fuses and delivers empty ones. The collected fuses are smelted down in a copper converter without any preprocessing.

Our partner AURUBIS AG in Hamburg, one of the leading copper producers worldwide and the biggest one in Europe provides us easy handling and optimum conditions for our fuse recycling process. AURUBIS produces row copper from the copper converter and copper of highest purity in an electrolyze process.

Beside the valuable components copper and silver from the ceramic and the quartz sand of the fuses we get slag which can be used in street and dike construction.

Compared with disassembling or shredding of fuses, the smelting procedure offers the safest and most environment-friendly way of recycling. Materials which could cause troubles, for example like asbestos, are gathered in the slag. The strict rules that apply when working with asbestos make disassembly a complex and costly process - as also is shredding or processing by pan grinder (a crushing process producing coarser results than a shredder) with subsequent melting down in the blast furnace.

Our recycling system has proved oneself for more than 15 years and is running successful in German power utilities and big industrial companies. Currently, in total we have 455 collecting places in Germany.

Following only a few of our collecting customers:

For small collectors who are not able to fill a complete Euro grid box pallet (GBP) we are able to provide so called "open" collecting places on request.

The association is financing the recycling-system and the logistics by the sales of copper and silver from the recycled fuses. For the collecting customers our recycling system is user-friendly as well free of charge.

Research benefits from the surplus

Surplus is sponsored for the engineering research in the field of fuse links and their application carried out at universities and colleges. So there will be different topics presented at ICEFA 2011 have been sponsored and supported by our association, such as:

1. Theoretical and experimental investigation of fault currents to be interrupted by PV fuses

2. The influence of fuses on arcing fault energy and personnel protective clothing required

3. The influence of current frequencies up to 1.000 Hz on power dissipation and time-currentcharacteristics of NH fuse-links

Our new aim – to support education of electrical engineers

Additionally and as a new and future aim of our association universities and colleges will be sponsored encouraging the education of electrical engineers in Germany.

Those engineers are the future guarantors for save and efficient power distribution systems including high-sophisticated modules as photovoltaic and wind power plants, smart grips, DC-networks and so on. Those engineers will safe the future application of fuses in a wide range of applications.

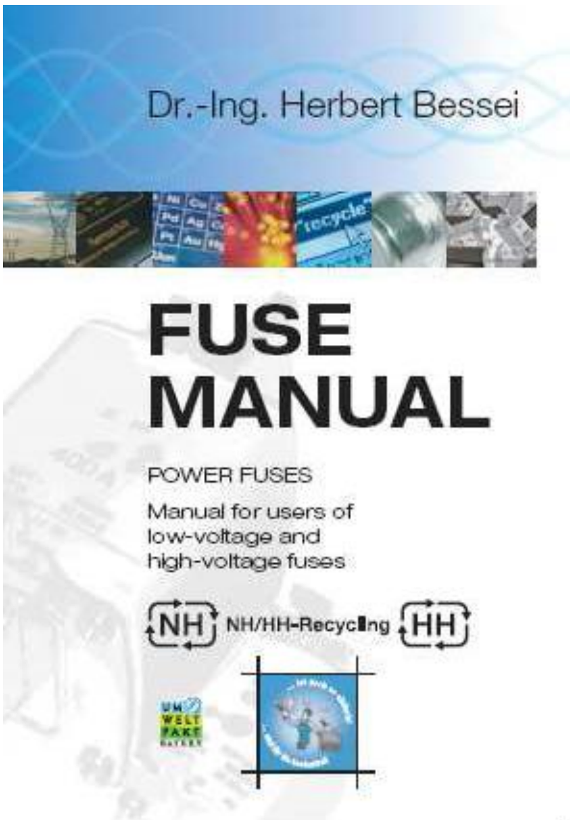
We want to close the gap of missing engineers in the field of electrical power distribution and we improve the general conditions by financial and professional support.

How does it work? Universities and colleges are asked to show their research and educational structure, their actual and future activities and their concept or roadmap in a letter of intent. This letter of intent can be downloaded by everybody in German language from our homepage nh-hh-recycling.de under chapter Förderungen, key word Absichtserklärung.

After receipt of the letter of intent our association will check and evaluate the concept and decide the financial support paid in form of a donation. The donated money can be used to buy hardware, equipment or software, to finance R&D projects and to finance a dissertation, a practical or a student by a stipend.

Our main interest is to support those who are working in the field of fuses, fuse-switches and their applications which of course is a wide field from standard power distribution topics to special things as DC networks, photovoltaic, e-cars, high-frequency applications or reactive current compensation.

Professional support is given on demand, independent from the financial support: we provide information about fuses in form of a powerpoint presentation, further special data or samples can be given on request. Our fuse manual is available in four languages now. In Future we will offer it in nine languages.



European Directives and Environment Regulations

The adoption of the European Directives and Environment Regulations such as WEEE, RoHS and EuP have effects on the fuse-link industry.

The WEEE – Directive, it stands for "Waste electrical and electronic equipment" which became into force in August 2004 is the core of a taking back and recycling system. The countries have to install a collection and take back system free of charge for consumers that ensure the return of the electronic

equipment from August 2005. For fuses, WEEE does not require recycling systems. Our fuse-recycling system is offering a user-friendly solution on a voluntary base.

The "Restriction of use of certain hazardous substances in electrical and electronic equipment," (RoHS) became into force in August 2004, valid in July 2006. For fuses the equipment RoHS category 9 "monitoring and control instruments" is relevant. Today, the category 9 is exempted from RoHS, but the reviews every 4 years may lead to the cancellation of all exemptions. European fuse-producers offer RoHS-conform products on a voluntary base.

The EuP directive (2009/125/EC) is requiring energy-friendly products.

Our association offers the most practicable and efficient recycling system of the world and provides excellent conditions to improve and support the application of fuses in the different markets. Our products and our recycling system comply with all European Directives and Environment Regulations.

For the sake of environment and natural resources

… and we are always one step ahead the directives and regulations. This demonstrates the increased awareness of the members of our association but also of our collecting customers concerning the matters of environment and natural resources.

And we hope that more and more people in other countries are going to establish similar recycling systems. BENELUX and UK just did it.

Our association gave support in the starting phase of implementation and thus makes us proud.

Ask us if you are interested to get more information.

www.nh-hh-recycling.de

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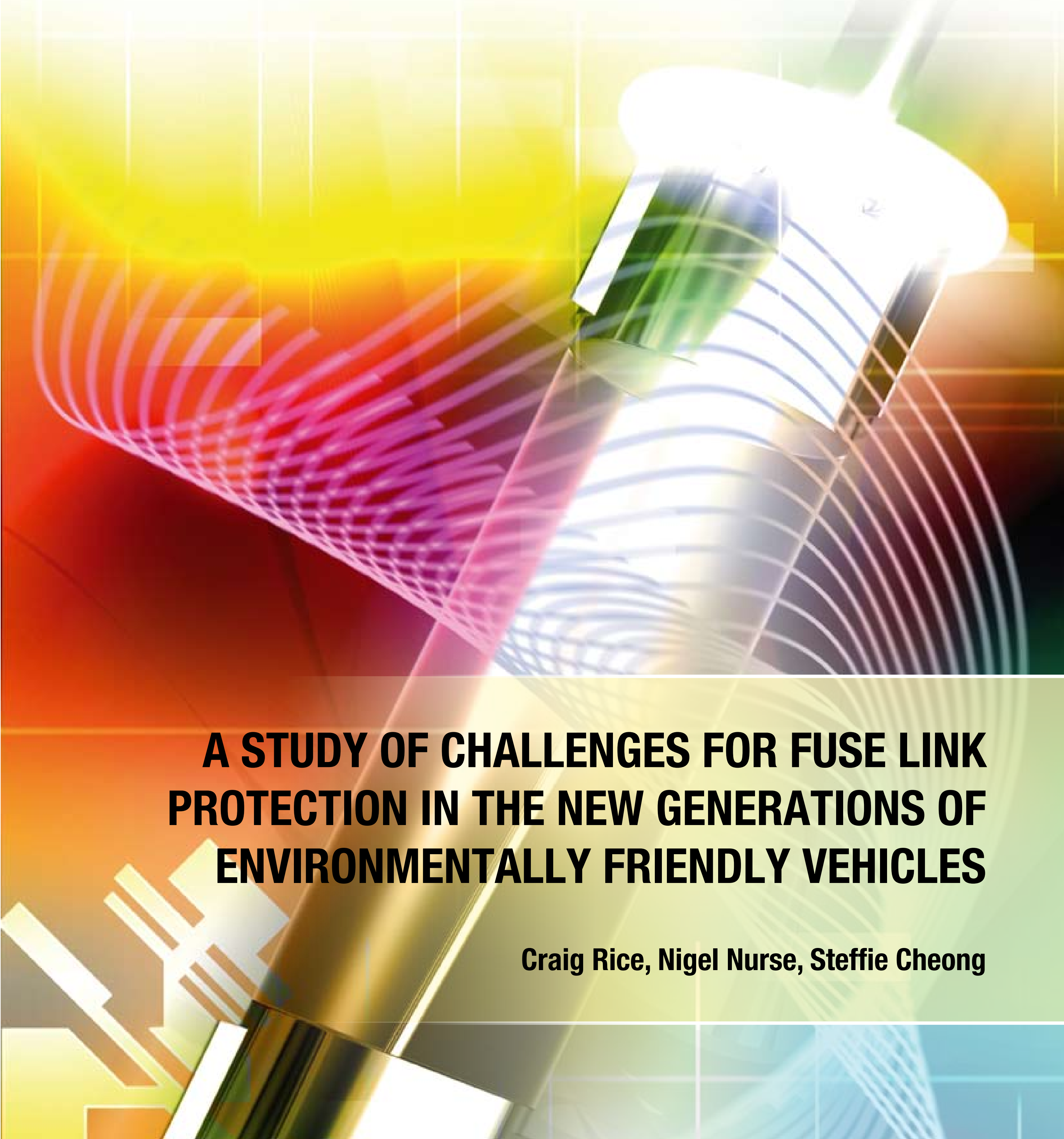


A STUDY OF CHALLENGES FOR FUSE LINK PROTECTION IN THE NEW GENERATIONS OF ENVIRONMENTALLY FRIENDLY VEHICLES

Craig Rice, Nigel Nurse, Steffie Cheong

A Study of Challenges for Fuse Link Protection in the New Generations of Environmentally Friendly Vehicles

Craig Rice, Nigel Nurse, Steffie Cheong

Affiliation, Cooper Bussmann, Burton on the Wolds, Leicestershire, UK, craig.rice@cooperindustries.com, nigel.nurse@cooperindustries.com, steffie.cheong@cooperindustries.com

Abstract

Electric vehicles are more environmentally friendly than traditional cars using fossil fuels, making them an ideal, real-world response to the challenge of reducing the environmental impacts of transportation. However, a number of key success factors will condition the future of the electric vehicle. Recharging infrastructure, range concern and driver safety are high on the discussion list. Most of these vehicles utilise an electric storage system together with electric drive train. To avoid rapid and uncontrolled discharge of the storage device in the event of an equipment malfunction or vehicle accident, there is a need to provide circuit protection to prevent further damage to equipment or injury to passengers. This paper explores some of the challenges encountered by the fuse world by looking at different configurations of the electric system and the specific requirements that the protective device will have to meet.

Keywords: electric vehicles, hybrid electric vehicles, fuse link, batteries.

1. Introduction

The history of Electric Vehicle (EV) has been documented as early as 1881 in Paris by Gustave Trouvé, five years before the alleged “invention of the automobile” by Benz and Daimler, followed by another tricycle in 1882 by W. Ayrton and J. Perry in England. These were lightweight vehicles, based on bicycle construction. These “first generation” electric vehicles had their heyday in the last decade of the 19th century but were gradually taken over by the development of the Internal Combustion Engine (ICE). These vehicles were more efficient and cost effective to operate.

Now in the 21st century, a new dawn of EV’s has arose. This is primarily driven by climate change, shortage of energy as well as economic reasons.

The automotive industry continues to investigate reducing its impact on the environment despite the current economic crisis. At the 2010 Clean Energy Ministerial in Washington D.C., ministers reaffirmed their commitment to previously announced targets for the deployment of EV. The International Energy Agency (IEA) estimates 20 million electric vehicles will be on the road worldwide by 2020 [1].

In UK, electric vehicles alone provide 19% of the 26% assigned to road transport, contributing to the overall carbon commitment targets for 2020 [2].

However, there are still numerous limitations to be resolved before the mass production of EV’s can be rolled out. In particular, the issues with energy / power density, lifetime performance, system costs and safety are still very much in debate. The electrical subsystem will also need to be revolutionised for reliability, space and cost.

Over current protection devices are essential in automotive electrical systems to limit the threat to human life and vehicle damage. The battery in conventional ICE vehicles, use the chassis for ground, which means that the current path actually passes through the body of the car. Battery packs in an EV, can be considered “a floating system” i.e. is completely electrically isolated from the chassis. Therefore, it is important that the EV has various safety disconnects built in. These include main contactor, circuit breaker, and fuse links. All of these can be used to manually disarm the electrical system, or operate automatically in the event of a short circuit, collision damage, or some other situation that causes a surge of current. This paper studies the present status of automotive and industrial fuse links and explores the challenges posed by the EV.

2. Main System

EV is a generalised term for “electrically propelled vehicle”. Other terms used are, battery electric/all electric (BEV), hybrid electric (HEV), plug-in hybrid electric (PHEV) and fuel cell electric vehicles (FCEV) – examples in Fig 1.

The advancements in Lithium Ion battery technology coupled with increasing oil prices, has made the EV more appealing. Drive or propulsion is provided by the chemical energy stored in such batteries together with electric motors and controllers. This is the equivalent of the ICE. The battery is typically re-charged by plugging it into an electricity supply. The method of connection is another top topic under discussion.

HEV’s typically operate in a charge-sustaining mode which uses both electric and ICE power sources as efficiently as possible such that the battery does not deviate outside a set parameter. HEV batteries can only be charged by the ICE generator or through regenerative braking.

PHEV’s also has a charge-depletion mode. In fact, there are several options which vary the amount or timing of battery discharge with the aim to improve fuel economy. PHEV batteries have the added advantage of being able to charge by external means.

FCEV’s typically utilise a hydrogen fuel cell to produce electricity and power the electric motor. Not surprisingly, this is a less attractive option for the EV due to the present costs and efficiencies of extracting and storing hydrogen. However, it is expected to expand significantly once the fuel cell technology advances to the next level.

Unlike conventional ICE vehicles, each of the above EV categories employs different control and electrical systems. As a consequence, this has an influence to the problem of revolutionising the sub components including over current protection devices.

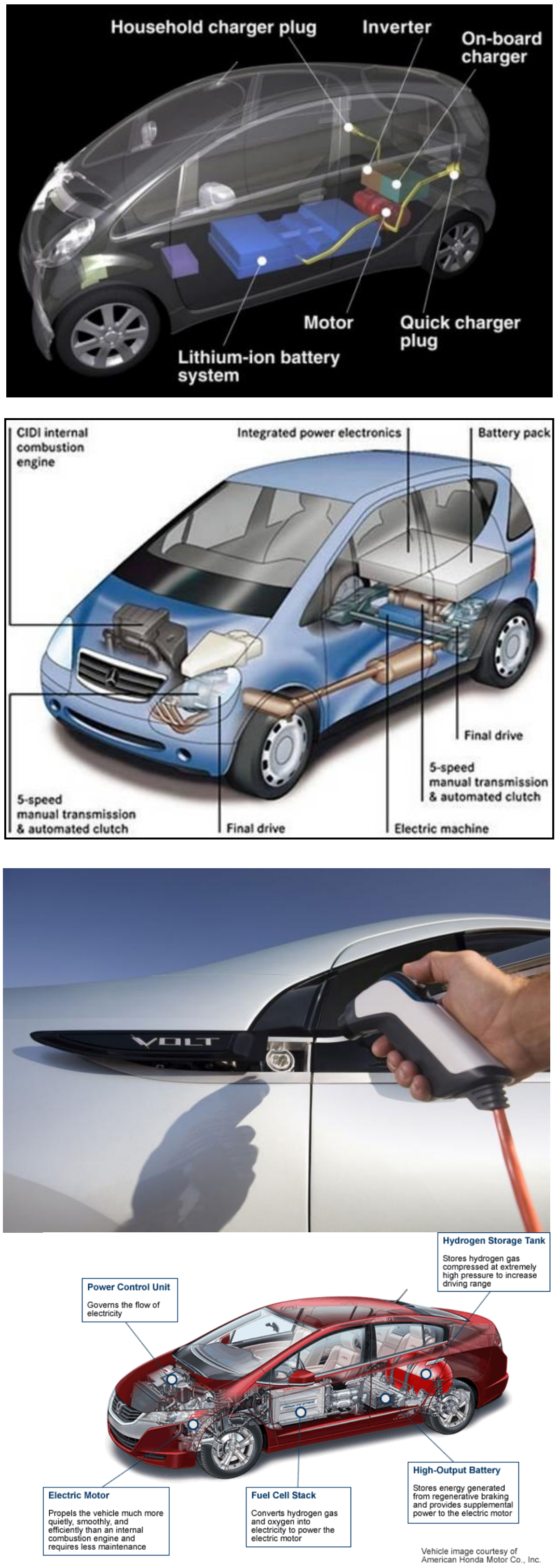


Fig. 1: From top to bottom. (i) BEV - generic; (ii) HEV – Mercedes-Benz concept; (iii) PHEV – Chevy Volt; (iv) FCEV – American Honda Motor Inc.

3. Protection Challenges for EV's

The use of an over-current protection device should be considered for the battery, charging module, cables, HVAC, heater, etc - see Fig. 2.

In general, apart from the emergency safety protection such as a Pyrotechnic Safety Switch, the most common form of over current protection device used in the EV is the fuse.

The fuse link's rated current is the RMS current it can continuously carry without degrading or exceeding the applicable temperature rise limits under well-defined and steady-state conditions. Many conditions can affect the current carrying capability of a fuse link and all aspects need to be considered to ensure continued and safe operation.

In general, the required rating of a fuse link, I_n, is governed by the following equation [3]:

$$I_n \geq \frac{I_{RMS} \times G}{K_t \times K_e \times K_v \times K_f \times K_a \times K_b}$$

I_{RMS}: Load RMS rating
I_n: Rated current of a given fuse
K_t: Ambient temperature correction factor
K_e: Thermal connection factor
K_v: Cooling air correction factor
K_f: Frequency correction factor
K_a: Correction for high altitude
K_b: Fuse load constant
G: Cyclic load factor

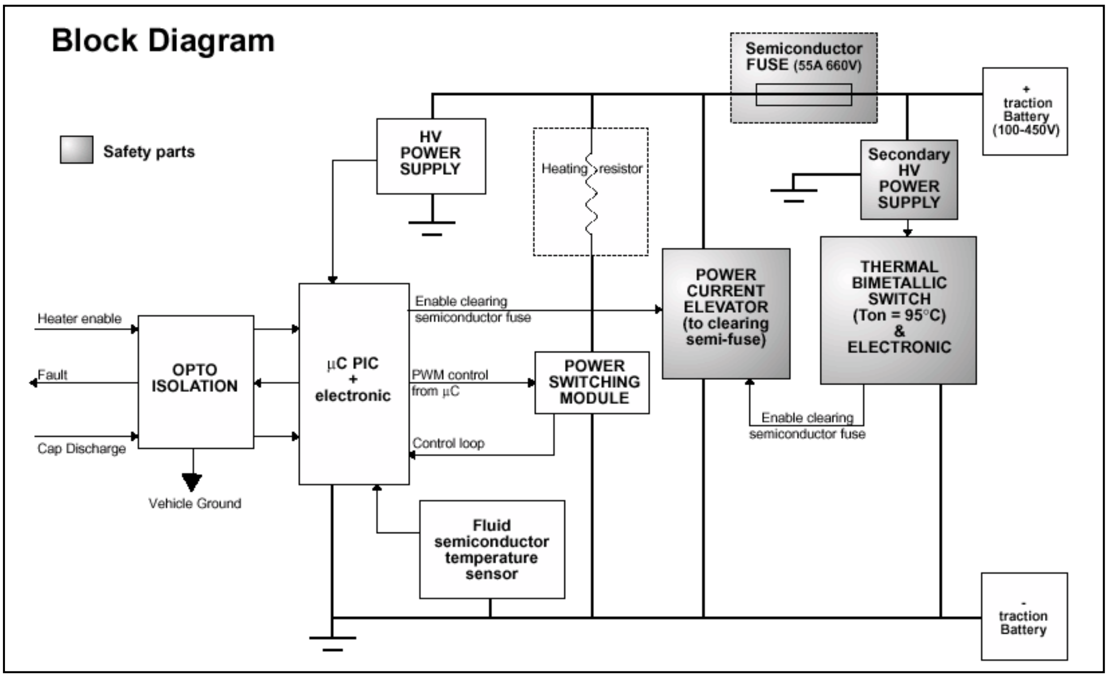


Fig. 2: Fuses requirement in the EV circuit

In the following, we will analyse the areas posed by EV's that will affect the above factors, directly or indirectly.

3.1 Voltage Level

Traditional automotive batteries were mostly lead-acid batteries and were 12Vdc, 24Vdc (heavy vehicles) or 42Vdc. This provided power for the starter motor, ignition system, lights and even the power steering.

With the expansion of EV's, the tendency is to go to a higher voltage, allowing higher power without drawing excessive currents. A comparison of motor efficiency showed an improvement; in particular, commutator losses at the brush decrease with higher voltages.

Whilst some cars have an independent lead-acid 12/24Vdc battery for the auxiliary system or a DC/DC converter for stepping down the voltage to a lower level for auxiliary supplies, many retain the same battery output voltage throughout to minimise the cable size and losses.

EV batteries can range from 150Vdc up to 800Vdc whereas the traditional automotive fuse links are only rated at 32Vdc and 58Vdc.

This means the traditional automotive fuse links cannot be used in most cases on EV's. Industrial fuse links or more specialised fuse links become the only available options for this voltage range.

3.2 Ambient Temperature

This variable is extremely crucial and is often underestimated when deciding the fuse selection. Increases in ambient temperature will reduced the life cycle of the EV battery and has a similar effect with the fuse. Normal ambient temperatures as per IEC 60269 for a fuse link, is up to 40°C (average of 35°C in a 24hr period and less over one year). However, today, EV ambient temperatures have been specified from as low as -40°C up to +105°C. As such, utilising Fig. 3, a fuse link temperature de-rating factor, Kt, could be as low as 0.5 which will have a serious impact on the selected fuse type.

This has the initial implication of doubling the fuse link's current rating before other factors are taken into consideration.

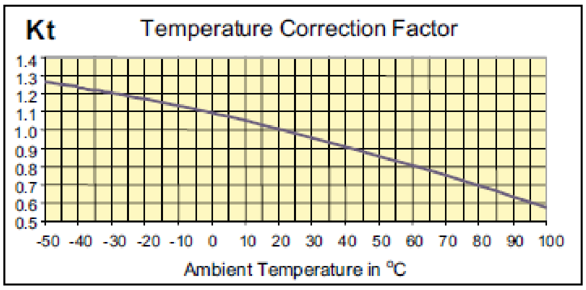


Fig. 3: Fuse link's temperature de-rating factor curve

3.3 Thermal Connection

Fuse links are generally mounted/connected using busbars or cables. The current density of the busbars/cables is defined in IEC 60269-4 and should be between 1 - 1.6A/mm^2. If the connection carries a current density less than this, then the fuse link should be de-rated as per the following graph [3].

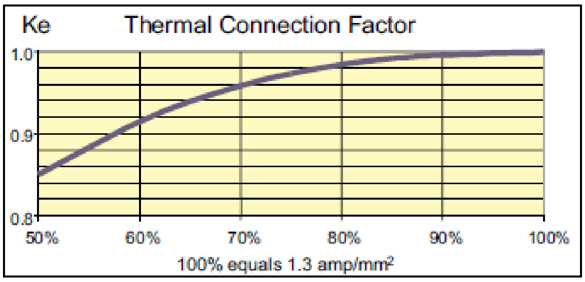


Fig. 4: Fuse link's thermal connection factor curve

In order to keep the weight, space and cost to a minimum, the automotive industry tends to opt for using small cabling.

A typical battery cable size is around 35mm^2 for a 200A continuous loading; a 27kW motor cable is around 25 mm^2; the auxiliaries such as HVAC, steering pump, heaters range from 2.5 mm^2 to 4 mm^2.

A thermal connection factor (Ke) of 0.8 can be applied (which is equivalent to around 15% of the IEC required cross sectional area for the fuse).

3.4 Cyclic Loading and Overload

When fuse links are subjected to current pulses (i.e. regular or irregular changes in load current), cyclic stress is induced owing to temperature variations. Degradation of the fuse elements can gradually accumulate and this may show as an increase in resistance. Consequently, current-time characteristics shift causing premature fuse fatigue and early operation during normal service. Under such circumstances, the intended protection will not be achieved. In order to avoid this condition, consideration has to be taken to ensure that there is an appropriate safety margin for the selected fuse.

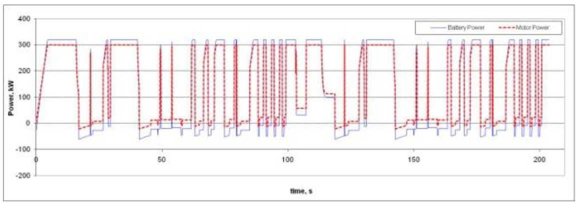
Unlike a PV system where the load profile is quite predictable, EV's have a very large and unpredictable cyclic load profile. Variables include geography, driver's style and specification of the car.

Depending on the battery characteristics, the current drawn at different speed / accelerations varies extensively.

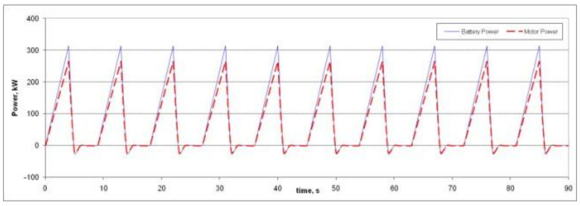
For example, using a VX1 battery,

At 20 Mph on a level road current drawn = 10 Amps
At 30 Mph on a level road current drawn is 15Amps
At 40 Mph on a level road current drawn is 25Amps
At 50 Mph on a level road current drawn is 40 Amps
At Maximum Power on an incline from standing start and full 'throttle', current drawn is 106 Amps.

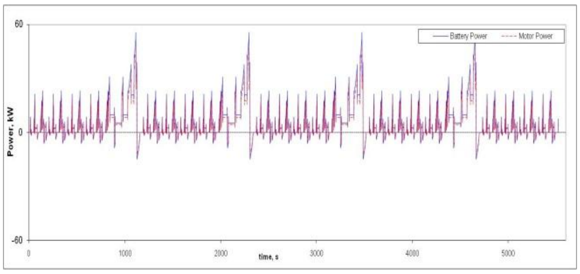
The following examples show the variation of loading under different situations. The profiles are from a high performance EV/supercar.



(i) A single cycle representing a standing start lap and one flying lap of the test track



(ii) Traffic light test



(iii) Profile over 30 mile range

Fig. 5: Load profiles of a 'supercar' prototype

The examples in Fig. 5 show how intense the loading can be and as such, a large cyclic loading de-rating factor (G) - up to 1.8 times - may need to be applied when determining the fuse link. Less arduous loading will incur a lower G factor.

The challenge here lies in the fact that whilst it is possible for the industry to provide the load profile of say an Electric Bus (predefined route and timetable), it is difficult to predict the "normal" current loading of an EV.

In addition, during the recharge state, there will be an overload condition for a pre-defined time for the motor-controller. It is important to ensure that the fuse is able to withstand this overload condition without melting and causing pre-mature fatigue.

Fig. 6 shows the profiles during pre-charging under different test conditions. All exhibit very high overload and cyclic loads, which can significantly affect the thermal stress of the fuse element.

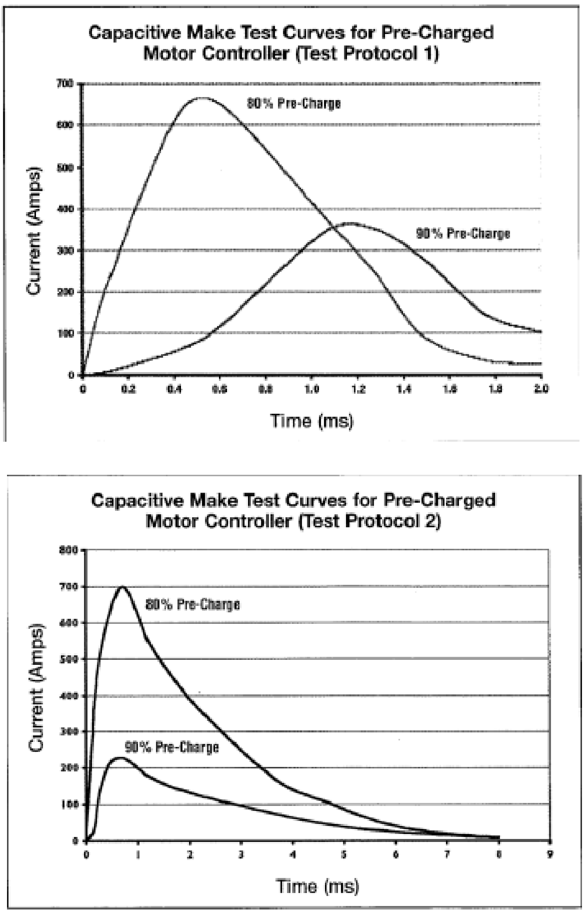


Fig. 6: Charging profiles

3.5 Weight and Space

Space and weight are premium in vehicles. Whilst traditional automotive fuse links such as blade fuses are tiny, industrial fuses are significantly bigger in both weight and size. However, with the voltage level requirement increasing, present day industrial fuse links or specialised fuse links seem to be the only available options.

Battery packs do not solely consist of battery cells, but also other subcomponents such as Battery Management System (BMS), contactors for switching, fuses, connectors, etc [4]:

- 10% of a battery volume and weight is BMS and HV components
- Another 5 – 10% is taken up with wiring and bus-bars
- 15 – 20% is in the housing and support structure
- 25 – 35% of battery weight is non cell content

Therefore, it is desirable to have the fuse link as small as possible.

However, when considering the variables such as high ambient temperature and cyclic loading, this will require up-rating the fuse link which may impact size and space. This is something that the automotive industry is now beginning to recognise.

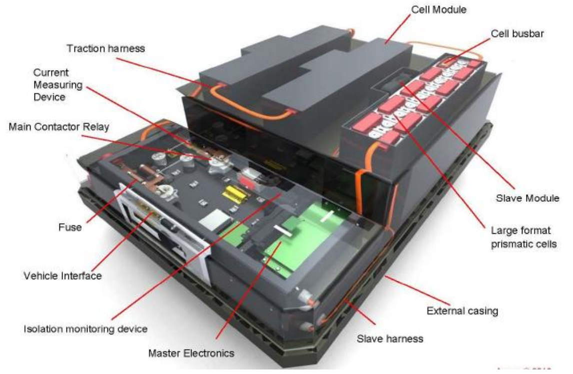


Fig. 7: Battery pack components [4]

3.6 Shock and Vibration

Harsh environments as seen in automotive applications, can be very demanding on larger components which are exposed to severe shock and vibration.

The car manufacturers normally issued their own shock and vibration specifications. However, these are generally in line with IEC 60068-2-6 for sinusoidal vibration excitation and IEC 60068-2-64 for wide band vibration excitation. For the mechanical shock requirement, this will normally be in line with IEC 60068-2-27 and IEC 60068-2-29.

It should be noted there is no requirement in IEC 60269 for shock or vibration testing of a fuse link. Although high speed fuses are expected to be better in terms of shock and vibration-withstand capability due to their very compact construction, it is important to test the fuse links, when installed under the specific application. Very often, it is not just the fuse links itself, but a combination of using good anti-vibration components and known processes/ procedures.

3.7 Automotive Quality Requirement

Today's existing automotive fuse links are made to automotive quality management system standard, ISO/TS 16949.

It is highly unlikely that the proposed solutions using larger fuse links in an EV application, will have been made/tested to this specification.

The automotive industry typically demands less than 10 Parts-Per-Million (PPM). The question for fuse link manufacturers is,

"Is this realistic or achievable?

4. Standards

At the time of writing, it can be said there is no complete, unilateral standard covering EV's.

It is globally recognized to have such standards which protects consumers, defines development, discourages the imposition of market barriers and establishes common components and systems used in EV's. Standards currently applicable to EV's are mostly for lead-acid batteries and nickel-metal hybrid batteries (NiMH).

Motor voltage, battery size, charging and discharging rate can vary significant from car to car. This poses problems to the component suppliers as each of these could be a custom solution - applicable only to one model.

Battery tray sizes, charging infrastructure, voltage level, protection, etc have been targeted for standardisation.

The European Commission has issued a legislative proposal for a common safety standard for EV's. This proposal is part of the wider European Strategy on Clean and Energy Efficient Vehicles which sets into action, the first part of the European Commission's roadmap on regulations and standards for EV's.

The proposed legislation aims to:

- Bring EU legislation in line with the United Nations Economic Commission for Europe (UNECE) legislation on approval of battery electric vehicles and their construction and safety requirements.
- Ensure that all vehicles marketed within the EU are constructed under a common safety standard for electric vehicles.
- Protect vehicle users from getting into direct contact with high voltage parts of the vehicle.
- Harmonise testing requirements in order to simplify approval of electric vehicles. Under the new type-approval system, automotive manufacturers will only need to obtain approval for a vehicle type in one Member State.

Whilst traditional automotive fuse links are built according to ISO 8820-3 (32Vdc or 58Vdc), this standard has not been updated to reflect the changes and requirements of the EV electric circuit.

The establishment of standard(s) for an EV will have far reaching implications and will impact everything from components and subsystems to charging infrastructure and national grid development.

5. Conclusion

This paper has attempted to address the major challenges posed to the fuse world in the EV market. Most of the current automotive manufacturers are using standard fuses, but it is clear that development is needed if trying to reduce size whilst maintaining the environmental, reliability and safety requirements.

Once international or global standards are approved, the focus will then turn to suppliers and manufacturers to provide a range of EV compliant products. There are several international committees reviewing the requirements - many have specific considerations. However, this "indecision" has not deterred automotive manufacturers from launching their EV's, but could, at a later date, impact those in general circulation.

The opportunity is huge. Pure electric vehicles are the future, but hybrids are gaining in popularity now - it can only get better as costs come down.

Watch this space!

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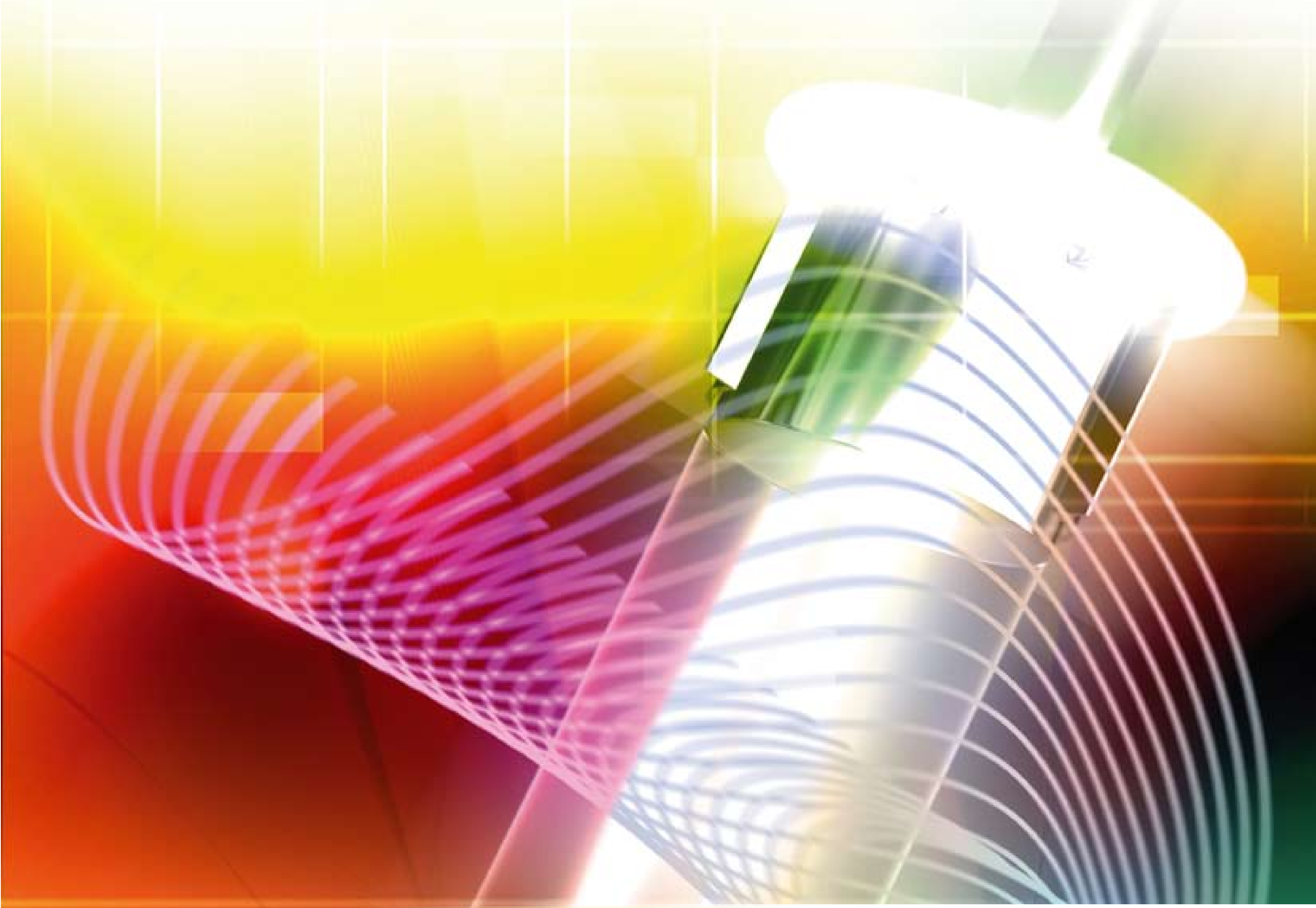

REQUIREMENTS ON FUSES IN THE TRIGGER CIRCUITS OF SPARK-GAP-BASED ARRESTERS

Arnd Ehrhardt, Stefanie Schreiter, Michael Rock

Requirements on fuses in the trigger circuits of spark-gap-based arresters

Arnd Ehrhardt[(1)], Stefanie Schreiter[(1)], Michael Rock[(2)]

[(1)] DEHN + SÖHNE GmbH + Co.KG., Hans-Dehn-Straße 1, D-92318 Neumarkt, arnd.ehrhardt@technik.dehn.de, stefanie.schreiter@technik.dehn.de

[(2)] Technische Universität Ilmenau, Gustav-Kirchhoff-Straße 1, D-98693 Ilmenau, michael.rock@tu-ilmenau.de

Abstract

Electronic trigger circuits are nowadays used in modern lightning current arresters. Due to their mode of operation, considerable impulse currents may occur in these trigger circuits. As a result, the components of the trigger circuit could be overloaded. This article describes a specially designed surge-proof miniature fuse that protects the trigger circuit in a lightning current arrester. The special application-specific requirements on this fuse will be pointed out in detail. The miniature fuse described in this article, which is mounted on a printed circuit board, is adapted to the load capacity of the trigger circuit. The fuse was designed with a high impulse current carrying capability and has a long-time ageing resistance and a high extinguishing capability for line-frequency currents.

Keywords: miniature fuse, lightning current arrester, trigger circuit, impulse current, ageing stability.

1. Introduction

Nowadays integrated electronic trigger circuits are essential to fulfil the variety of requirements placed on modern lightning current arresters. Due to the basic functional principle of the arrester, impulse currents that considerably stress the individual components may occur in these trigger circuits.

This articles describes a specially designed impulse-current-resistant miniature fuse for protecting the trigger circuit in a lightning current arrester and shows the special application-specific requirements this fuse has to fulfil, for example impulse current carrying capability, ageing resistance as well as a high follow current extinguishing capability. Moreover, the functional principle of the fuse under normal operating conditions as well as in case of overload and ageing of the surge protective device is described in detail.

2. Design and functional principle of a modern lightning current arrester

The increasing integration of information technology systems with their electronic components, which are extremely sensitive to overvoltage, fundamentally changed the lightning and surge protection requirements over the last years.

Today's lightning current and surge arresters are mostly mounted on DIN rails in low-voltage systems. For this reason, the low voltage protection levels required for electronic systems frequently cannot be gradually realised by means of large-scale and complex decoupling networks.

The lightning protection zones concept [1] required for optimum lightning and surge protection has to be increasingly applied in confined spaces. Surge protective devices which are supposed to ensure lightning equipotential bonding and the protection of electronic devices against energetic field-related and conducted interference are directly installed at the entrance point of power and data lines into a building or an installation. Lightning equipotential bonding prevents that destructive partial lightning currents enter the electrical installation. For this purpose, lightning current arresters must be able to carry energetic impulse currents of waveform 10/350 µs in case of a direct lightning strike. Coordinated surge protection for the electrical installation and terminal devices connected to it additionally requires that the arresters are able to carry impulse currents of waveform 8/20 µs caused by injections in case of nearby lightning strikes several times without destruction.

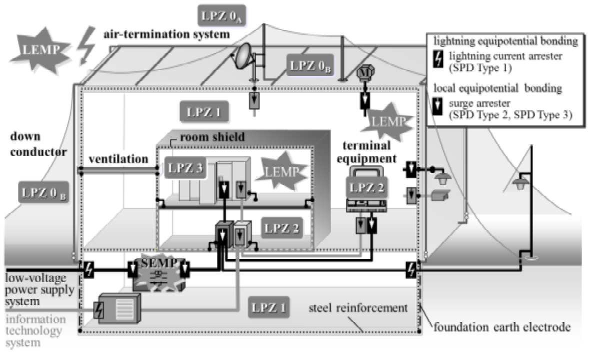

Fig. 1: Lightning protection zones concept

This article deals with spark-gap-based lightning current arresters for use in low-voltage power supply systems. Such lightning current arresters are installed at the entrance point of the electrical supply lines into a building, typically in the main distribution board or upstream of the energy consumption meter.

Figure 1 shows a typical arrangement of surge protective devices (SPDs) in conformity with the lightning protection zones concept [2, 3]. In case of particularly compact installations it is advisable to gradually reduce the voltage protection level by means of a single arrester combining SPD type 1 (2.5 kV) and SPD type 2 (1.5 kV) so that this arrester ensures a direct transition from LPZ (LPZ = Lightning Protection Zone) 0_A to 2.

Due to the required reduction of the voltage protection level from typically 2.5 kV to < 1.5 kV, the spark gap of regular lightning current arresters would trip more often without energetic assessment, for example already in case of switching overvoltage or so-called burst impulses. If modern surge protective devices are activated by means of a low-energy interference as described above, the power supply shall not be interfered with during or after a discharge, for example by means of mains follow currents, supply voltage dips or even activation of the upstream overcurrent protective device resulting in power failure.

To avoid these disadvantages, modern surge protective devices feature a high follow current limitation, ensuring power supply even in case of low-performance supply with rated currents of the power supply fuse ≥ 20 A gG/gL.

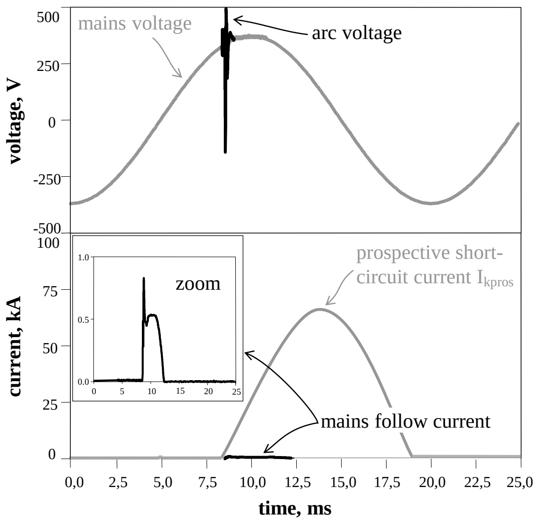

Fig. 2: Follow current limiting capacity of a lightning current arrester in case of a prospective short-circuit current of 50 kA

Figure 2 shows a current-voltage characteristic for the activation of a lightning current arrester with high follow current limitation.

The prospective follow current of e.g. 50 kA is reduced to a negligible residual current of e.g. lower than 1 kA.

Since a repeated activation due to the required low voltage protection level would accelerate ageing of such a lightning current arrester, it is advisable to prevent that the spark gap trips frequently, particularly in case of small, low-energy interference. In case of a modern lightning current arrester this is achieved by an energetic assessment of the interference by means of the integrated trigger circuit of the lightning current arrester according to Figure 3. Due to its components, the trigger circuit fulfils the function of a surge arrester and a certain amount of energy is needed to activate the powerful spark gap by an ignition impulse.

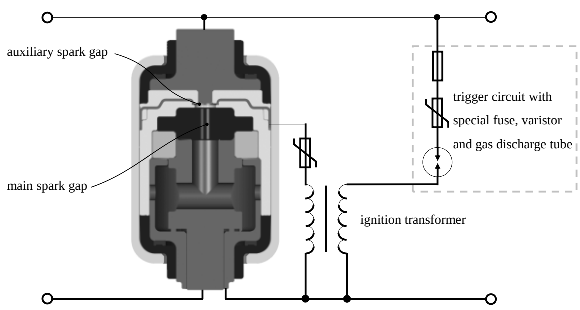

Fig. 3: Schematic diagram of the spark-gap-based lightning current arrester and the trigger circuit

The trigger circuit arranged in parallel to the spark gap consisting of a varistor connected in series to a gas discharge tube (see Figure 3) protects against overvoltage independent of the spark gap. Low interference such as burst impulses, low-energy switching impulses, but also impulse currents of waveform 8/20 µs (injections) up to several kA are directly discharged via this trigger circuit without igniting the spark gap. The load on the spark gap, particularly in case of mains follow currents, is thus considerably reduced and premature ageing due to frequent switching is prevented.

Not only the spark gap, but also the surge protection elements of the trigger circuit are subject to ageing. Moreover, the lightning current arrester may be exposed to a temporary overvoltage (TOV = Temporary Overvoltage) resulting in overload of individual elements and/or malfunctions, for example due to incorrect installation.

For this reason, a special overcurrent protection fuse is integrated in the path of the trigger circuit. This article particularly deals with this special fuse which is integrated into the trigger circuit of a modern lightning current arrester. The design of this special fuse is harmonised with the overall function of the arrester and is described below.

3. Requirements on the overcurrent protection elements in the trigger circuit

The special fuse in the trigger circuit is supposed to protect the circuit elements from energy overload and to safely disconnect the trigger circuit from the power supply in case of faults. In addition, the status of the special fuse is to be indicated.

The space available in a DIN rail mountable lightning current arrester only allows relatively small fuse sizes. Therefore a 5 x 20 mm type in accordance with the IEC 60127-1 [4] standard is used.

Common mounting of a miniature fuse (cartridge fuse) on a printed circuit board by means of a separate fuse holder requires a lot of space on the trigger printed circuit board. If a miniature fuse is mounted on a printed circuit board by means of wired connection caps, mounting and welding is complex and results in an additional high voltage drop, which unnecessarily increases the so-called voltage protection level of the arrester. Therefore a special double connection cap was designed for the special fuse which is shown in Figure 4 and which provides an additional reinforcement of the cap base of the fuse.

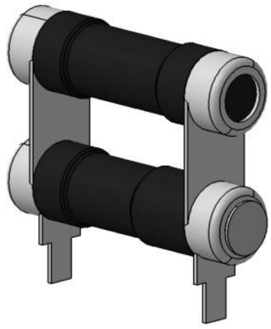

Fig. 4: Fuse combination with special connection caps

In order to ensure the required arrester performance, high melting integrals and thus fuse elements with a large cross-section are necessary. The fuse element cannot be designed as a round wire since the required wire sizes prevent safe mechanical installation of the connection caps. For this reason, the fuse element is designed as a strip. It is not soldered and only provides a single protective layer to prevent e.g. oxidation. The rolling process is controlled so that the melting integral value is not reduced with regard to the theoretical material value. When integrating the fuse element into the fuse enclosure, it is ensured that the fuse element does not contact the enclosure wall, is not twisted and is surrounded on all sides by a silica sand mixture which is very coarse for the small size.

The cap for printed circuit board mounting ensures a low-impedance connection due to its flat contact lugs and a high mechanical strength of the combination. Due to this low terminal impedance, only small voltage drops occur in case of steep impulse currents so that the voltage protection level specified for the arrester is reliably maintained. A low inductive voltage drop across the fuse itself is achieved by using a special low-impedance fuse element designed as a strip. Despite the confined space, the contact lugs on both sides allow defined positioning, mounting and easy welding.

The impulse-current-resistant special fuse can either be used alone or in combination with a parallel indicator fuse indicating the status of the fuse. In case of the fuse shown in Figure 4, the status of the special fuse is indicated by means of the striker of the additional indicator fuse which activates the status indication of the lightning current arrester. Due to the small size of the special fuse, no additional indicator wire has to be used. If suitably rated, the indicator fuse also switches as soon as the special fuse trips and its striker is pushed out with the force of a coil spring (several N). The status of the special fuse can also be indicated electrically.

Individual elements of this combination fuse are additionally fitted with an insulating heat shrinkable sleeve e.g. to extend the isolating distances and thus to increase the dielectric strength of the fuse.

The requirements and the functional principle of the special fuse in lightning current arresters depend on the operating states of the surge protective device, the supply voltage, and the performance of all functional components of the complex arrester and will be described in detail.

3.1 Requirements during normal operation

The test procedures described in the IEC 61643-11 [5] standard serve as a reference for the quantity and intervals of the loads the entire lightning current arrester must be able to handle without restriction. These tests predominantly load the spark gap.

Under normal operating / mains conditions the trigger circuit of the surge protective device is disconnected from the power supply by means of the gas discharge tube and the special fuse is de-energised. It is only when the gas discharge tube is activated according to its dynamic spark over voltage that current flows through the special fuse on the trigger printed circuit board.

Dimensioning the special fuse for a characteristic fuse parameter, the rated current, is therefore not relevant for this application. If used as described above, the special fuse has an equivalent nominal current rating < 16 A.

The integrated trigger circuit assesses the energy of the interference and activates the spark gap at a defined limit value to relieve these components. For this reason, both impulse currents of waveform 8/20 µs and 10/350 µs with a low amplitude and cut-off impulse currents of these waveforms with a higher amplitude flow through the integrated fuse until the spark gap is activated. In addition, the integrated fuse may also be loaded by low-energy impulses with a higher current steepness, e.g. in case of burst impulses.

If lightning current arresters are adequately dimensioned, impulse currents with a peak value up to approximately 5 kA of waveform 8/20 µs can be discharged via the trigger circuit (printed circuit board current) without igniting the spark gap. This corresponds to a Joule integral of approximately 380 A²s.

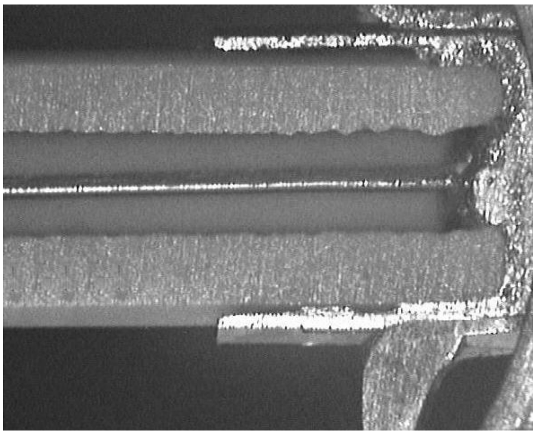

Fig. 5: Section of a fuse element after 30 x 5 kA 8/20 µs

Figure 5 shows a fuse element in an open fuse after 30 impulse currents of 8/20 µs waveform with 5 kA without visible signs of ageing.

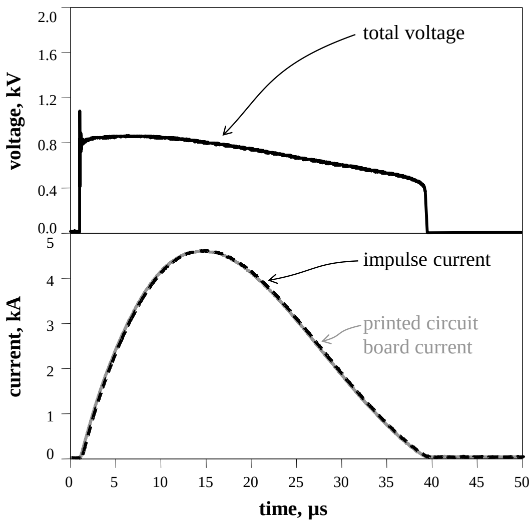

Fig. 6: Protection level of the arrester without ignition of the spark gap at 5 kA 8/20 µs

The corresponding current and voltage curves can be found in Figure 6. The residual voltage of the entire arrester is considerably lower than the required 1.5 kV, the voltage drop directly across the fuse being some 10 V.

The special fuse must not be subject to ageing during these adiabatic loads. The fuse element is dynamically loaded within a matter of some µs by extremely high current forces in particular in case of the “cut-off“ impulse currents with a high amplitude.

Figure 7 shows the current and voltage characteristics across the lightning current arrester during the ignition of the spark gap at a load of approximately 9 kA 8/20 µs.

An impulse current of waveform 8/20 µs flowing through the trigger circuit is cut off as soon as the spark gap ignites as shown in Figure 7 (printed circuit board current). This happens under consideration of all tolerances of the trigger circuit and the spark gap if the current is greater than approximately 5 kA. This can be referred to as a cut-off 8/20 µs wave that loads the fuse. For safety reasons, the special fuse is dimensioned so that impulse currents of waveform 8/20 µs with values of Joule integral of more than 500 A²s are discharged several times without damage.

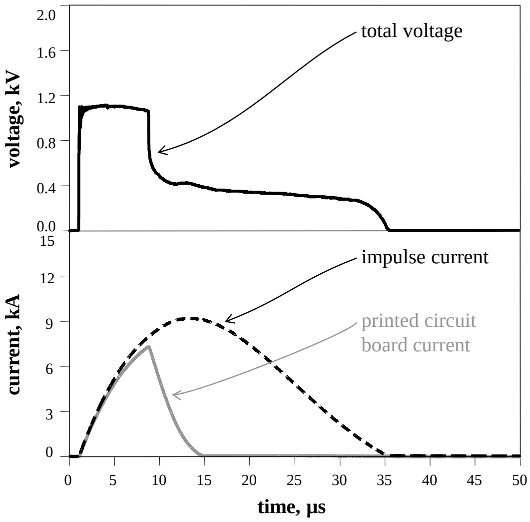

Fig. 7: Protection level of the arrester with ignition of the spark gap at 9 kA 8/20 µs

The lightning current arrester is rated for impulse currents of waveform 10/350 µs up to e.g. 25 kA. In case of such loads the trigger circuit already ignites the spark gap within the rise time of the current impulse. Therefore the behaviour of the trigger circuit and the load on the special fuse do not fundamentally differ for impulse currents of waveform 8/20 µs and 10/350 µs since both impulses have roughly the same front time.

In case of an impulse current of waveform 8/20 µs of e.g. 25 kA only a peak current value smaller than 8 kA occurs across the fuse (Fig. 8).

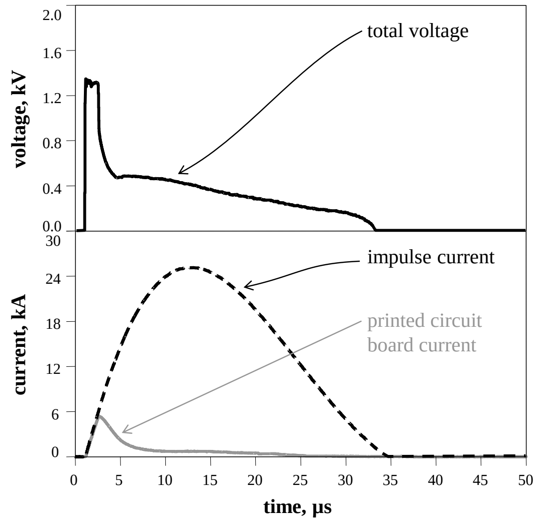

Fig. 8: Protection level of the arrester when loaded with 25 kA 8/20 µs and the spark gap ignites in the impulse front

With less than 200 A²s, the adiabatic load on the fuse is frequently smaller than in case of a full wave of 5 kA 8/20 µs without ignition of the spark gap (see Fig. 6).

3.2 Requirements in case of overload and ageing

The surge protective device can be heavily loaded by little load e.g. in case of incorrect installation. Similarly, frequent loads on the surge protective device can cause ageing of the individual components. In both cases, the special fuse should put the trigger circuit into a safe state, which is disconnected from the power supply, and the relevant status should be indicated.

Figure 9 shows a current and voltage curve of a significantly aged spark gap with a high ignition delay time. The adiabatic load on the fuse is already approximately 400 A²s to 500 A²s. The special fuse can handle such cut-off impulse currents with high amplitudes up to approximately 10 kA at a later ageing stage of the spark gap for a limited number of loads.

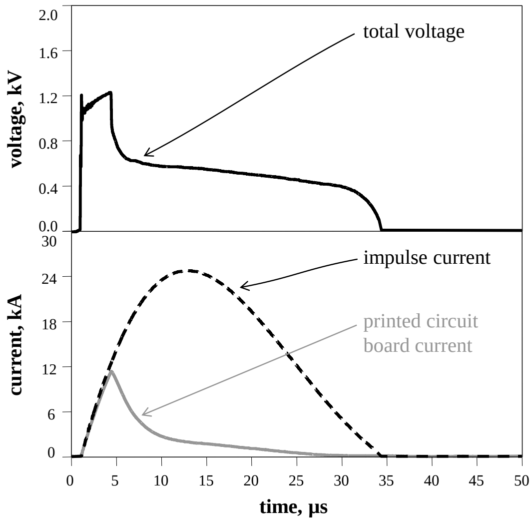

Fig. 9: Protection level of the arrester when loaded with 25 kA 8/20 µs and an aged spark gap ignites in the impulse front

Nevertheless, after several loads of this kind, the fuse element shows clear signs of ageing such as diffusion of the surface coating and diffusion on the solder contact as well as partial signs of melting at the surface of the fuse element. Figure 10 shows examples of fuse elements with such signs of ageing.

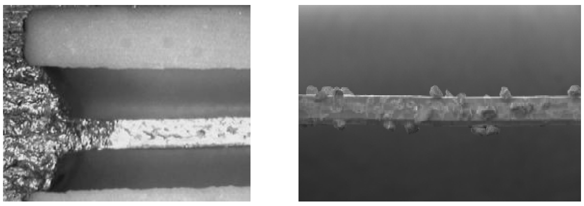

Fig. 10: Diffusion on the solder contact, diffusion and signs of melting at the surface of fuse element

If the load limit of the special fuse and/or the other elements of the trigger circuit is reached, the trigger circuit of the lightning current arrester is safely disconnected from the power supply. This is directly indicated by the status indication / transferred to a monitoring unit via a remote signalling contact.

Not only the spark gap is subject to ageing due to a high number of loads, but also the components of the trigger circuit. Both the gas discharge tube and the varistors can handle the loads individually, however, ageing cannot be entirely ruled out.

If the varistors fail due to ageing, a limited short-circuit might flow through the trigger circuit. The special fuse must safely handle this power-frequency fault current. Owing to the current-limiting disconnection of the power-frequency fault current by means of the fuse, the trigger circuit of the arrester is disconnected from the power supply. This is indicated by means of the indicator fuse.

3.3 Additional requirements

In case of very high impulse current loads on the arrester and/or extremely aged spark gaps, the load on the trigger circuit is significantly increased by the amplitude of the cut-off impulse current. If the fuse is loaded with a peak current value of approximately > 10 kA according to Figure 11, the fuse may already trip during the rise of the impulse current.

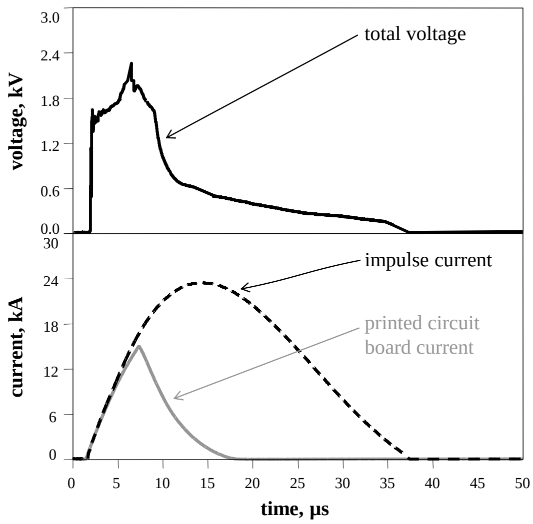

Fig. 11: Behaviour for a tripping fuse in case of an extremely aged spark gap

If in such cases the spark gap is not activated by the trigger circuit in due time, the spark gap is safely ignited by the switching voltage which occurs across the fuse during the disconnection process and which can reach high values of more than 2 kV. This is intended and is an "emergency operation function" for the arrester. The formation of a high switching voltage by means of the fuse in this case serves for the passive ignition of the spark gap which, as a consequence, safely discharges the impulse current.

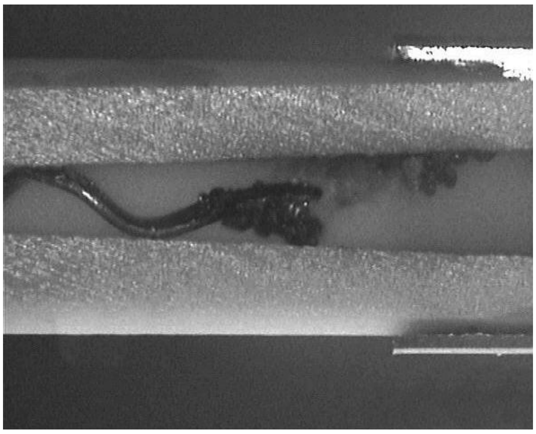

Fig. 12: Wave-shaped deformation of a fuse element after a high dynamic load with an amplitude of > 10 kA

If the fuse is loaded with these high current amplitudes, the fuse element does not melt any more due to an adiabatic current load, but it is mechanically broken due to the high dynamic force of the flowing impulse current. This is due to a repeated wave-shaped deformation of the fuse element (Figure 12). Where necessary, the exact breaking point can be influenced by means of an adequate design (predetermined breaking point) of the fuse element.

If the breaking point is not predetermined, the fuse element mostly breaks at the end where it is welded to the end caps and is already slightly bent due to the manufacturing process. During manufacture, the fuse element is mechanically processed (rolled) so that it is considerably reduced as soon as it breaks due to automatic twisting (like a corkscrew).

Very quick overload and ageing of the varistors in the trigger circuit might be caused e.g. by incorrect installation. In this process, the lightning current arrester is permanently exposed to extremely high power-frequency voltages. The components of the trigger circuit, however, are not designed for this values. In such a case the integrated fuse must safely disconnect the trigger circuit. Figure 13 shows the disconnection of the fuse for example in case of quick overload of the varistors.

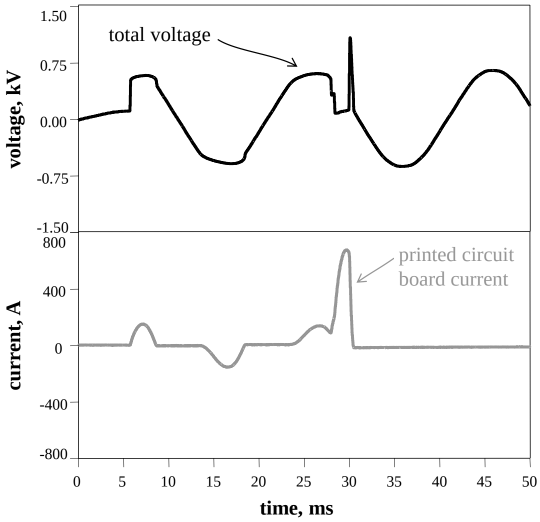

Fig. 13: Behaviour of the fuse in case of overloaded components

The passive spark gap is dimensioned so that surge protection is ensured with an increased voltage protection level (< 4 kV) even after the trigger circuit failed.

4. Summary

The trigger circuits used in spark-gap-based lightning current arresters are to be protected by means of a fuse. This special fuse has to fulfil special requirements due to the functional principle of the arrester. The fuse is supposed to show a defined behaviour both under normal mains conditions and in case of interference, overload e.g. due to incorrect installation and ageing of the individual arrester elements.

The parameters of the lightning current arrester such as lightning and impulse current carrying capability and voltage protection level must not be negatively affected by the fuse. Thus the special fuse must be able to carry small impulse currents several times and must be resistant to ageing at the same time. Furthermore, the fuse can safely handle high power-frequency currents also in case of an increased supply voltage.

For this reason, not only high values of the Joule integral and a high switching performance, but also a low-impedance and dynamically solid design were required. A solely mechanical status indication of the special fuse can be achieved by a parallel indicator fuse with spring-loaded striker.

To fulfil the high requirements, the fuse is provided with mechanical and insulating components. In addition, the special fuse was designed so that the switching voltage during the disconnection of the fuse is sufficiently high for a passive ignition of the spark gap in the arrester under certain fault conditions.

A specifically designed special fuse of type 5 x 20 mm with a slow-acting partial range characteristic meets these requirements.

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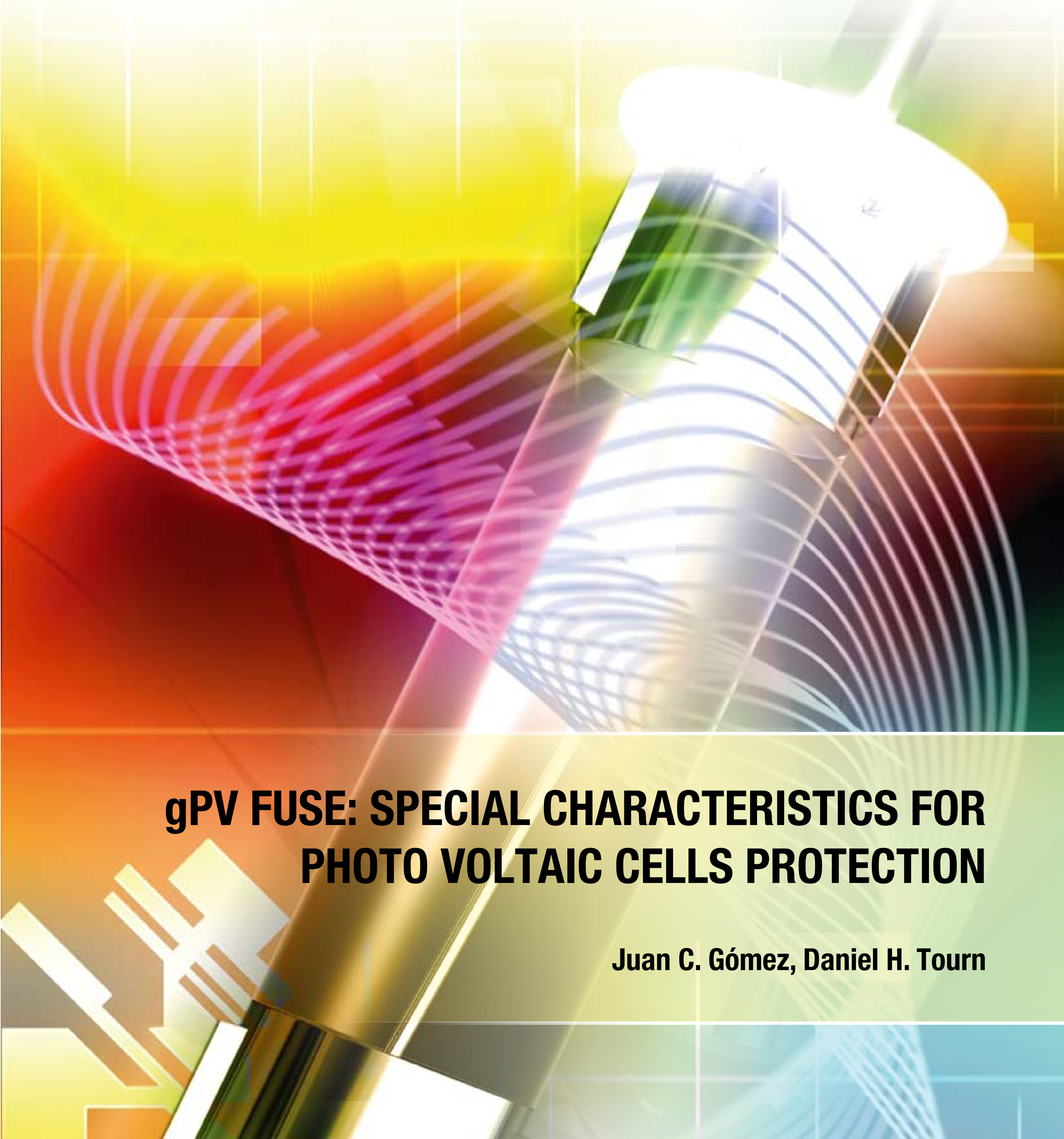

gPV FUSE: SPECIAL CHARACTERISTICS FOR PHOTO VOLTAIC CELLS PROTECTION

Juan C. Gómez, Daniel H. Tourn

gPV fuse: special characteristics for photo voltaic cells protection

Juan C. Gómez, Daniel H. Tourn

IPSEP, Rio Cuarto National University, Argentine, jcgomez@ing.unrc.edu.ar

Abstract

During the last 50 years, the application of Photovoltaic cells (PV cells) has increased at a high speed. Also the number of cells forming strings and arrays raises, for which the terminal rated voltage, is reaching today values of the order of the thousand volts and the faults currents are slowly increasing its magnitude. PV cells have special characteristics that require protective devices specifically designed for this application, among which the fuse presents optimum features. The main PV cells characteristics are: dc power generation, low short-circuit current magnitudes and X/R ratios (< 25 ms), behavior highly influenced by temperature, etc. Besides the use in the system of storage batteries and reversible inverters, could generate inverse currents due to cells shade, unbalances, and faults. The most used gPV fuse specification is the new IEC 60269-6, that gives some rough guidelines such as: g breaking range, 10 kAdc as minimum breaking capacity, cyclic condition to determine rated current, not applicability of "gates", fuse selection steps, etc. In order to meet the PF cells characteristics and IEC specifications, several brands of fuses have appeared in the market, showing the actual trend for that application. Also fuse manufacturers give "application rules" that have some inconsistencies and difficult the fuse selection. A summary of the market available fuses and their characteristics is presented, also discussing the advantages and disadvantages of their parameters and characteristics, criticizing some shortcomings and over-dimensioning. The need for more coordinated work between PV cells and fuses manufacturers is stressed, indicating the areas where this work is required.

Keywords: photovoltaic cells, dc fuses, low current interruption, inverse currents, application rules.

1. Introduction

During the last fifty years, the application of the photovoltaic cells (PV cells) for the electric power production has increased at a high speed, besides the exploitation of solar energy that initially represented a rarity or sophistication, has become today a sustainable, and mature technology which adapts to the present necessities [1].

The energy content of the solar radiation is on the average of the order of the 1.000 W for square meter, varying thoroughly according to the hour of the day, the time of the year and the geographical location, being for instance, our country Argentina extremely favored for its location [2].

The photovoltaic cell makes the direct conversion of solar radiation into electricity, having the advantage of being formed by modules, simply growing to constitute big generations associating cells, with a useful life of around 25 year. The typical conversion efficiency of the solar generation by using PV cells is ranging from 10% to 15%, acceptable value due to the solar energy has no cost.

This technology advances with the speed with which the photovoltaic cells increase its efficiency, as lower its cost and also as improve its aesthetic appearance. With it, the electricity generation from solar energy is becoming an alternative source to the conventional ones, attractive for being a clean source (free of environmental contamination) and day by day with better economy. The power and energy production from solar radiation increases at world level, whose tendency follows and exponential curve [2].

The biggest energy demand coming from this source bears to the necessity of grouping every day bigger quantity of photovoltaic cells, forming longer strings of cells in series, and parallel arrays of high number of cells. Figure 1 shows a scheme of this type of PV structure. Due to this arrangements the terminal rated voltage, is reaching today values of the order of the thousand volts and the faults currents are slowly increasing its magnitude.

Besides, PV cells have special characteristics that require protective devices specifically designed for this application, among which the fuse presents optimum features.

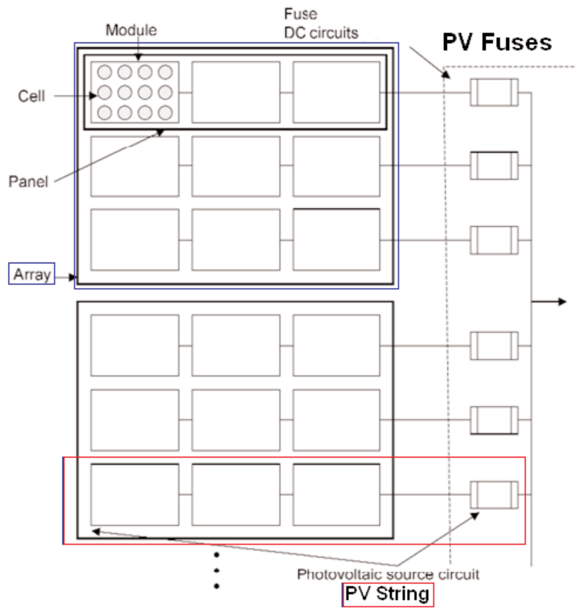

Fig. 1: Photovoltaic cells typical structure.

2. Photovoltaic cells main characteristics

As it is well known, PV cells possess particular characteristics, as for instance they generate electric power of the direct current (dc) type, its per cell voltage is very low, of the order of 0.3 V for the germanium cell and of 0.7 V for the silicon cell, what allows to assemble modules of 17 V and 35 V, having 36 and 72 series cells respectively, what makes them appropriate to charge batteries of 12 V and 24 V.

The more used solar panels in systems with power higher than 20 kW are those of poli-crystalline silicon type, with square shape having side dimensions of 4", 5" and 6", or 10 cm to 15 cm which are able to give a maximum current for panel of 7.5 A. Wide differences exist among the nominal characteristics of the same panel type among different manufacturers, differences that reach to 35%, for what the study of the selection of the protection should be made on the specific characteristics of the panel to install.

For their application in interconnected form with the 110 V or 220 V networks, exploitation completely different from the simple application in isolated places to supply a few appliances demanding a low power amount, numerous cells are required in series. The more accepted dc voltage for this application is between 900 and 1,000 V dc, the first figure is of wide spread in USA and the second is more applied in Europe [1].

As PV cells form groups of modules in series and parallel, similar to the capacitors banks and storage batteries, problems of voltage unequal distribution are presented, causing faults of individual modules and for that circulating currents among modules in parallel, denominated reverse or residual currents, are very frequents. For their constructive characteristics, PV cells have the particularity of only supply low short circuit current values, with low X/R relationships, requiring for its protection of protective device having specific characteristics.

In summary, the main PV cells characteristics are: dc power generation, low short-circuit current magnitudes and low X/R ratios (< 25 ms), and also its behavior is highly influenced by ambient temperature.

In addition, the obtained energy from the solar to electricity conversion should be transformed into alternating current (ac) with 50Hz or 60 Hz, in order to be able to be used locally, injecting the surplus to the distribution network, requiring for it of an inverter dc/ac that also carries out the injection control. In certain cases the equipment includes storage batteries, in order to regularizing the supply, with what important reverse currents can appear in the event of faults, unbalances or cells shadowing.

Cells partial or total shadowing, caused for instance for a branch tree or dust over the cell, is particularly critical due to the generation of high reverse voltage, also some cells operate as load instead of being a source, thus output is dramatically reduced, hot spots are generated, and local damage could be produced. As the fuse can not protect against the effect of shadowing, the solution roots on the utilization of blocking diodes (connected in series with the string fuse as shown in Figure 2). Also, in order to protect individual cells, bypass fuses are used.

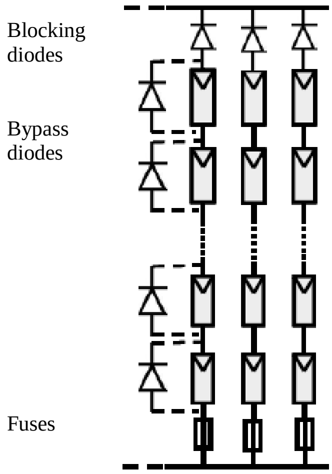

Fig. 2: Typical circuit with fuses, bypass and blocking diodes.

The IEC Standard specify the reference conditions, called STC (Standard Test Conditions), for defining rated values and test specifications of solar cells and modules, which are [3]:

- Cell temperature of 25ºC
- Irradiance intensity of 1,000 W/m2
- Light spectrum according an Airmass (AM) of 1.5

Where AM is the optical path length through Earth's atmosphere relative to that at the zenith at sea level.

The Standard Test Conditions were designed in order to ensure comparability among photo voltaic cells from dissimilar origins and different manufacturers.

The rated values or characteristic data of a photo voltaic cell are:

- In = operating current
- Impp = maximum possible working current of a line (MPP = Maximum Power Point)
- Un = operating voltage
- Umpp = maximum possible working voltage of a line (MPP = Maximum Power Point)
- Isc = short circuit current (Isc MOD short circuit current of a module or string, similarly Isc ARRAY) at STC, usually is approximately 1.1 Impp
- IMOD REVERSE = maximum permissible reverse current of a PV module.
- Ipm = maximum power current
- Uoc = no-load or open circuit voltage of a module or array at STC
- Upm = maximum power voltage

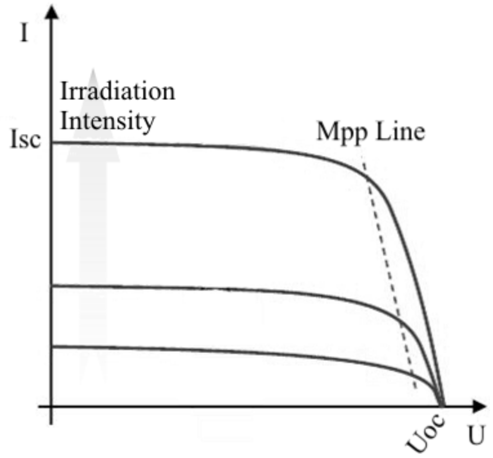

Fig. 3: Current – voltage characteristics, showing the meaning of the Maximum Power Point.

As it was already mentioned, the short circuit current Isc that supply each cell is function of the climatic conditions in the installation point, that is to say of the temperature, solar radiation and height over the sea level. If PV cells are located in high zones, low temperatures and solar radiations higher than 1,200 W/m2 can be reached, which requires of correction factors.

The correction factors for maximum solar radiation are as follows, see Table 1 [4].

Table 1. Correction factors for maximum solar radiation

Climatic Zone	Maximum Solar Radiation	Correction Factor
Normalized	1,000 W/m^2	1
Moderate	1,200 W/m^2	1.2
Moderate mountainous	1,400 / 1,600 W/m^2	1.4 a 1.6
Africa	1,400 / 1,600 W/m^2	1.4 a 1.5

Equally, the Isc is affected by the ambient temperature, being given the correction factors in % /ºC (for example 0.07 % /ºC).

The voltages of the string of cells are quite variable (no load voltage, Uoc stc, is also determined under standard test conditions), thus due to the possibility that extreme operation conditions are presented (as for example temperatures of - 25 ºC) the corresponding correction factors given in % /ºC should be used (for example 0.4 % /ºC).

3. gPV Fuse Characteristics

As the demand of PV cells and the number of installations increase, the necessity of having effective protection against electric transients like as short circuits, overloads, reverse currents and surges is also increasing at a high rate [5].

These new requirements and the present very pressing necessities of electric power, have lead to the design, development and setting in the market of a new series of fuses for PV cells protection whose class is denominated gPV, appropriate for the protection of the manufacturing world leaders' of photovoltaic cells.

At present time it is used in Europe the IEC 60269-6 of recent appearance (year 2010) as design tool, standard that specify the particular characteristics for fuses with this application, similarly it is in study in USA an UL standard with the same purpose, being shortly expected their approval [6].

Optimal protection is reached with fuses located inside the cells string and also in the array output, denominated “string fuse” and “array fuse” respectively [7].

The string fuse functions are [8]:

- Protection in both poles
- Protection required if there are two or more parallel strings
- Always required in systems with batteries or reverse feeding from inverter (high short circuit currents)
- Cable overload protection
- Protection against double earth faults in array and string cabling
- Protection against reverse currents caused by module failures
- Similarly, the array o sub-array fuse functions are:
- Protection in both poles
- Protection against double earth faults in sub-array and array cabling
- Overcurrent protection of sub-array cabling.
- Protection in systems with reverse feeding of inverter.

- Short circuit protection in battery operation if available.

The IEC 60269-6 standard specifies for the fusible gPV the non-fusing (melting) current during one hour as Inf = 1.13 In, where In it is the fuse rated current. Equally it indicates the fusing (melting) current within one hour as If = 1.45 In. The rest of the time – current characteristic can be freely drawn by the fuse manufacturer; several curves have been already proposed by them. The rated current is determined in the classic form of standard IEC 60269-1. Also the mentioned standard indicate the fulfillment of the "Cyclic load" test, which require that 3,000 specific load cycles have to be passed without change of the fuse-link characteristics. Besides it is specified the "Functionality at temperature extremes" that has to be verified with In/If at 50 ºC.

The Inf e If values specified by IEC 60269 change depending on the fuse class, being 1.25 and 1.6 respectively for class gG (≥16A); 1.1 and 1.6 for gR; 1.25 and 1.6 for class gS; and finally gPV 1.13 – 1.45 for the under study class gPV; where the times varies from 1 h to 4 h as fuse rated current function.

Correction factors should be applied on the fuse rated current for work conditions different to the standard one, as shown in Table 2:

Table 2. Effect of heating of neighboring fuses, specified in EN 60469-1.

Number of circuits	Derate Factor
2 – 3	0.9
5 – 6	0.8
6 – 9	0.7
10 or more	0.6

As the average load of the fuses usually does not overcome to 70% or 80% of their rated value, only an additional load derating is required when six or more circuits are nearby, when high losses fuses are used, overcoming each of them the 3.4 W limit value (for the case of high rated currents, normally higher than 32 A) [4].

The fuse rated current is determined for 25 ºC, the cells are normalized to same value, but they can operate at higher temperatures, for what the fuses should be derated to such temperatures by means of correction factors, such as shown in Figure 4 (shown as an example of information of one of the well known fuse manufacturers).

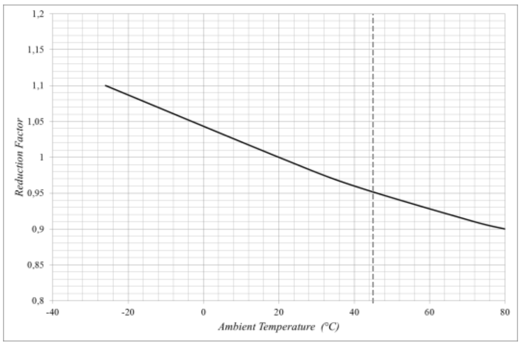

Fig. 4: Fuse rated current correction factor as temperature function.

In what concerns to the maximum breaking capacity, a minimum value of 10 kA is specified that seems to be too low in comparison with that of other classes of fuses (minim breaking current for gG class of 50 kA), but to interrupt the short circuit current of the photovoltaic systems it is more than enough.

It should be kept in mind that the time constant (relationship L/R) of the solar cells fault current, for which this breaking capacity is guaranteed, is very low with values from 1 ms up to 25 ms, that makes a great difference with the traditional applications in direct current like the case of railroad and underground short circuit currents that demand values of the order of the 80 ms. Being the minimum L/R of 1 to 3 ms following IEC 60269-6. Most of the manufacturers indicate breaking capacities between 30 and 40 kA, in spite that IEC 60269-6 only specify ≥ 10 kA.

The fuse test voltage should be 20% higher than the unloaded cell voltage under the worst atmospheric conditions. In general, the fuse test voltage is of the order of 1.1 of the rated voltage value (for example 1,000 Vdc and 900 Vdc respectively). It is normal in several fuse types that the test voltage for this class of fuses is the same one that that of operation (normal work condition), for what is common that rated characteristics are given for two work voltages, for example 900 V and 1,000 V (or 1,100 V).

In what concerns to dimensions, for low rated currents, there is enough available space in the standard NH 0 size for such currents, tensions and rated breaking capacities. For very low current values, 1/10 A to 30 A and 1,000 Vdc, it is wide applied the size 10 x 38 mm (adopted by the following manufacturers; Bussmann, Jean Muller, Littelfuse, OEZ, Schurter, Siemens, Socomec, ETI, SIBA, MERSEN, etc.). On the other hand, for higher rated currents, it is widely used the NH 0 and 1c standard size (must be remembered the extension of the series allowed by IEC 60269), from 32 A up to 160 A and 1,000 Vdc whose dimensions of body and total length are for the NH0 66.5 and 125 mm, and for the NH1 71 and 135 mm respectively. For rated currents higher than 160 A the following NH sizes are used but now with longer bodies. The NH1 size covers up to 160 A, the NH2 up to 250 A and the NH3 up to 400 A, all them for 1,000 Vdc, with body and total lengths of 129 and 194 mm, 129 and 209 mm, and 129 and 209 mm for sizes NH1 to NH3 respectively (for 500 V the dimensions for NH2 and NH3 are also similar among them, that is to say 72 mm and 149 mm).

Consequently, the requirements for fuses suitable to protect PV cells are [8]:

- Fuse rated voltage at least equal to 1.2 U_{oc} (applied up to dc 1,100 V that allows for extreme operating conditions such as temperatures up to - 25 °C),
- Fuse rated currents up to 25 A for string protection fuse and up to 400 A for array or sub-array protection fuses,
- Safe breaking of low fault currents,
- Is mandatory to have characteristic of full-range protection, class gPV (under no circumstances aR fuse should be applied),
- Fast operation,
- Resistant against cyclic loading,
- Low power dissipation, and
- Compact dimensions.

When fuses do not fulfill IEC specifications the following situations can arise and the indicated risks could take place.

- Too high fuse rated current:
  - Module charged with improper currents
  - Reverse current withstand exceeded

There is danger of overheating and fire.

- Too low fuse rated current:
  - Interruption of currents still inside acceptable borders

Service interruptions and loss of earnings

- L/R<1 ms:
  - Insufficient rated breaking capacity for the installation

Fuse explosion, arcing and fire hazard

- Nonconformity gPV-requirements related to cyclic loading:
  - Fuse operation during normal or standard work conditions

Service interruption and loss of earnings

- Requirements functionality at temperature extremes not fulfilled (e.g. exposure of junction box to direct sunlight):
  - Interruption during standard operation

Service interruption and loss of earnings

4. gPV Fuse application rules

The fuses suitable for the protection of the PV cells should fulfill the following requirements:

The modules and fuses should support continually the direct direction residual current without excessive temperature rise following IEC or the corresponding standards.

The currents that the fuse can be called to interrupt, are the reverse currents caused by failed modules, currents of double fault to earth and the ones due to connection errors, which the fuse should interrupt in reliable form and at the right time [9].

In what concerns to rated current, in order to avoid the unwanted operation (melting) of the fuse under normal operation conditions and in the event of a fault of another parallel string, the rated current of the fuse should overcome the short circuit current of the module or respective string in at least 40 %, that is $In \geq 1.4\ Isc$.

The reverse residual current supplied by the power system or by the remaining modules in parallel, represents a serious interruption problem. This inverse current Isc is obtained by multiplying the short circuit current of the module (affected by the environmental conditions through the corresponding correction factors, usually between 1.2 and 1.6), for the number of modules in parallel less one ($Isc\ REVERSE = (n-1) * Isc\ MOD$).

In order to protect the photovoltaic modules of an inverse current that could overcomes the supported value, the minimum fuse operation current should be smaller than the one allowed and tested of the module. The photovoltaic modules are usually tested with a reverse current of the 1.35 times their reverse current value during two hours, being the pass condition the lack of evidence of overheating, for what the protective device should be able to interrupt such a current in a shorter time. Same manufacturer recommend I MOD REVERSE = 1.35 Maximum module rated fuse.

It must be remembered that for the fuse it is defined the melting current If (also called big test current) of 1.45 In that operates it in less than one hour.

The use of the fuse can be avoided if the capacity to support inverse current is superior to the residual one, that is I MOD REVERSE > Isc REVERSE.

If In >1.4 Isc, the fuse is melted with 1.82 Isc

In order to assure the coordination of the module capacity of supporting reverse current (I MOD REVERSE) with the fuse disconnection, it is recommended the use of a factor of 0.9 for the fuse rated current, that is In = 0.9 I MOD REVERSE [8].

For these studies, in conservative form the current collaborations from the storage batteries and from the inverter are neglected.

In case the solar module is factory assembled, the protection of the cables is already insured, in contrary case should be verified that the cables support the short circuit current of each module so many times as modules had in parallel, that is n * Isc MOD. This protection is determined based on the Iz conductor current in the traditional form. Being Iz is the conductor permissible current carrying capacity [10].

If several PV cells systems are operating together, the rated current of the group fuse should be at least 1.2 times the total short circuit current of the group.

The North American code, NEC defines the maxim circuit current as 125% of the current of short circuit of the photovoltaic cell, Isc, indicating that the conductors and the overcurrent protective devices shall be designed for 125% of the maxim circuit current, that is to say 156% of the Isc.

Additionally the BS EN7671, Sec 712 for Solar Photovoltaic (PV) Power Supply systems specifies that the conductors load capacity should be equal or bigger to 125% of the Isc.

The Isc is given by the cells manufacturers in its leaf of characteristic data that typically is only of the 110 to 115% of the current of maximum power Ipm of the solar module. The Isc is also determined under the normalized conditions previously described.

These values indicate that the short circuit current is very limited and therefore the fuses should operate indeed with very low overcurrents values. The fuse designer's task is extremely complicated for the requirement for the fuse of interrupting low current values with high direct current voltages.

SUMMARIZING

Requirements:

- Un depending on expected lowest ambient temperature (see Table 3) [8].

Table 3, Correction Factor for rated voltage as function of ambient temperature.

TºC	20 /24	19/15	14/10	9/5	4/0	-1/-5	-6/-10	-11/-15	-16/-20	-21/-25	-26/-30	-31/-35	-35/-40
CF	1.02	1.04	1.06	1.08	1.1	1.12	1.14	1.16	1.18	1.2	1.21	1.23	1.25

- Number of parallel strings higher than two
- Tripping current of protection device:
- 1.4 * Isc MOD ≤ I TRIP ≤ 2,4 * Isc MOD
- 1.25 * Isc ARRAY ≤ I TRIP ≤ 2.4 * Isc ARRAY

Selection of fuses (according IEC60269-6)

- Un = 1.2 * Uoc MOD respectively according IEC62548
- In ≥ 1.4 * Isc (Isc MOD or Isc ARRAY respectively)

Taking into account:

- Ambient temperature of 45°C (reduction factor 0.945)

Differing Values according to chart (rated current as temperature function)

- A higher irradiation of 1,200W/m² (factor 1.2)
- Cyclic loading (fixed reduction factor 0.9)

In ≥ 1/0.945 * 1.2 *1/0.9 * Isc = 1.4 * Isc

- For string fuses: In ≤ 0.9 * M MOD REVERSE.
- If tested maximum reverse current withstand value of the module is specified
- For (sub-) array fuses: In ≤ Iz ARRAY CABLE
- For cable and line protection if other sources (e.g. batteries) can provide over-currents

5. Selection Methodology

Depending on the wanted capacity of the photovoltaic system, several cells will be connected in series (string) and several strings in parallel, in order to reach the wanted voltages and currents.

The systems that possess three or more strings in parallel require protecting each string, since the current of the generated fault can cause damages to the conductors or other cells. The values of short circuit currents generated when faulted, are of the order from two to three times the rated current, the standard fuses are not adapted to this protection type and they cannot be used. These weak overcurrent values have needed of the development of fusible able to eliminate this defect type.

The adopted solution is to place a fuse in each string, reducing the damage and minimizing personal risks, protecting this way the conductors and isolating the failed cells. It cannot be placed to earth neither the positive pole neither the negative, for what is required of a fuse in each pole of the string of cells.

The fuses should be of more voltage that the string, being recommended that it overcomes in 15% to the corresponding for no-load conditions, for that that Vn ≥ 1.15 Voc * M with M similar to the number of cells in series of the string.

The fuse rated current should be between 1.5 and 2 times the current Isc (stc) of each line. The cable should withstand a current value superior or similar to the fuse melting current If.

According to RISE the trigger current should be higher than 1.25 Isc and smaller to 2 Isc.

Needed data to determine a satisfactory protection

- M, number of series modules
- N, number of paralleled strings
- I_{sc} (stc), cells string short circuit current
- U_{oc} (stc), cells no-load voltage

6. Conclusions

The methodology for the PV cell and gPV fuse coordination is presented in summarized form, indicating the main PV cells special characteristics that require of a purposely designed fuse. The traditional g class fuse is not suitable for this protection, its use pose personal and equipment on risk. The need for more coordinated work between PV cells and fuses manufacturers is stressed, indicating the areas where this work is required.

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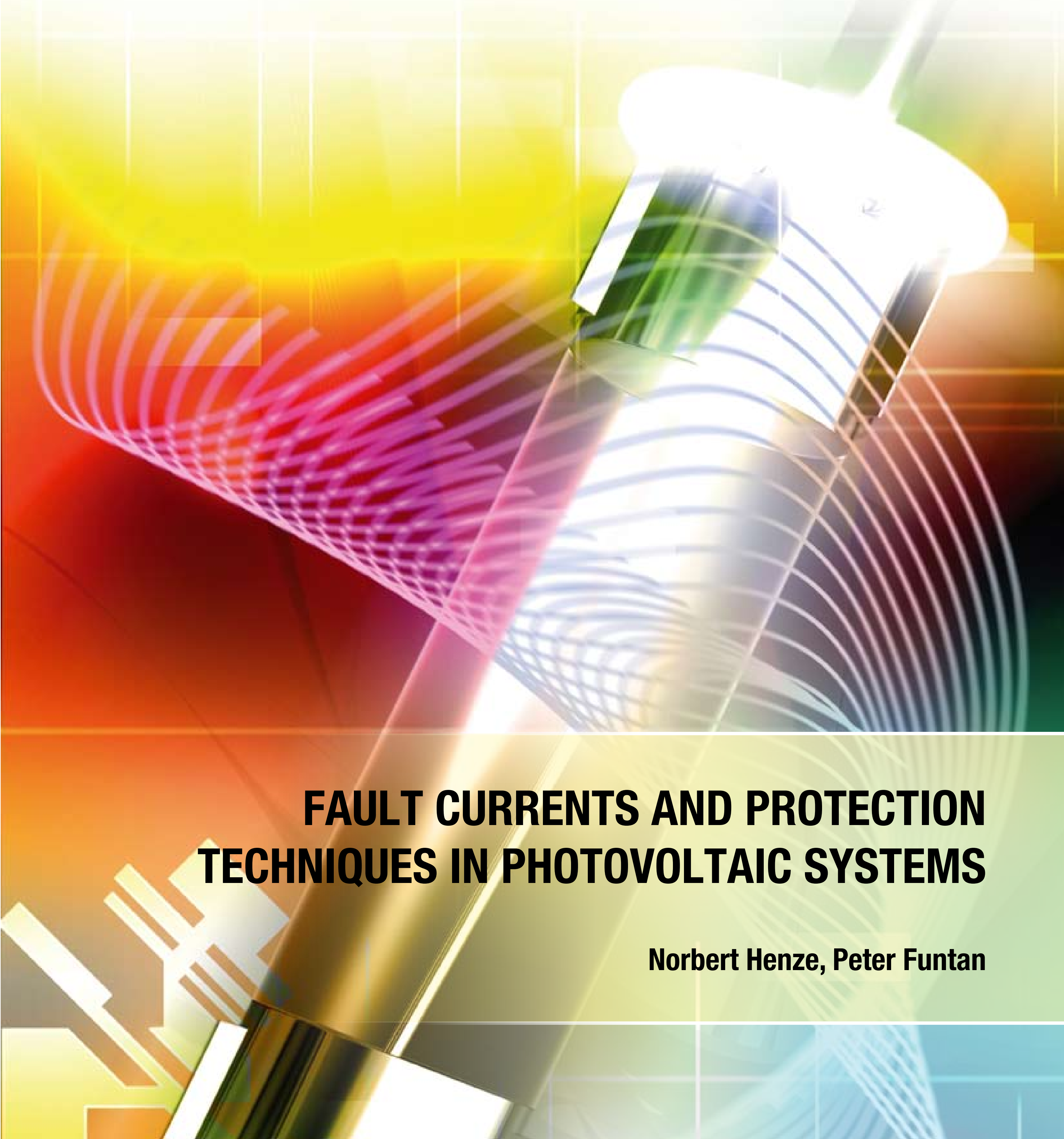

FAULT CURRENTS AND PROTECTION TECHNIQUES IN PHOTOVOLTAIC SYSTEMS

Norbert Henze, Peter Funtan

Fault Currents and Protection Techniques in Photovoltaic Systems

Theoretical Considerations of the Use of Fuses in Photovoltaic Systems

Norbert Henze, Peter Funtan

Fraunhofer Institute for Wind Energy and Energy System Technology IWES, Area: Systems Engineering and Grid Integration, Königstor 59, D-34119 Kassel, norbert.henze@iwes.fraunhofer.de, peter.funtan@iwes.fraunhofer.de

Abstract

The use of fuses in photovoltaic systems is being controversially discussed among experts. On the one hand, the proper operation of the system is not supposed to require the use of fuses and in addition is considered a possible source of error. On the other hand, there is the insecurity that inadmissibly high currents may flow through the strings concerned even in regular operating conditions, e.g. in case of shading and partial snow cover [1]. Non-compliance with quality standards regarding modules and conductions or inadequately implemented installations are proven to be additional sources of error which have to be included in the considerations. Furthermore, discussions on deviating reverse current behaviour of different module technologies, missing information about securing the strings on the part of the module manufacturers or the necessity to apply the fuses only in case of certain converter concepts, contribute to the uncertainty. Missing regulations for dimensioning and not yet existing standards for solar fuses complete the present confuse situation.

Keywords: PV fuses, reverse current potential, regular operation, faulty operation, earthing fault.

1. Present situation regarding the application of fuses in photovoltaic systems

Due to improved general conditions for the supply of electricity from photovoltaic systems, an extremely dynamic market has developed in recent years. Germany took a pioneering role; countries like Spain, France, USA, Italy and Greece followed the German example by taking the appropriate steps. Worldwide it is assumed that approx. more than 40 GW in photovoltaic power was installed at the end of 2010. Presently the market can be divided into three essential segments that are characterised by typical power classes. At the end of 2008, 5.3 GW of photovoltaics were installed in Germany. About 40% of the systems were installed in private homes in the power range under 10 kWp. 50% of the grid-connected systems can be assigned to the market segment of agricultural, commercial and public buildings. Only 10% are set up as open-field installations. In Spain, for example, a completely different image emerges. Here, approx. 95% of the installed PV power of 3.317 GW was set up in form of open field installations [2].

Utilisations in medium and large power range have to be considered as main areas of application. It is difficult to evaluate the exact potential regarding the market share of PV installations in which fuses might be utilised due to the fact that many large-scale plants are also realised with string converters where usually no fuses are applied.

2. Technical aspects of the application of fuses

In order to optimally lay out a solar generator, it has to be adapted to the selected converter. Thereby an important criterion is the dimensioning of the voltage range. It will be realised by serially wiring solar modules to one string. Correspondingly, the number of modules shall be adapted in such a way that the maximum voltage of the converter is not exceeded at any time to avoid its destruction. To achieve higher performance, several strings with the same number of modules are connected in parallel. Now, at the latest, the engineer shall decide whether to apply string fuses. If several module strings are commonly operated in parallel in a solar generator, the reverse current capacity of the utilised modules has to be taken into account. This is defined by a maximum amperage with which the module can be operated in forward direction without causing any permanent damage to the module. To ensure this, two specifications are required by the manufacturers according to relevant standards. Both, the reverse current capacity of the module, and the type of the overcurrent protection shall be indicated. The necessary test specifications are described in the relevant standards. However, these specifications in the datasheets are still not being observed correspondingly. That particularly affects the type of protection. It may be assumed that the manufacturers retain a certain degree of insecurity caused by the lack of regulations regarding the dimensioning of fuses.

It is undisputed that a parallel connection of strings in a solar generator might cause reverse power flows. However, the operating conditions leading to a reverse flow have to be known. In general, a distinction has to be made whether it is a regular operating condition or a faulty operation [3]. To be in a position to judge whether fuses are necessary at all to protect modules and cables, all possible general conditions under which a solar generator is operated must be taken into account. Thereby the most important aspects are the number of strings available in parallel, the reason regarding type and intensity leading to the reverse flow, the earthing concept of the solar generator, the converter topology and, not at least, the technical data of the modules and their technology itself. For the dimensioning of the fuses the rated values for voltage and current must be taken into account. Basically, these values arise from the module data, the operating conditions expected at the location as well as from the system design of the planner.

Those currents capable to trigger fuses in the solar generator can only result from a total current of the rest generator. The most unfavourable case would be if a rest generator could feed back into a single string. However, this is only possible if the string concerned has a lower voltage level compared with the rest generator.

2.1. Theoretical considerations regarding the probability of reverse current

For a better understanding please see the following example describing the case of energy recovery of a solar generator into a single string. The characteristic line K1 can be assigned to a solar generator with 25 strings. The characteristic line K2 represents an electrically reduced single string as it would result in case of a fault (e.g. short circuit affecting the modules). If this string is operated parallel to the solar generator with the characteristic line K1, it can be considered as a connected load. For this reason the characteristic line K2 is depicted as load curve K2* (reflection at neutral axis). This parallel connection originates a new characteristic line K3. The open circuit voltage U_{oc} of the resulting characteristic line can be derived from the intersection (S1) of the characteristic lines K1 and K2*. For all characteristic lines the MPP points (MPP1, MPP2, MPP3) are sketched in.

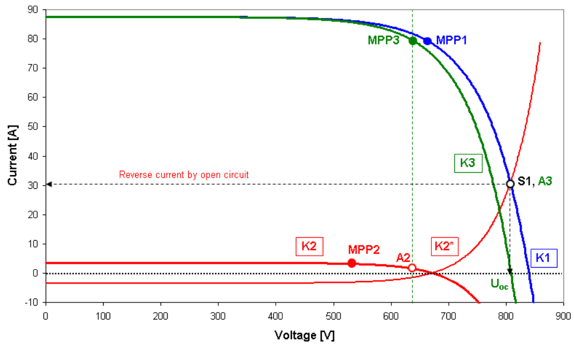

Fig. 2.1: Circumstances in case of reverse current load of a defect module string

Operating this constellation, for example, at a converter in MPP (point MPP3), the operating point A2 of the defect string will be shifted from its MPP point (MPP2). A reverse current would not flow. It appears more critical if the solar generator is in open-circuit mode, i.e., the converter is switched off or separated from the solar generator. In this case a significantly higher reverse current appears (operating point A3). The larger partial generator is on an open-circuit voltage level and feeds into the defect single string with a high reverse current. In this case, the reverse current will cause damage if no precautions are taken.

3. Operating conditions with reverse current potential

The volume of reverse current and possibly its distribution basically depends on the relation between feeding part and reverting part of the solar generator. Dimensions and general conditions to be considered here exceed the module-specific electric parameters and characteristics. Considerations must also include operating conditions, converter conceptions or earthing conceptions as well as possible errors caused by external influences or faulty installations. As a rule, there must be generally distinguished between regular and faulty-based operating conditions in the photovoltaic system.

Basically, regular operating conditions are determined by external influences. This includes partial shading, snow coating or temperature differences of the modules. Production-related tolerances or operating conditions influencing the PV system (MPP operation, open-circuit operation) must also be taken into consideration. Faulty operating conditions include, e.g., interruptions, earth faults, defect bypass diodes and installation errors. Here, too, all possible operating conditions of the PV plant have to be taken into account. Likewise, planning errors can lead to irregular operating conditions.

3.1. Reverse current situations during regular operation of the photovoltaic system

The regular case is that all solar modules are installed at the same angle and identical orientation. All modules are operated under nearly the same surrounding conditions. That means that all possible influencing factors like irradiation intensity, module temperature, mode of installation, orientation and wind influence have the same effect on all modules. If these conditions are given, it can be assumed that there are no reverse currents. In practice, however, diverse situations are possible that do not comply with the normal prerequisites mentioned before. In the view of some theoretical considerations these cases shall be examined to that effect if there exists any reverse current potential.

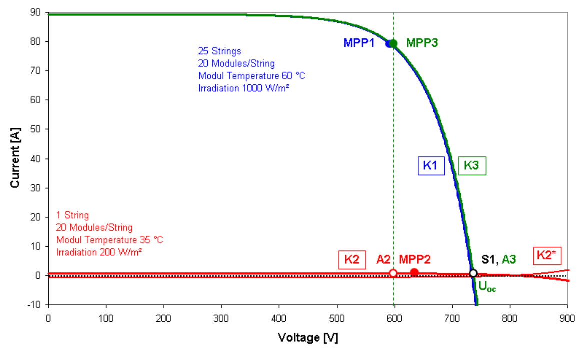

Fig. 3.1: Operating conditions of the solar generator in case of homogeneous shading

Example: Differing irradiation intensities – Due to different distribution of irradiance, a partial generator or string manifests a reduced module temperature by 25 °C, resulting in a higher voltage depending on the technology. For example, a mutual shading between modules of the lowest row in case of tracking systems or divergent orientation of partial generators situated on rooftops. The individual string is no longer operated in the MPP (shifting of the operating point A2 to the left, image 3.1). In the open-circuit mode there is also no reverse current relevance.

Example: Snow coverage – A situation that only small areas of a solar generator are covered by snow occurs if part of the snow slides from the generator surface with beginning thaw. In this operational event it is assumed that the solar generator covered by snow only receives a homogeneous irradiance of 10 W/m². The module temperature of the area covered by snow is 0°C.

Fig. 3.2: Solar generator partially covered by snow

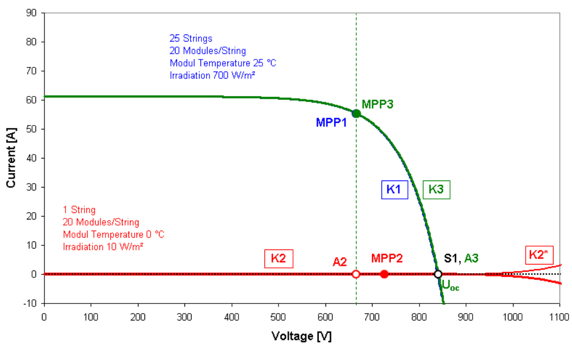

Fig. 3.3: Operating conditions of the solar generator partially covered by snow

A realistic temperature of the modules in wintertime is 25°C at an irradiation intensity of 700 W/m² and surrounding temperatures around the freezing point. The characteristic lines K1 and K3 are nearly congruent. Reverse currents into the snow-covered string are not possible.

Example: Large temperature differences – In certain situations it may occur that an individual string is operated at higher module temperatures compared with the rest generator. This might be conceivable in case of a building-integrated system where building segments obtain little back ventilation or even constructed with insulation techniques. Assuming that individual façade elements have additional thermal insulation, over temperatures between 40°C and 50°C are possible. Then the maximum module temperature would achieve values of up to 80°C. For the shadowed generator part a module temperature corresponding to the ambient temperature of 30°C is assumed. The irradiance only amounts to 300 W/m².

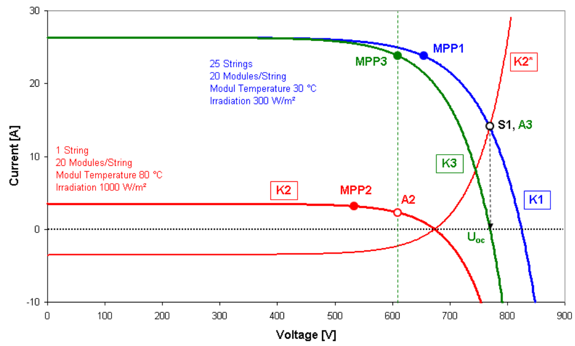

Fig. 3.4: Reverse current conditions at a large temperature difference

If this theoretical case occurred – which is considered to be unlikely – in an open circuit situation would flow a reverse current of approx. 15 A. The MPP of the affected string would be left in direction of the open circuit voltage (A2).

A realistic case can occur if part of a façade (e.g. the balustrade area) is accomplished as insulated PV element while another part is realised as a curtain façade.

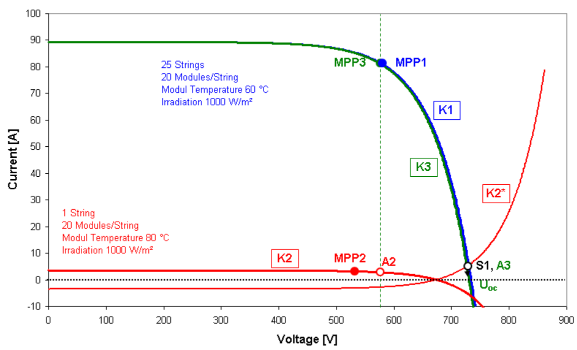

Fig. 3.5: Reverse current conditions at temperature difference and high irradiance

In comparison with the conditions assumed above, the irradiation intensity is the same on the solar generator and the thermally insulated string. This assumption is based on a temperature difference of 20°C. In this case, too, there would be no reverse current in the MPP operation of the converter. In the open-circuit mode a reverse current of approx. 5.5 A appears, i.e. about 1.5 times the short-circuit current of the module. The module should cope with reverse currents of this magnitude at any time.

Example: Reverse current characteristic dependent on technology – In comparison with crystalline modules, thin-firm modules show a flatter characteristic of the I-V curve. However, this circumstance has a positive effect in relation to the reverse current problematic. The following chart compares the two technologies. The assumed operating parameters of both module types were chosen identically. The assumption in both cases is based on an individual string reduced to 16 modules, not corresponding to a regular operation mode. The flatter curve of the characteristic line of the thin-film modules results in a lower reverse current. Due to clarity reasons the resulting characteristic lines have been omitted.

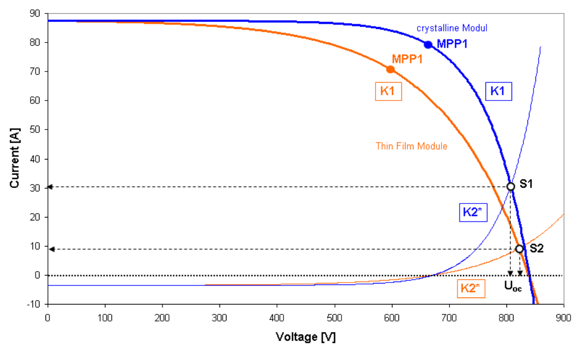

Fig. 3.6: Reverse current characteristic dependent on technology

Thin-film modules are less vulnerable to reverse currents than crystalline modules due to the flatter curve of the characteristic line. However, manufacturers are more reserved with regard to the reverse current carrying capacity of these modules.

3.2 Reverse current situations during faulty operation of the photovoltaic system

A photovoltaic system is comprised of diverse components ensuring the functional of the entire installation. During the whole life cycle of the system, solar generator and module cables are exposed to weather conditions. In the most unfavourable case this also applies to generator terminal boxes, DC circuit-breakers and converters. In view of the reverse current problematic, the errors in the installation of the modules, mounting systems and cabling are particularly significant. Special attention has to be paid to earth faults, defect bypass diodes or installation errors. Due to existing experiences, earth faults are assumed to be the most probable error source. However, detailed statistics regarding the cause of damage are not available. Those insurers offering at least rudimentary statistics register these errors under “technical failures” or attribute them to deficiently realised installations.

Case of failure: Defect bypass diodes – Bypass diodes are integrated in the connection box of a solar module. Their task is to minimise the losses within the module in case of shading. The probability is considered low that a bypass suffers a defect. Up to now there have only been occasional reports of damages. The most frequent cause of damage may be the impact of inductive overvoltage caused by indirect lightning effect. Here it can be that several diodes in several modules are affected.

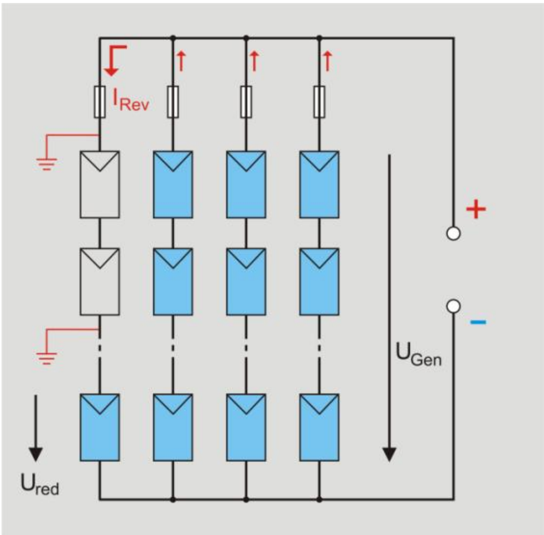

Fig. 3.7: Reverse current at conducting defect bypass diodes

If there is a failure of the bypass diodes, two different cases shall be distinguished. An interruption has no consequences for the reverse currents. However, if the diode has a conducting defect the corresponding module part will be short-circuited. This means that the affected string is operated with the rest generator at reduced voltage. But damaging reverse currents can only flow if several bypass diodes have conducting defects at the same time. The probability can be considered low that this defect appears.

Case of failure: Earth fault – There are numerous reasons for earth faults. In most cases, the solar module itself and the complete DC installation can be assumed to produce the failure. Breakage of glass, damaged back side foil or reduced insulation resistance are the most common faults on the side of the module. In view of the installation, frequent reasons for an earth fault are material fatigue, animal chewing damage or improper installation of cables. Reports from insurers and appraisers show that technically accepted rules of engineering are frequently not respected when installing the system.

The considerations must include the converter concept and the earthing conditions on the DC side. Reverse currents in case of an earth fault can only occur when parts of a string or solar generator are short-circuited by one or several earth faults. The proportion of the bridged modules has a direct influence on the magnitude of the occurring reverse current.

Fig. 3.8: Examples for earth faults (breakage of glass, cable damage, material failure)

Systems with unearthed solar generator

If converters with galvanic isolation are used in a PV system, the solar generator shows no definite voltage conditions regarding the earth potential. It is assumed that this type of installation concept can be found most frequently in the segment of the lower and medium capacity range. Manufacturing the solar modules in accordance with protection class II as well as installing the cabling in an earth fault and short-circuit proof way, it is assumed that an overload on the DC side is protected according to a normative interpretation of IEC 60364-712 (DIN VDE 0100-712). Due to the lack of earth potential, a single earth fault puts nobody at risk or causes reverse currents in any part of the solar generator. It is assumed that the fault can be detected and removed within a reasonable time.

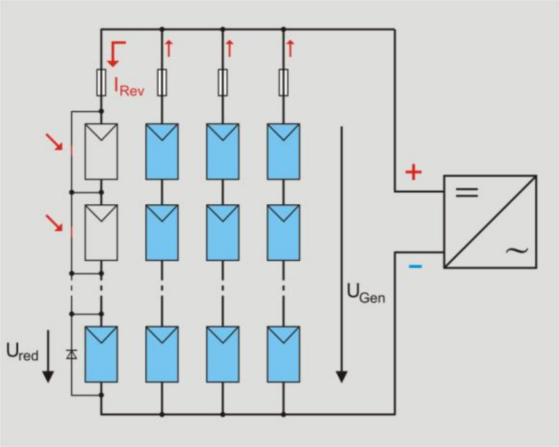

Fig. 3.9: Double earth fault of a solar generator without earth potential

Only if there is a second earth fault, parts of the string can be short-circuited, for example via the utilised frame system. Then the connection to the earth potential will be established by using the usually earthed frame system. Due to the fact that the frame system is considered a reference potential, it is comprehensible that in case of two earth faults in different strings larger parts of the solar generator are short-circuited.

Systems with earthing of active parts

If there is a galvanic isolation between the DC and AC side it is permitted to earth an active conductor of the DC system. Optionally, it is also possible to realise a midpoint earthing.

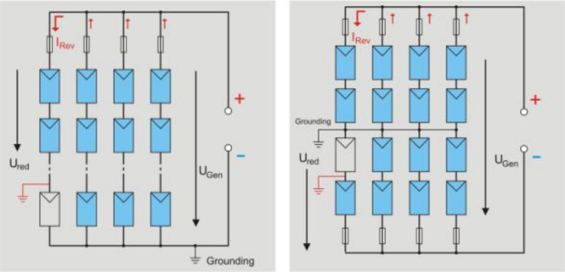

Fig. 3.10: Simple earth fault in systems with earthing of active parts of the solar generator

With respect to the voltage conditions in the solar generator, such systems present clearly defined conditions. However, it is a disadvantage that high earth currents can already flow when a single earth fault occurs, which – in the most unfavourable case – reach the short-circuit current of the entire solar generator. The distribution of this system is relatively rare.

Systems without single galvanic isolation

According to DIN VDE 0100-712, section 712-413.1.1.1.2, a fault current protection switch is compulsory for systems without a single galvanic isolation between the DC and AC side. As a result, the poles of the solar generator are alternately directly connected to the neutral conductor of the mains. This again is connected to the neutral point of the power transformer, which in turn is earthed. This means that there is a direct connection to the earth potential. The consequences are similar to those of systems with earthing of an active part of the solar generator. In case of a single earth fault, a fault current against earth would happen and consequently trigger the fault current protection switch immediately, putting out of operation the system (solar generator in open-circuit mode).

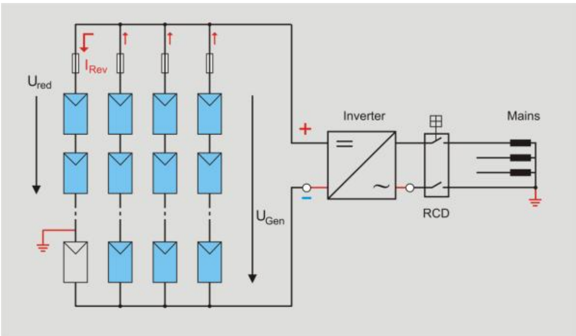

Fig. 3.11: Simple earth fault of solar generators without simple separation

Again, the probability of reverse currents is higher than in systems with galvanic isolation between DC and AC side.

Case of failure: Installation error

In case of subsequent connection of cables and connectors on the roof, it can happen that the plugs are connected incorrectly. This should not be a problem as long as module strings are always installed following the same pattern of installation. When changing the installation pattern – e.g. roofs on different levels where string formation is only possible by using two generator levels – wrong polarity within one string can cause that the voltage of the incorrectly connected module is no longer available. In case of reverse current, the bypass diodes of the affected module will become conductive. Depending on the number of incorrectly connected modules, there can be a considerable reverse current flow.

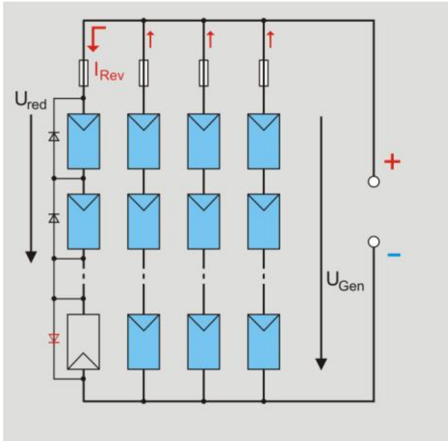

Fig. 3.12: Reverse current conditions for the case of an incorrect polarity connection

The cases of failure described above show that already at the moment a failure occurs, reverse currents with destructive potential might appear. Thereby, the magnitude of the reverse current is directly connected to the electric reduction of the damaged string. The worst case is considered to be the open-circuit mode of a crystalline solar generator.

A first evaluation of manufacturer's data regarding the information on the reverse current capacity has shown that the double short circuit current under STC conditions can assumed to be the typical reverse current load (green line in the following graph).

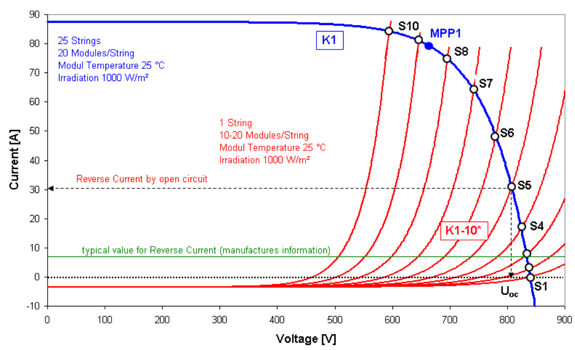

Fig. 3.12: Reverse current load of electrically reduced strings (K2 to K10)

Intersection S1 corresponds to a not electrically reduced string in comparison with the rest generator. Higher voltage differences lead to correspondingly higher reverse currents. The following image depicts a string reduced by 1 to 10 modules each (K2-10*). It can be assumed that a string which is voltage-reduced by approx. 10% is just in a position to durably carry the resulting reverse current.

4. Summary

In a medium and large power range, photovoltaics offer a large potential to apply fuses. The expert opinions differ widely whether fuses are necessary at all. The theoretical considerations clearly show that no serious reverse currents are to be expected in the regular operation of solar generators, even applying a large number of strings. This is confirmed by extreme operating conditions that hardly ever appear in a real application. Other conditions occur when the system changes over to the non-regular operating mode by reason of a failure. In this case – taking into account the earthing concept of the solar generator or the selected converter concept – it has to be determined whether fuses will be used. The currently applicable standard is based on the fact that a single fault can be controlled. However, multiple faults have not yet been taken into account but deserve to be taken as relevant. It has to be considered that a PV system represents a valuable investment asset and possibly utilised far longer than the expected useful life. No user is expected to remove a functioning system just because its fixed service life of 20 to 25 years is over. As a consequence, there will appear aging-related multiple faults caused by deterioration.

Certainly it would be wrong to restrict the fault analysis merely to the MPP operation of the converter where the risk of reverse current shows a considerably lower potential. There will always be situations in which the system changes into open-circuit operation, even under favourable irradiation conditions (maintenance, repair, power failure). Therefore, the open-circuit mode has to be considered as the critical operating condition.

It cannot be answered definitively whether the typical reverse current capacity with twice the short-circuit current at STC indicated by the manufacturers is to be evaluated too cautiously. There remain considerable uncertainties particularly regarding the new thin–film technologies. In view of the crystalline modules it may be assumed that voltage differences from up to 10% between a faulty string and the rest generator surely lead to reverse current but without causing thermal overloads.

The measurements regarding thermal behaviour of fuses under real conditions, which are still in progress, will provide important information on interpretation of fuses.

The authors whish to the thank the “Association for the Promotion of Environmentally-Compatible Recycling of Disused LV HRC/HV HRC Fuse Links” for the support of this work (www.nh-hh-recycling.de).

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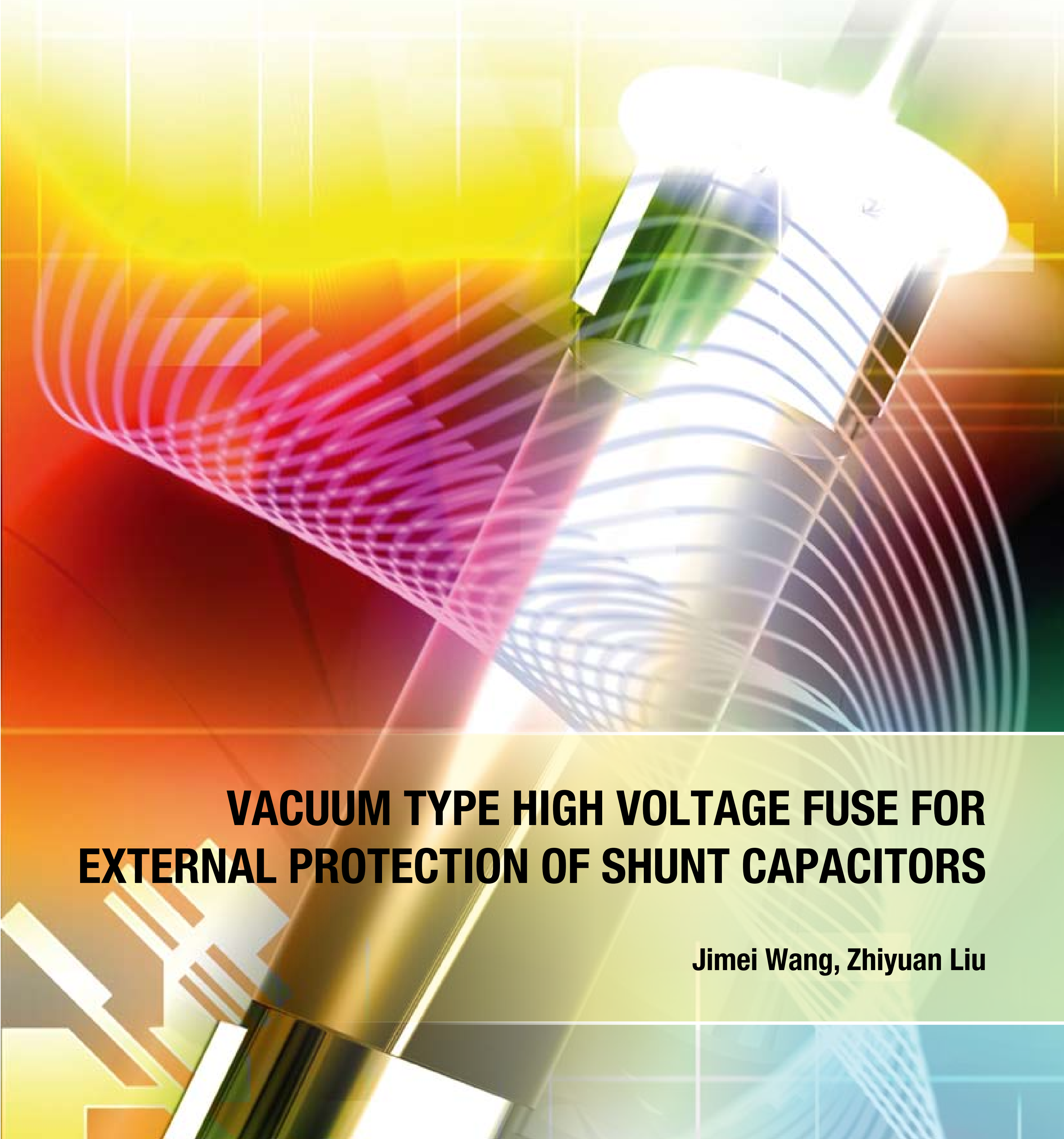

VACUUM TYPE HIGH VOLTAGE FUSE FOR EXTERNAL PROTECTION OF SHUNT CAPACITORS

Jimei Wang, Zhiyuan Liu

Vacuum type high voltage fuse for external protection of shunt capacitors

Jimei Wang, Zhiyuan Liu

Xi'an Jiaotong University, Xi'an, P.R.China, liuzy@mail.xjtu.edu.cn

Abstract

The high voltage shunt capacitor protection fuse are designed according to GB15166.5-94 standard[1]. The rated voltage is 3~3.5kV as shown in Table 4.3.1 and the frequency is 50Hz. It protects single capacitor or parallel capacitors.

Table 4.3.1: unit: kV

Rated voltage	3	6	10	15	20	25
Highest voltage	3.6	7.2	12	17.5	24	40.5

The rated current are 12.5, 20, 25, 31.5, 50, 80, 100 and 200A, The insulation level is as GB110022 standard. Capacitive current interrupting capacity (kA r.m.s.) of the fuse is 20 times or 50 times of rated current. Other parameters are defined by manufacture and users. Inductive current interrupting capacity (r.m.s.) are 3.15, 6.3, 8, 12.5, 16, 25, 31.5 and 40kA.

The overload protection characteristics of the high voltage fise are as following: at 1.5 times of rated current, melting time is less than 75s; at 2.0 times of rated current, melting time is less than 7.5s; And conventional non-fusing current is 1.1 times of rated current; where fuse element doesn't break in 4 hours.

Temperature rise of the high voltage fuse should be measured by alcohol thermoneter as required by GB3988.2 standard.

Keywords: vacuum, shunt capacitor, fuse.

1. Introduction

The interruption performance of the high voltage fuse is shown in Table1.

Table 1

Interruption performance	
Inductive interruption test	Possibility passing througth inductive current 1)
	Nonpossibility passing througth inductive current 2)
Capacitive current inerrrupting test 3)	
Discharge current interrupting test	

Note: 1) this application examples are:

——Fuse for capacitors group

——Single fuse of dalta connection group of nonserise

——Single fuse of star connection group with neutral ground of nonseries unit

2) This application examples are:

——Single fuse of star connection group of neutral without to ground

——Capacitors group of series unit

3) Star connection capacitors group of neutral point without ground is protected by fuse for capacitive current interrupting test

The discharge withstanding performance of the high voltage fuse: it should withstand a rush current whose first half cycle amplitude exceeds 70 times of rated current in required procedures.

The anti-erosion layer of the high voltage fuse: all exposed metal surface should be protected that there is no erosion on the nice surface.

Indication device of the high voltage fuse: there should be obvious fused indication and it should work reliably.

High voltage fuse in the same series products should have same installation size and can be replaced easily.

Basic requirements of discharge withstanding tests:

a. There are 5 discharges in 10 minutes for a fuse, discharge frequency is

i) For fuse whose rated current is less than 31.5A:

$$f(kHz) = 1.2U_{m0}^{+20}\%$$

ii) For fuse whose rated current is greater than 31.5A:

$$f(kHz) = 0.8U_{m0}^{+20}\%$$

Where U_m——Maximum voltage (kV)

b. There is 100 discharges in a time interval defined by manufacture and discharge frequency is $0.8U_{m0}^{+20\%}$ kHz.

For fuses in same series, the fuses with maximum rated current and minimum rated current should be tested.

The test can be done with any voltage level.

Current amplitude ratio of neighbor waves in the discharge test is 0.8~0.95.

In metal short circuit test, fuse can be replaced by a conductor whose impedance is much smaller negligible than that of test circuit.

The required first half cycle current amplitude, oscillation frequency and current decay coefficient can be gotten by adjusting test circuit and the parameters can be confirmed by oscillogram. The fuse should be in conductive state after tests.

2. Study on Vacuum-type Full-Range High Voltage Fuse for Single Shunt Capacitor Protection

So far there is no fuse that can meet the requirements of both overload current protection and short circuit current protection for a single shunt capacitor in all over the world[2].

To meet the requirements, a current-limiting fuse that can meet the requirements of both overload protection and short circuit current protection is developed by cooperation of Xi'an Jiaotong University, Hangzhou Boda Electrical Apparatus Company and Shanghai Kerui Vacuum Electrical Apparatus Company, which follows the GB15166.1~15166.5 standard. It is shown in Fig.1.

Fig.1 Vacuum type high-voltage current-limiting fuse with double protection characteristics

There is only an expulsion fuse that is used for single capacitor protection in China now, which can only meet the overload requirements. There is a back-up fuse that can be used for short circuit current protection only. If both requirements are needed the 2 fuses should be used in series. But their cost are high and installation are not convenient.

According to Chinese national standard for high voltage fuse, pre-arc time-current characteristics of expulsion fuse with overload protection should follow that in Table 3. And its conventional non-fusing time should be greater than 4 hours at 1.1 times rated current.

Table. 3

Time of rated current A	1.5	2.0
Melting time, s	≥75	≥7.5

1. Design ideas

Generally high voltage current-limiting fuse is belong to back-up fuse as shown in Fig.2. It only meets the requirements of short circuit current protection. For overload current, only current over 3.5 times rated current can be interrupted reliably. For example, a current-limiting fuse with rated current 100A can interrupt current when it exceeds 350A.

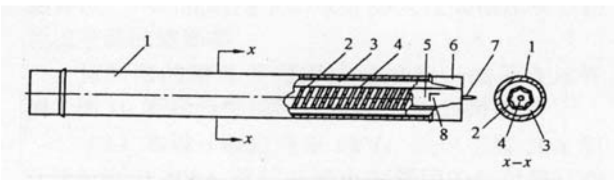

Fig.2 General configuration of high voltage current-limiting fuse

In addition, there is overvoltage and explosion hazards when back-up fuse is used for single capacitor protection. We designed a quick interrupting fuse element.

Now let's analyze interrupting principle of expulsion fuse. It uses short fuse element. With overload current, a spring pulls the short fuse element and breaks it. When the short fuse element is broken, a high temperature arc is initiated, which makes gas-generating material in arc extinguish tube generates a lot of high temperature gas. The gas expulses the arc and makes the arc longer. Thus the arc is extinguished. The expulsion fuse is used for many years. It is reliable and simple. But its structure is open and its size is large. And it has fire hazard. We uses vacuum fuse to replace it. Vacuum fuse has smaller size, high reliability and safety. It meets all requirements in standards and a novel design.

2. Example of Design

Fuse for shunt capacitor protection with rated voltage 6kV, rated current 50A and interrupting current 40kA[3]

(1) Vacuum type fuse is used for overload current protection

Basic requirements: fuse element should be melted at 1.5 times rated current (1.5×50=75A) in 75s. It should be melted at 2 times rated current (2×50=100A) in 7.5s. It should not be melted at 1.1 times rated current (1.1×50=55A) in 4 hours. At first selecting (0.5×4=2mm^2) copper is used to cut and try method for measuring pre-arc time-current characteristics. By adjusting design size of fuse element many times (0.5×3=1.5mm^2) copper with length 10mm is chosen finally. Its pre-arc time-current characteristics is shown in Fig.3

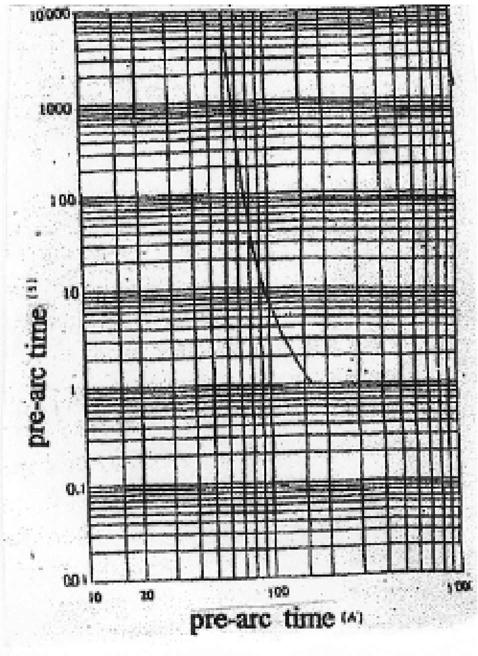

Fig.3 Time-current characteristics under vacuum condition of 5×10^{-4}Pa

Configuration of vacuum fuse is shown in Fig.4, Where 1 is output terminal to connect current fuse terminal, 2 is ceramle envelope, 3 is shield, 4 is copper fuse element and 5 is linkage.

(2) High speed current-limiting fuse is used for high overload current and short circuit current protection

Pure silver is chosen as fuse element. Its total length is 300~320mm. Current density at neck is j=200A/mm^2. The configuration of high-speed current limiting fuse element 4 is shown in Fig.5.

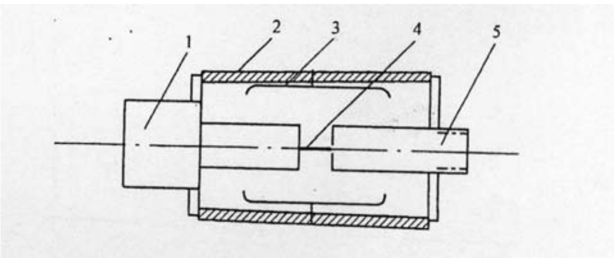

Fig.4 Configuration of vacuum fuse

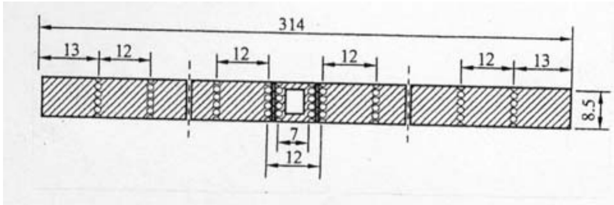

Fig.5 Configuration of high-speed current-limiting fuse element

The length of fuse element is $L = 2\times13 + 24\times12 = 314$ mm. The cross-section area of the fuse element is $A = \frac{I_n}{2} / j = 25/200 = 0.125$ mm^2. The hole diameter is 1.5mm and their separation distance is 0.2mm. Fuse element width is $(1.5+0.2)\times5 = 8.5$ mm. Total hole separation distance is 0.2×5=1mm. Fuse element thickness is 0.125/1-0.125mm. There should be 2 fuse elements in parallel with rated current of 50A.

Most of the available parts of back-up fuse except fuse element can be used in the new designed fuse for high overload current and short circuit current protection.

Fuse element of the high speed current-limiting fuse can be processed as wave shape, as shown in Fig.6.

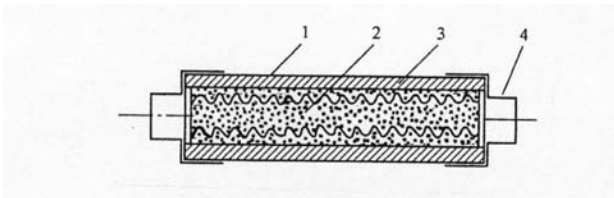

Fig.6 Cross-section configuration of high-speed current-limiting fuse

(3) The designed fuse for shunt capacitor with rated voltage 6kV, rated current 50A and interrupting current 40kA has passed interrupting capacity tests in test laboratory of XIHARI. The results show that it meets the requirements of Chinese standard.

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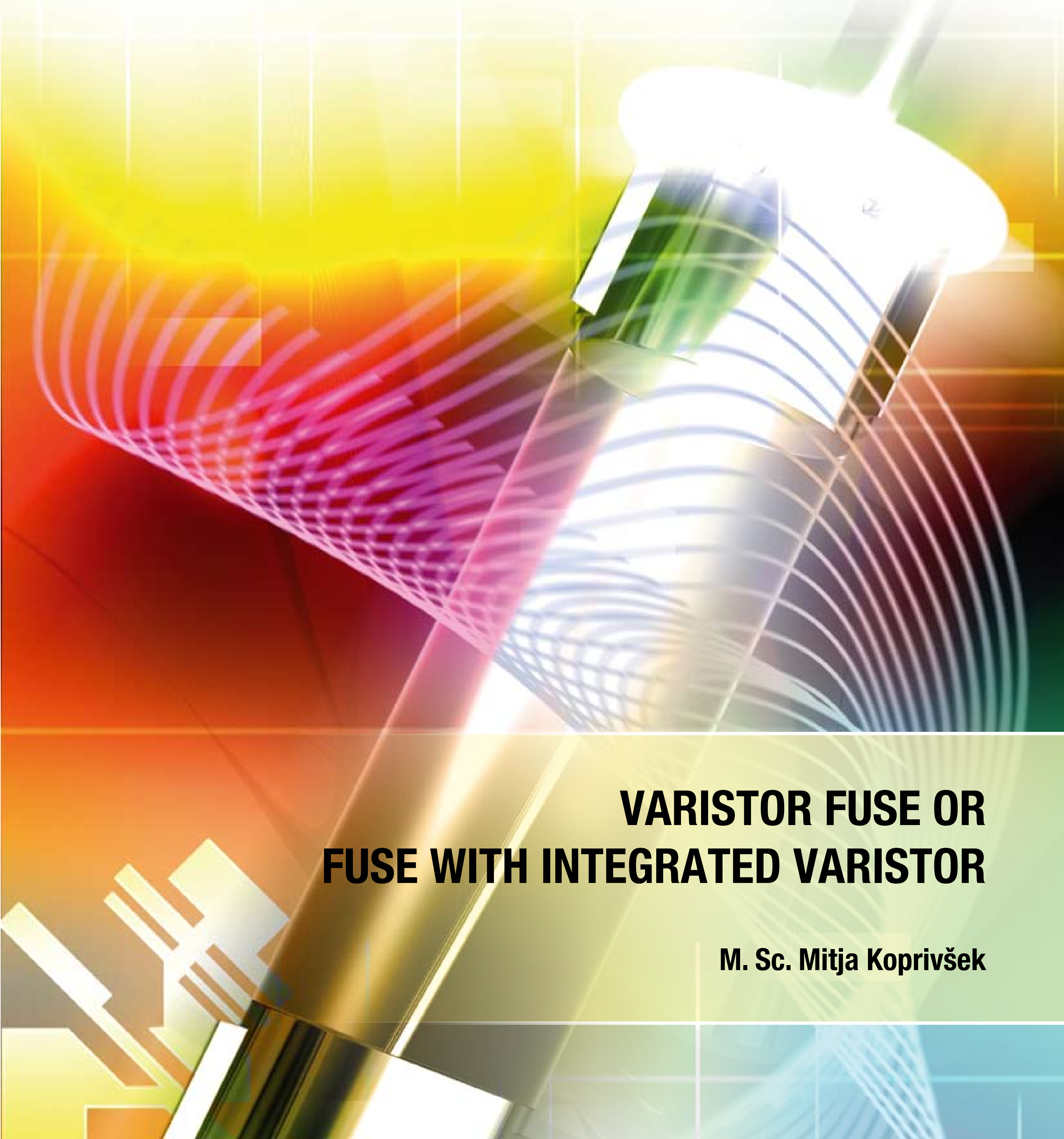


VARISTOR FUSE OR FUSE WITH INTEGRATED VARISTOR

M. Sc. Mitja Koprivšek

OPENING LECTURE OF THE DAY

Varistor fuse or fuse with integrated varistor

M. Sc. Mitja Koprivšek

ETI Elektroelement d.d., Obrezija 5, 1411 Izlake, Slovenia, mitja.koprivsek@eti.si

Abstract

Metal-oxide varistors, or MOV's are well known solution for protection of electrical installations against transient over-voltage impulses, occurred as a consequence of lightning and switching processes. By experience we know, that the MOV's has to be protected by an overcurrent protection device to cut the abnormal current, occurred by improper behaviour of MOV caused by temporary over-voltage. One of such protection devices are special fuses, known as Surge Rated Fuses.

This contribution shows very new construction of integrated product, where both, MOV and a Fuse are incorporated in one product. Advantage of this idea is mainly in strongly reduced dimension.

Keywords: MOV, varistor, fuse, protection, integration.

Introduction

MOV's are very well known solution for protection against transient over-voltage impulses, caused by the lightning and other unexpected events in electrical network and installations. But on the other hand it is also known that the problems with overheating of the MOV body may occur. There are at least two reasons for this overheating. First reason could be a damaged varistor, which could represent conductive path with certain resistance already at rated voltage. The consequence is a current through the MOV varistor, which is over-heated and could lead to heavier damages. Second reason is an occurrence of frequency overvoltage of longer duration which causes the MOV to react and thus the MOV opens the path for short-circuit current. In both cases, the actual current through the MOV can be from the value less than 1A up to the value of several kA. In such cases fatal consequences can appear, namely, the MOV can explode.

Therefore, these cases have to be prevented in order to prevent the damage on installation where MOV is installed.

Protection principles already available

In this article only two or three existing typical solutions are taken into account. The first is very simple with soldered wire under spring force. In case of over-heating of the MOV, the solder is melted and spring opens the contact of the wire and thus the MOV is not any more in connection. The problem of this solution is, that the contact has no breaking capacity and is not capable to open correctly the short-circuit currents. An example of this solution is given on the market bay one of the MOV producers and it is presented on next picture.

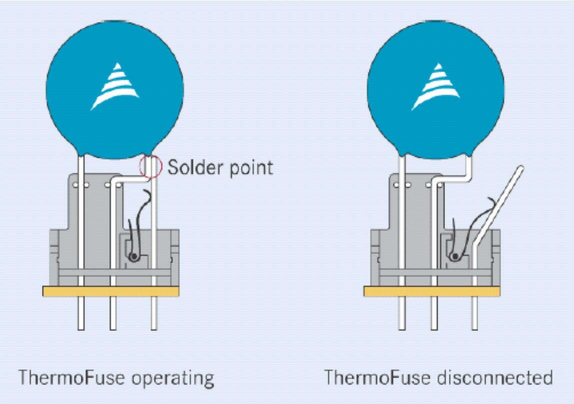


Fig. 1: Source: http://www.epcos.com/web/generator/Web/Sections/Components/Page,locale=en,r=263282,a=490608.html?_requestid=6566275

Next solution is a special fuse, connected in series with MOV. Such fuse, called SFR Surge Rated Fuse has to pass the transient over-voltage impulse of certain value, e.g. 10kA 8/20, but should open the circuit in case of over-current before the MOV would explode. A disadvantage of this solution is how to make SRF fuse for lower over-currents. Next disadvantage is also in the fact that additional wiring is needed to connect the MOV unit and SRF unit.

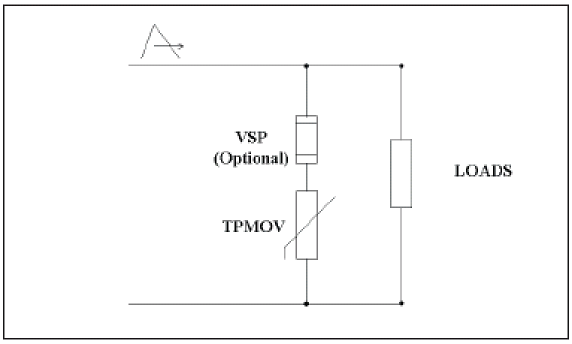


Fig. 2: Source: http://ep-us.mersen.com/catalog/surge-protection/mov-protection-fuses/surge-protective-devices-vsp-mov-fuses/

The next solutions are more advanced and compact and they are explained in technical papers of the producers. Some of them are using fuses and some of them are using some other means how to detect and to break any kind of a longer duration current through the varistor, before the MOV gets too hot and explode.

The Problem

To my opinion there are at least two problems which are connected with each other:

- How to extinguish an arc in the thermal switch after the solder has been melted?
  - The right solution is a fuse, because the fuse is the best way how to clear an arc followed by short-circuit current.
- But the fuse (SRF fuse) has difficulties to cover lower currents e.g. under the value of 1A, knowing the fact that also these current could damage the MOV.

So, basically, we should try to find a solution in a fuse, which will be able to react not only to the very low current, but also to react on the temperature, exposed from the MOV at the low current. Of course, such fuse has also cover high short-circuit currents.

Next problem is also how to make a product which is compact and the number of parts is as low as possible.

The solution

Solution is based on cylindrical shape of MOV with silver electrodes on the outside and inside wall of cylinder.

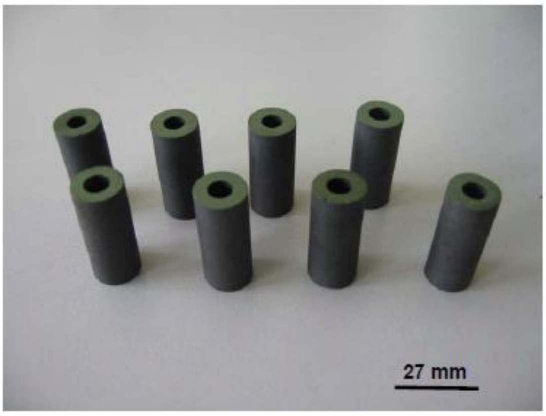


Fig. 3

MOV cylinders as a basis for next step. Below there is cylindrical MOV equipped with silver layers inside and outside of the cylinder. These silver layers are electrodes.

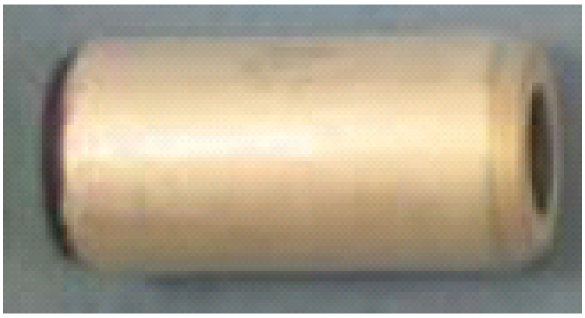


Fig. 4a

Fig. 4b

Next step of the solution is how to integrate cylindrical MOV and cylindrical fuse in one product. The picture below shows the innovative construction where the cylindrically shaped MOV is placed inside of the cylindrically shaped ceramic fuse body. One electrode of the MOV is connected with the contact cap of the fuse and the other, inner electrode is connected with the melting element.

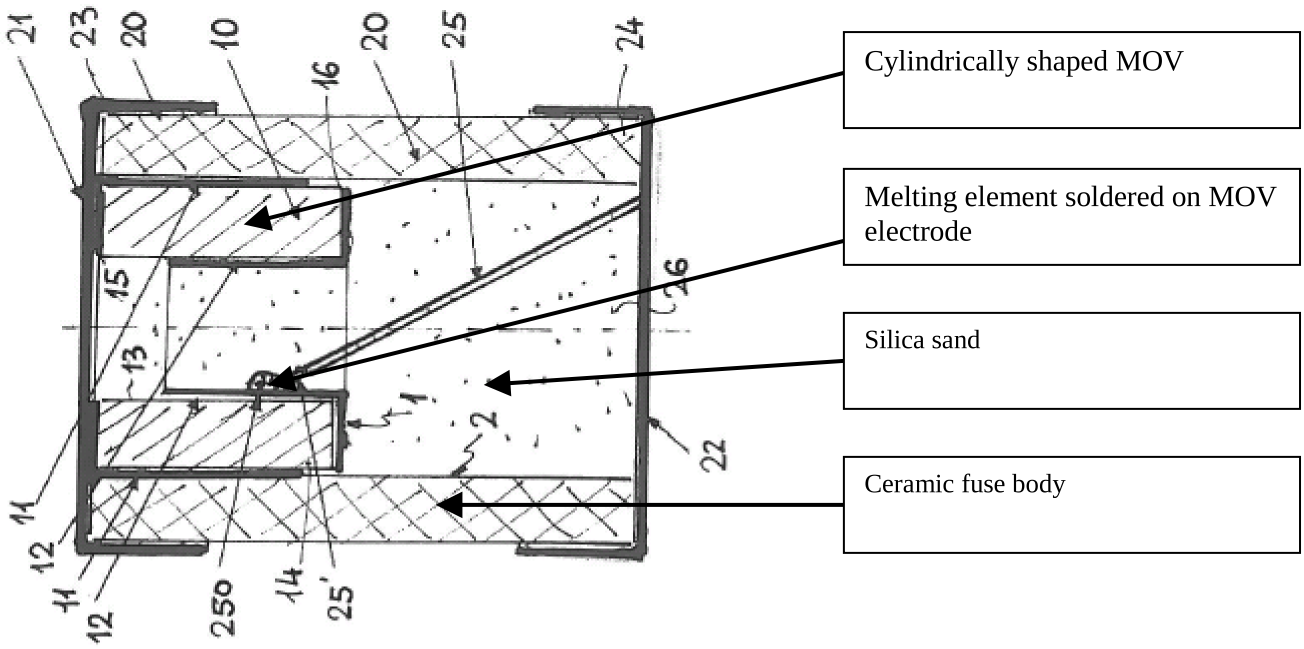


Fig. 5

The construction of melting element is meant to fulfil several functions. First of all has to pass the transient current impulse of certain value of kA, shape 8/20, very similar as SRF fuse.

Secondly, it has to cut the short-circuit current, when the power frequency over-voltage is so high that the MOV resistance is closed to zero for a longer period of time.

And the third function, probably most important, is how to cut the currents of lower values in order to cut the current before the MOV explodes. On Fig 6a we can see the connection part of melting element, where the solder layer has two roles. Firstly, it connects the melting element to the inner electrode of the MOV, and secondly to provide the well known M-effect on the first constriction nearby.

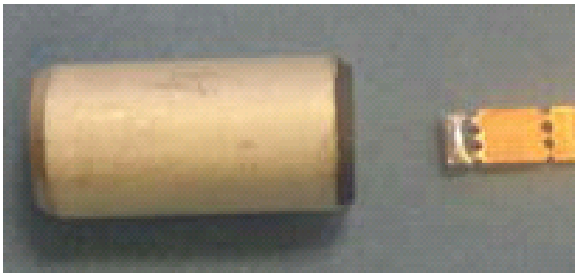
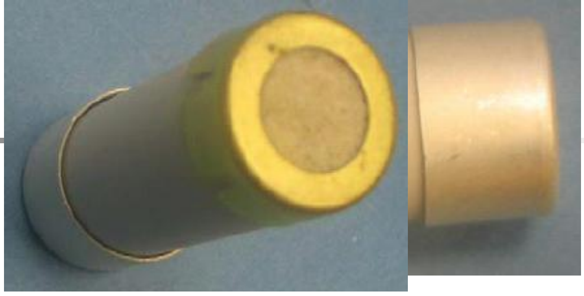


Fig 6a

Fig 6b

Fig6a shows the melting element just before it has been welded (soldered) inside of the MOV and fig6b shows the placement of the MOV with melting element inside of the body of cylindrical fuse size CH22x58.



Conclusion

This concept, called Varistor Fuse or Fuse with Integrated Varistor could be very convenient solution, especially in PV installation because of higher DC voltages and high exposure to the lightning.

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FUSE APPLICATION IN MEDIUM VOLTAGE SWITCHGEAR

Jože Pihler, Marjan Stegne, Peter Kitak, Adnan Glotić,
Bogdan Fluher, Igor Tičar, Jože Voršič

Fuse application in medium voltage switchgear

Jože Pihler, Marjan Stegne, Peter Kitak, Adnan Glotic, Bogdan Fluher, Igor Tičar, Jože Voršič

University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17, 2000 Maribor, Slovenia, joze.pihler@uni-mb.si

Abstract

Switch-fuse combinations are built in to most distribution and industrial medium-voltage switchgear cells. These fuses are responsible for protecting the distribution transformers. They are usually used to protect both voltage-transformers and auxiliary-transformers. In pole-mounted transformer substations, it is possible to combine the disconnector with the fuses (fuse-disconnector, disconnector-fuse) or the fuses only at the medium-voltage level of transformer protection. However, recently-constructed switchgear may exclude fuses. Instead of fuses, circuit-breakers with defined (usually lower) short-circuit breaking capacities are combined with protection devices that take over the role of protection. Moreover, it is possible that smaller pole-mounted transformer substations are no longer protected by fuses anymore when considering the medium-voltage level.

The purpose of this paper is to explore the roles and functions of those fuses mounted on indoor or outdoor systems, and applied for the protection of the medium-voltage level. Those other possibilities that exclude fuses for device protection for medium-voltage switchgear are also explored and analyzed.

Keywords: medium-voltage fuse, distribution transformer, switch-fuse combination, protection, thermal field calculation.

1. Introduction

Fuse-application, as a protection element in the power grid, practically started at the inception of electrification. Despite the fact that the fuse is a relatively old invention, from the technological point of view, it is still a crucial protection element in all electrical engineering applications. In cases of serious faults in installations or power networks, the fuse is the ultimate and last protection barrier. When all other protection elements fail, the fuse is the only one that remains.

The fuse enables the highest breaking capacity, as well as the ability to prevent short-circuit, in comparison with other protection devices (disconnectors, circuit-breakers). This property is enabled by the simultaneous workings of individual construction parts, mainly a melting element and quartz sand, which has the highest specific heat regarding vaporization. It means that the fuse is capable of quenching an arc within the shortest possible time. The consequences of the latter also include very low cross-over integrals of energy and cut-off currents, which is another advantage of the fuse. The fuse is also very affordable.

In comparison with circuit-breakers, fuse protection is more convenient for conductors and other devices, because they are less loaded in the cases of short-circuit currents. Replacing a melting fuse-element immediately after disconnection, means bringing-back the protection device to its previous condition, respectively. Nowadays, when all processes and power systems are automated, this characteristic may represent a disadvantage, which is clearly pointed out by opponents of fuse application. Power-supply interruption should be minimal (in ms), which is impossible when fuses are manually replaced. One of the goals of this paper is to research and present circumstances at medium-voltage level for external and internal devices, and to suggest fuse-applications.

2. Importance of a fuse as a protection element in distribution facilities

A fuse in a distribution medium-voltage power grid is mainly used as a protective element for:

- power transformers and auxiliary transformers and
- voltage transformers.

High voltage fuses consist of two parts, which are fuse-link and fuse-base. Based on their ability to limit the current, high voltage fuse-links can be divided into:

a) Current-limiting types [1]: This type is widely used around the world with more than 95% in Europe. They are for external use (protection of external distribution transformers) as well as the use in internal areas – switchgear cells. Properties and basic characteristics of these fuse-links are given in standard [1]. This is fuse that, during and by its operation in a specified current range, limits the current to a substantially lower value than the peak value of the prospective current. This standard defines three classes of current-limiting fuses:

Back-Up fuses, which are capable of breaking, under specified conditions of use and behaviour, all currents from the rated maximum breaking current down to the rated minimum breaking current.

General-Purpose fuses, which are capable to of breaking, under specified conditions of use and behaviour, all currents from the rated maximum breaking current down to the current that causes melting of the fuse element in 1 h or more.

Full-Range fuses, which are capable of breaking, under specified conditions of use and behaviour, all currents that cause melting of the fuse element(s), up to its rated maximum breaking current.

In practice, the most important characteristic is Back-Up, which means protection within a limited current area.

b) Non-current-limiting types [2]: Fuses with such a melting fuse-link are called expulsion. They are mainly used in the USA and the UK as well as in countries that are historically-related to the two previously mentioned. Fuse element melts and arcs, the expulsion effect of the gases produced by the interaction of the arc with other parts of the fuse results in the current interruption in the circuit. Another common characteristic is that they are essentially non-current-limiting. They are characterized by a relatively low arc voltage and so do not significantly reduce the value of the first peak of a fault current. They also, therefore, extinguish current at a natural current zero, when the proper dielectric condition have been established.

2.1 Fuse application for the protection of transformers

Fuse-links and switches are most frequently used to protect distribution transformers. In practice, there are four possible realizations:

a) Fuses for low voltage and high voltage

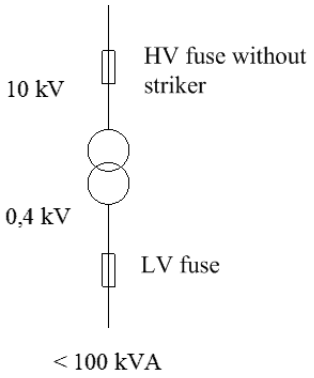

Fig. 2.1: Protection with fuses on the high-voltage and low-voltage sides.

This protection (Fig. 2.1) is used for transformers of the lowest apparent power (up to 100 kVA). In this case there must be an interruption of voltage on the high-voltage side in front of the fuses. High-voltage fuses do not require strikers. Such realization is the cheapest and is used for pole-mounted transformer substation (Fig. 2.2).

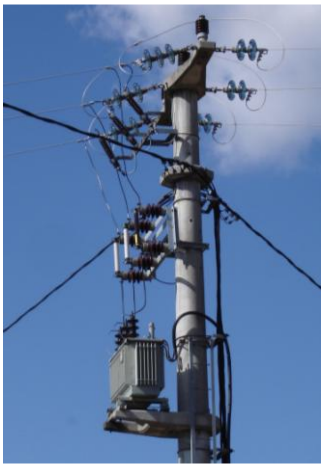

Fig. 2.2: Protection with fuses on the high-voltage side.

b) Fuse-disconnectors on the HV side and fuses on the LV side

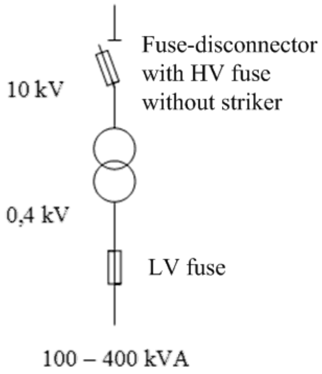

Fig. 2.3: Protection with fuse-disconnector on the HV side, and with fuses on the LV side.

A fuse-disconnector (Fig. 2.4) on the HV side enables a supply turn off and a visible separation. It is also used for pole-mounted transformer substations with apparent power from 100 to 400 kVA.

Fig. 2.4: Protection with fuse-disconnector.

c) Switch-disconnectors in combination with fuses on the high-voltage side and the fuses on low-voltage side

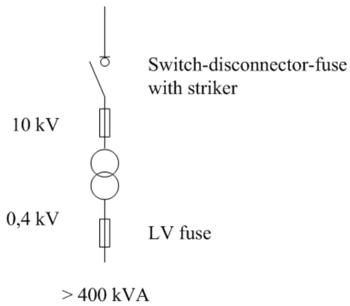

Fig. 2.5: Protection with switch-disconnector-fuse and fuses on the HV side and fuses on the LV side.

This concept is used in enclosed transformer stations with apparent power of over 400 kVA. The advantage of a switch-disconnector (Fig. 2.6), in comparison with a disconnector, is their ability to breaking nominal currents. A switch-disconnector or switch is usually equipped with a trigger mechanism, which is activated by a striker in the fuse. Short-circuit in one or two phase's causes a fuse to burn out. A switch-disconnector enables three-pole opening within the single phases of two-phase short-circuits.

Fig. 2.6: Protection with switch-disconnector-fuse on the HV side.

d) Čebulj protection

The use of Čebulj protection is an upgrade of the procedure previously described. Čebulj protection measures the current on the secondary low-voltage side, and in the case of an overload, the switch-disconnector turns off the primary-side of the transformer.

e) Recent realizations

Realizations with circuit breakers, that have lesser short-circuit breaking, and work in connection with special protective relays, have been in use for quite some time.

2.2 Standardization

Standards provide terminology, technical characteristics, and minimal technical requirements when choosing those fuses, intended for the protection of a power grid. These standards directly relating to fuses, are presented in the continuation.

a) IEC 60282-1:2005 High-voltage fuses – Part 1: Current-limiting fuses [1]

This standard is used for all types of high-voltage current-limiting fuses, which are constructed for external and internal use in AC systems of 50 and 60 Hz, as well as for nominal voltage over 1000 V. Some of the supplied fuses contain fuse-links, which are equipped with an indicator or a striker. These fuses are described within this standard. The correct working of a striker in combination with the triggering mechanism of a switch-device exceeds the area of this standard, and is covered by IEC 62271-105 [3].

b) IEC 62271-105:2002 High-voltage switchgear and control gear - Part 105: Alternating current switch-fuse combinations [3]

This standard applies to three-pole units for public and industrial distribution systems, which consist of switch-units that include a switch-disconnector and current-limiting fuses. These are capable of:

- At nominal recovery voltage, to interrupt every current up to and including the nominal short-circuit breaking current;
- At nominal voltage, to turn on circuits up to their nominal short-circuit breaking current.

In this standard, the term 'combination' is used for a functional unit, which consists of the components. Every connection of the given type of switch and fuse defines one type of combination.

In practice, different types of fuses are combined with one type of switch, which gives more combinations with different characteristics, especially in regard to the nominal current.

c) IEC 62271-107:2005 High-voltage switchgear and control gear – Part 107: Alternating current fused circuit-switchers for rated voltages above 1 kV up to and including 52 kV [4]

This standard applies to three-pole operated units for distribution systems that are functional assemblies of a circuit-switcher and current-limiting fuses designed so as to be capable of:

- breaking, at the rated recovery voltage, any load or fault current up to and including the rated short-circuit breaking current;
- making, at the rated voltage, circuits to which the rated short-circuit breaking current applies.

Their use is intended for circuits and applications that only require regular mechanical and electrical endurance. Such applications cover HV/LV protection of the distribution transformers, but they cannot be applied for distribution-transmission lines and electric machines that are used as compensation devices. Short-circuits with lower currents, all up to a current, that can be interrupted by a switch that is a part of the functional unit, are solved with additional devices (strikers, relays, etc.) that with adequate placement trigger only a switch, which is a part of the entire device. Fuses are added with the intention of ensuring that the short-circuit breaking capability, of the device, is higher than for the switch itself.

d) IEC/TR 60787 (2007-03) Ed. 1.0, Application guide for the selection of high-voltage current-limiting fuse-links for transformer circuits [5]

Basically, this standard represent a technical report for distribution transformers, which is used as a fuse 'user-guide' that fulfils the requirements of the IEC 60282-1 standard: High voltage fuses - 1. Part: Current-limiting fuses [1]. Because of that, this standard is considered to be informative and not normative.

The subject of these instructions is to determine criteria for coordination, respectively for the adjustment of high voltage fuses with other components that are part of a circuit with a transformer. It is also important to give directions when choosing fuse-links in regard to their time-current characteristics and nominal values.

3. Overview of current conditions regarding HV fuses` applications

There are five distribution companies in Slovenia and each of these five companies cover urban as well as rural areas. Electrical equipment containing fuses is built-in within external pole-mounted transformer substations, cable and wall transformer substations, and distribution transformer substations.

3.1 Pole-mounted transformer substation

Pole-mounted transformer substations are external transformer substations that are mounted onto a concrete pole or iron pole, and are of 20/0.4 kV voltage and an apparent power from 35 up to 250 kVA. The high voltage side of the transformer is constructed, in most cases with a disconnector at a previous location as well as with fuses and a discharge arrester, on the pole where the transformer is located (Fig. 2.1 and 2.2). On the low-voltage side, an electrical cabinet is located with low-voltage fuses for individual branches. A fuse-disconnector can also be used instead of high-voltage fuses (Fig. 2.3). Transformers located in some smaller transformer substations (20 and 35 kVA) are no longer protected by fuses anymore on the HV side.

On average per year, there are 5-15 faults on these transformers. The most common reasons are atmospheric overvoltage, and animals, since the transformer terminals and fuse terminals are not insulated. In that case where a fuse burns-out within a single phase, the voltages of the LV side (supply service) are no longer symmetrical. The other problem that appears is the safety of personnel when they are replacing faulty fuses.

3.2 Substations with indoor switching devices

These substations are constructed of metal sheets, concrete, or are brick-built. The electrical equipment is internally assembled and is not exposed from the weather. The apparent power of these substations is from 250 kVA to 1000 kVA and a voltage of 20/0.4 kV. They are used in both rural and urban areas. The high voltage side of the transformer is mostly protected with fuses added to a switch-disconector (switch-disconnector-fuses - Fig. 2.6), and have a striker as well as a mechanism for triple-pole disconnection of the supply when a fuse burns out (Fig. 2.5). The low-voltage branches are also protected by fuses. The described switch-fuse combination is often already replaced by combinations of a circuit-breaker and corresponding protection. This means the abandonment of high-voltage fuses.

3.3 Distribution transformer substation

These are air or gas-insulated transformer substations of 110/10 or 20 kV. The medium voltage part is always assembled internally. Fuses are applied to protect auxiliary transformers and voltage instrument transformers within measuring cells. Measuring cells that are insulated with gas SF_6, already use combinations without the protection of voltage measuring transformers with fuses.

4. Innovations and trends when using HV fuses

Recent innovations in high voltage fuses are related to new ways of applying fuses, and method for replacing fuses with other protective devices and combinations.

4.1 New methods of fuse application

The most important innovation is the application of fuses in the so-called self-protection transformer [6], [7].

Fuses are located in the housing of the transformer. The interruption of the circuit, in cases of fault, is based on the following options:

- three-phase current disconnection in the case of an internal fault,
- three-phase separation from the power-grid,

The triple protection system consists of:

- three high voltage limiting fuses,
- high voltage switch disconnector and
- low-voltage short-circuit devices with the capabilities of detecting level and oil pressures.

This transformer also contains epoxy-bushing, which prevents contact with parts under the voltage (Fig. 4.1)

Fig. 4.1: TPC transformer with epoxy-bushing for external assembly.

Another improvement in the successful application of high voltage fuses is the I_S limiter [8]. In cases of short-circuit, this quick switch-gear device triggers opening of the main conductive part. This part is designed to conduct high values of current under normal working conditions. The current switches to a parallel fuse that has high breaking capacity, which in a very short period of time limits the first increase of a short-circuited current.

The I_S limiter works as a good conductor under normal working conditions. In the case of fault, the limiter detects and limits the short-circuited current, so that its maximum value is never reached. The advantages of the limiter are:

- no additional power losses,
- no additional voltage drop,
- decrease in power grid resistance (parallel connections of transformer branches)
- limiting of short-circuit current at the first increase of the current,
- Improvement in power quality.

The I_S limiter consists of a main conductive system, which is designed for high nominal currents (yet it has a low breaking capacity), and from a parallel fuse with a high breaking capacity.

A small energy saver is used to save energy in those cases when the main conductive system is interrupted. A short reaction time, needed for a considerable limitation of the peak value of the short-circuit current, protects the system's components against distractive, dynamic and thermal overloading. A measuring and triggering system is required for a reliable working of the limiter. The electronic component constantly measures the value and the degree of current increase throughout the limiter, and compares them to previously set values. Each individual phase has a separate measuring and triggering system. In the case, if the both previously set values are reached or exceeded simultaneously in any of the phases, the limiter is trigged immediately. The primary construction parts are shown in Fig. 4.2.

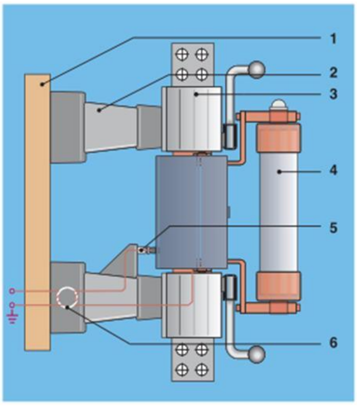

Fig. 4.2: Base and link of I_S limiter; 1-base plate, 2-insulator, 3-head pole with clamp, 4-fuse, 5-telescopic contact, 6-insulator with pulse transformer.

4.2 Fuse substitution with other protective combinations

The so-far existing method of protecting medium voltage cells is carried out with a switch-disconnector-fuse.

Quite a number of manufacturers of switchgear that contain dry air or gas SF_6 as a medium in their program, already introduced an alternative combinations. Circuit breakers and protective relays are used instead of a switch-disconnector-fuse. This combination, for its functioning, requires current transformers that send information to the relay, which than works when the circuit breaker turns off. The used circuit breaker usually has a lower breaking capacity. Realizations of circuit breakers with a vacuum or SF_6 gas are available. As a protective device, a simplified realization of the relay is applied, with an overload current and short-circuit current protection.

The next novelty is the application of a circuit breaker and a special protective circuit, which is used for circuit breaker triggering. The important elements in this circuit (Fig. 4.3) are the LV fuses. In this case, under normal working conditions, secondary currents flow through a low-impedance circuit with a fuse. Due to low impedance, a relatively low voltage occurs in the secondary circuit. In this case, practically no current flows through the triggering coil. In the cases of fault currents, one or more fuses (A, B and/or C) burn out and break the overcurrent value. The only remaining path for current to flow after fuse disconnection is a rectifier bridge and triggering coil of the circuit breaker through special voltage winding that is optimized in regard to the characteristics of the triggering coil.

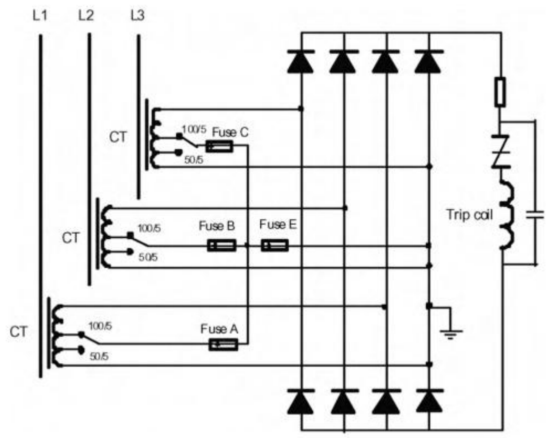

Fig. 4.3: New protection system based on the TLF (Time Limite Fuse).

The final alternative for high voltage fuses is the abandonment of those fuses for protecting small transformers (35 kVA up to 50 kVA). Fig. 4.4 shows an example of such a realization.

Fig. 4.4: Pole-mounted transformer substation with an unprotected transformer.

Transformer from Fig. 4.4 is completely unprotected because the manufacturers claim that a short-circuit current, in these grids, is lower in comparison to one that can be sustained by a smaller transformer.

5. Proposal for eventual new protection solutions regarding internally and externally assembled facilities

In regard to the available equipment, on both the European and World markets, as used to protect internally and externally-assembled transformer substations, and on the basis of expert opinions when it comes to the protection of transformer substations, the following is suggested:

- within internally-assembled air insulated facilities, it is reasonable to preserve the present condition, respectively a switch-disconnector-fuse. Within newly-built facilities, devices insulated with gas SF_6 are not recommended, due to environmental hazards. The recommended devices are those insulated with dry air and solid insulation if the solution is financially affordable and necessary due to the lack of space (small dimensions). These devices contain, instead of fuses, circuit-breakers with protection. For this type of protection, besides the price, it is necessary to consider the amount of time when the protection is active, as well as the circuit-breaker. The previously-mentioned amount of time is significantly longer in comparison to fuses. It is also necessary to consider breaking capacity, and a number of possible operations of the circuit-breaker.

- voltage transformers, located in air insulated devices are protected by fuses and because of such, in the case of a fault without protection, there is another protection, which interrupts the power supply. For other devices, the voltage transformer integrated into a device, does not need any protection.

- For the so-called small pole-mounted transformer substations, of up to 50 kVA, the suggested protection is without any fuses. But it includes overvoltage arresters and appropriate selective protection using the remote-controlled circuit breakers of the entire HV branch, from the distribution transformer substation (DTS) to the last transformer substation. The previously mentioned is based on the fact that the short circuit current value in the distribution power grid is lower, in comparison to the transformer (25 times the nominal current) for a time interval from 3 to 3.5s. By abandoning HV fuses, the problems that occur with fuse replacement, are avoided (safety). In the cases of longer faults, the entire HV branch of the distribution transformer substation is out of power (the protection of the DTS works). Due to this, when the transformer substation is unprotected by HV fuses, the use of selective protection with the remote-controlled circuit breakers of the entire HV branch is suggested, from the distribution transformer substation (DTS) to the last transformer substation.

- For other pole-mounted transformers substations of apparent power above 50 kVA, the use of HV fuses and overvoltage protection is still recommended, but with complete insulation, protection for all the transformer terminals and fuses for. Small compact transformer substations, installed on the ground are recommended, mainly because of worker safety, and the other advantages offered by mechanical protection of such transformer substations. In those areas where access to pole-mounted transformer substation is available via a crane, throughout the year, it is possible to use self-protected transformers, which contain fuses in oil. If this procedure is put into force in the Slovenian market, it will be necessary to replace the entire transformers when fuse burns out.

6. Conclusion

The goal of this paper was to research the current application of fuses within the power distribution system, trends and innovations, and the proposals of authors for the future use of fuses at different facilities.

The fundamental decision regarding, which protective device to apply in power distribution system, is based on a good knowledge of fuse properties, and the capabilities of other protective systems, as well as the actual conditions within those parts of the system, where devices are built-in. In a power distribution system, HV fuses are still utilized because they are quick and capable of interrupting high short-circuit currents. However, it is understandable that some specific distribution MV devices should be protected by new devices instead of fuses.

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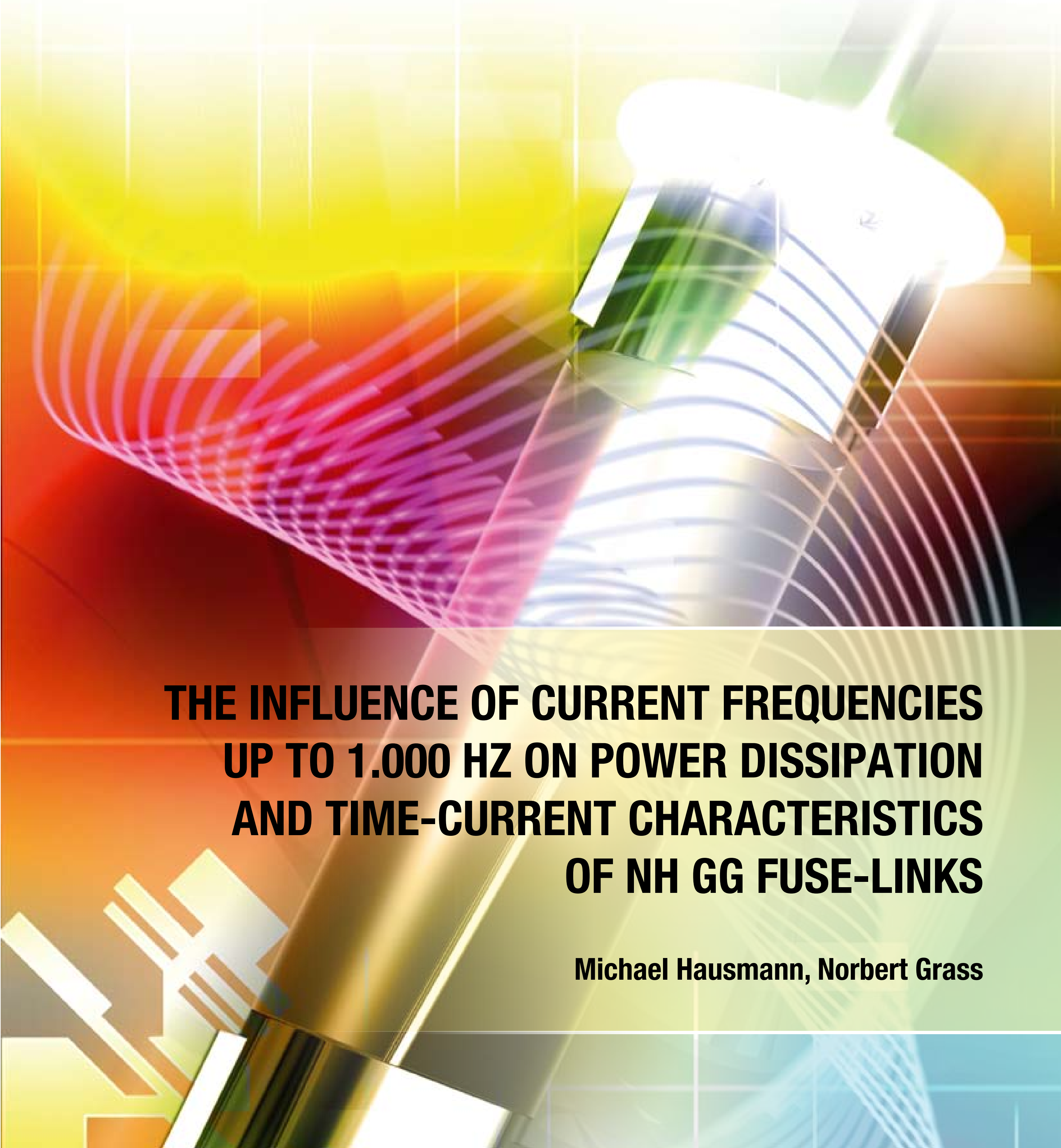

THE INFLUENCE OF CURRENT FREQUENCIES UP TO 1.000 HZ ON POWER DISSIPATION AND TIME-CURRENT CHARACTERISTICS OF NH GG FUSE-LINKS

Michael Hausmann, Norbert Grass

The influence of current frequencies up to 1.000 Hz on power dissipation and time-current characteristics of NH gG fuse-links

Michael Hausmann, Norbert Grass

GSO University of Applied Sciences Nuremberg, Kesslerplatz 12, 90489 Nuremberg,
michael.hausmann@ohm-hochschule.de, norbert.grass@ohm-hochschule.de

Abstract

In this paper, theoretical and experimental studies on the influence of higher frequencies of the load current on the power dissipation of NH gG fuse-links will be presented. By means of a power electronic converter, currents with variable frequencies and amplitude were fed thru NH gG fuse-links and model fuse-links with up to four parallel fusible conductors. The power dissipation and the pre-arcing times of the fuse-links have been compared at 50 Hz, 400 Hz and 1.000 Hz. Based on the power dissipation at different current frequencies, reduction factors for the fuse-link rated currents have been calculated, to obtain time-current characteristics similar to 50 Hz rated frequency currents. The pre-arcing times are shown in a time-current characteristic diagram of a standard fuse-link. The results are particularly gaining relevance due to increasing contents of harmonic currents in public grids and industrial plants.

Keywords: current frequencies, NH fuse-link, time-current characteristic.

1. Introduction

Today's power grids can have substantial amounts of harmonics or a higher base frequency in their voltage and currents. In airplanes for example, the board voltage has a base frequency of f = 400 Hz. In industrial grids, harmonics are generated by power electronic devices such as converters. These high frequency currents influence the behavior of the fuse-links. Standard fuse-links are designed for current frequencies of f = 50 Hz to 60 Hz. At these low frequencies the d.c. resistance dominates the behavior of the fuse-link.

At higher current frequencies the current thru the fuse is no more evenly distributed. This leads to higher power dissipation of the fuse-link and increasing temperature-rise. Due to this effect, premature operation of the fuse appears to be possible.

When feeding the fuse-link with high frequency currents the skin and proximity effect has to be considered. The skin effect describes the influence of the high frequency on the current density of one conductor. The proximity effect describes the influence of currents in different closely arranged conductors to each other. Both effects depend on the frequency of the current, the geometrical design of the fuse-link and the cable arrangement of the device where the fuse is installed [1-3]. All effects have an influence on the power dissipation and the pre-arcing time of the fuse-link. The effect of higher frequency currents is also described in [4] where also derating factors for the fuse links are calculated and discussed.

In this paper experimental results of measuring the power dissipation of a fuse-link are presented. During the experiments, fuse-links with parallel fusible conductors have been examined. As a result of the increased power dissipation, reduction factors for the rated fuse currents are calculated to obtain the same thermal behavior of the fuse compared to 50 Hz rated frequency. After that, the pre-arcing times of the fuses were drawn into a time-current chart of a standard fuse-link.

2. The experiment

In the experiment the fuse-links were loaded with currents of f = 50 Hz, 400 Hz and 1.000 Hz using a frequency converter. Due to the switching frequency of the converter, harmonic components in the fuse current are also generated. These harmonics can only be reduced by using large harmonic filters. So the harmonics of the fuse current were measured and then considered in the next calculations and simulations of the fuse-link.

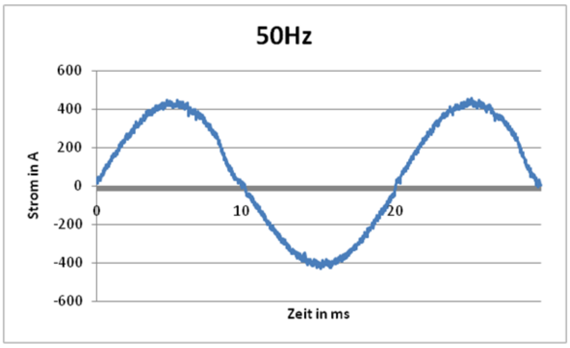

Fig 1: current with I = 300 A and f = 50 Hz

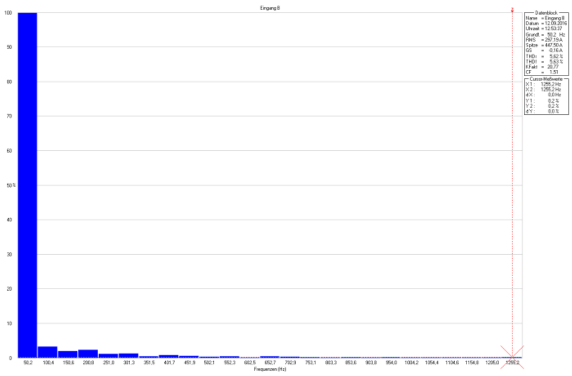

Fig 2: Harmonics at I = 300 A and f = 50 Hz

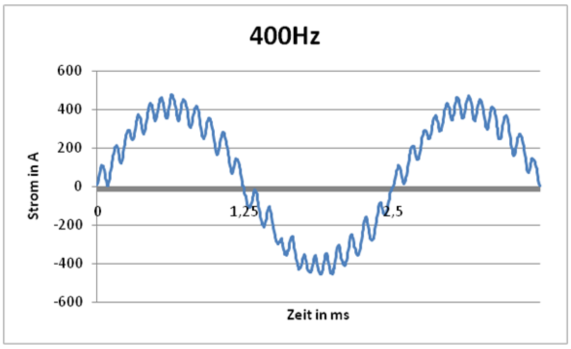

Fig 3: current with I = 300 A and f = 400 Hz

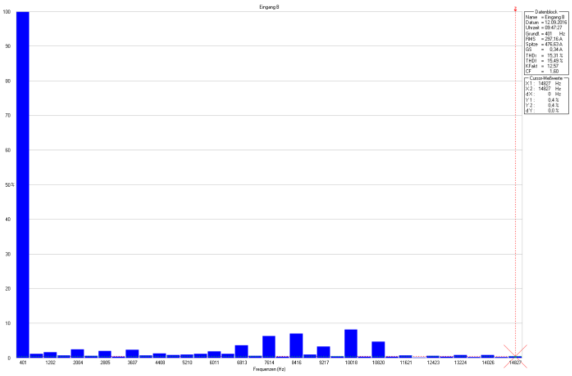

Fig 4: Harmonics at I = 300 A and f = 400 Hz

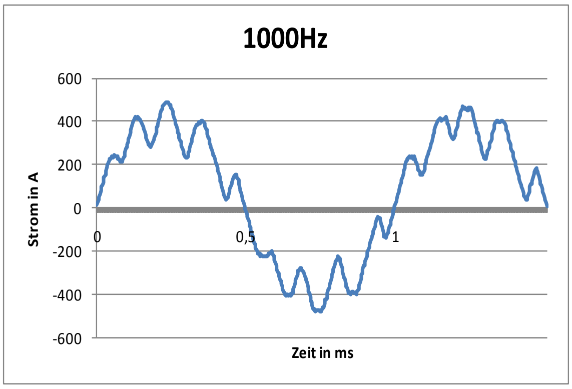

Fig 5: current with I = 300 A and f = 1.000 Hz

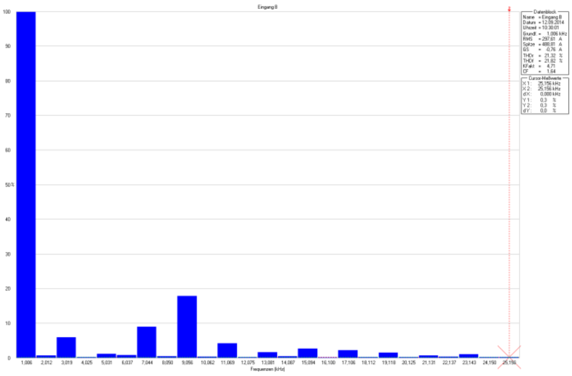

Fig 6: Harmonics at I = 300 A and f = 1.000 Hz

There is a significant difference in the fuse current harmonics between f = 50 Hz and f = 1.000 Hz. Due to the fixed switching frequency of the converter of f_s = 10 kHz, the contents of current harmonics are increasing with higher base frequencies (see Fig 1 to Fig 5 6?). Nearly no switching frequency can be seen when generating currents of f = 50 Hz.

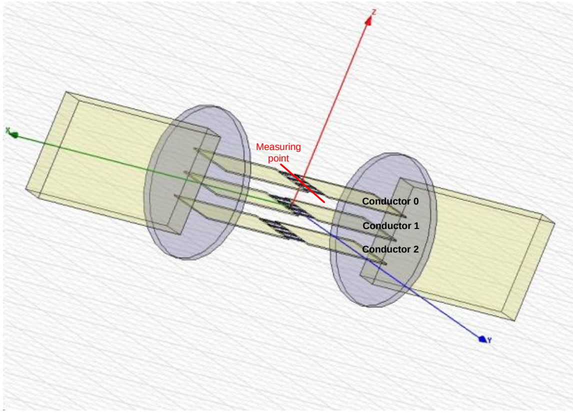

Fig 7: model of the fuse-link in Maxwell 3D simulation program

Fig 7 shows the 3D model of a fuse-link with three parallel fusible conductors. It is assumed that one fusible conductor can carry a current of I = 100 A. All the effects on the fuse-links were referenced with a 3D finite element simulation using Maxwell 3D simulation tool.

2.1. The Skin Effect

Equation (1) shows the calculation of the skin effect in a round conductor [5].

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \kappa}} \qquad (1)$$

With:

$$\omega = 2 \cdot \pi \cdot f$$

μ = Permeability,

κ = electric conductivity

With equation (1) the eddy current depth at f = 1.000 Hz is 2,1 mm. Due to this equation, the skin effect has no influence on the 0,5 mm thick conductor.

The skin effect can be seen on the finite element simulation results (see Fig 8). In the simulation a flat rectangular conductor was fed with currents of f = 100 Hz, 1.000 Hz and 10.000 Hz. The simulation results in Fig 8 show that the current density is higher at both edges of the conductor than in its center.

The skin effect must be calculated using equation (2) [5]. In this equation the current density can be calculated over the width of the conductor.

$$J_x(z) = \frac{I_0}{2 \cdot b} \cdot \gamma \cdot \frac{\cosh(\gamma \cdot z)}{\sinh\left(\gamma \cdot \frac{d}{2}\right)} \tag{2}$$

The calculated current density was checked with the finite element simulation. The simulation results were normalized to get a current independent distribution of the densities.

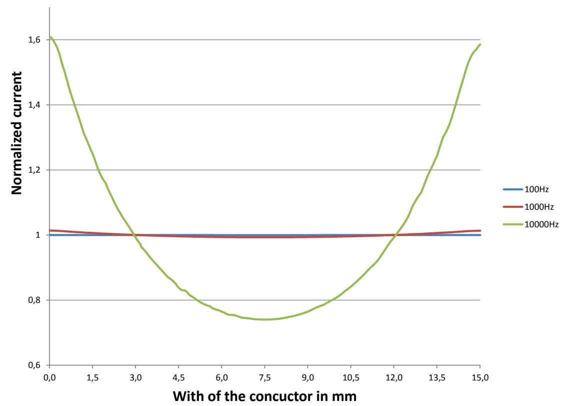

Fig 8: Current density in a flat rectangular conductor over the widths of the conductor

The simulation results in Fig 8 show the power density over the width of the conductor.

The effect is stronger at current frequencies of f = 10.000 Hz but can also be identified at frequencies of f = 1.000 Hz. At lower frequencies, the current density of the fusible conductor is approximately homogeneous.

2.2. The Proximity Effect

The proximity effect describes the influence of currents in different adjacent conductors. The effect depends on the geometric arrangement of the fusible conductors [2, 6]. In the experiment, only parallel conductors were considered (see Fig 7). In order to obtain a realistic model of the fuse-link, the 3D model was built after a real fuse-link. Restrictions were placed in the center of the fusible conductors to achieve a current density similar to that of a real fuse.

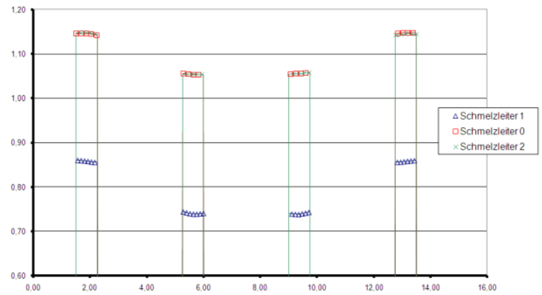

Fig 9: Current density in a fuse-link with three fusible conductors an a current with f = 1.000 Hz

The simulation results in Fig 9 show the skin- and proximity effects. The current density is increased in the edges if only one fuse-element is considered. This comes from the skin effect in the single conductor.

The current densities in both outer conductors (conductors 1 & 2) are higher than the density in the center conductor. This effect can be seen in every fuse-link with a minimum of 3 conductors.

Due to the two effects, there is a change of the a.c. resistance $R_\sim$ of the fusible conductors shown in equation (3) [5].

$$R_\sim = R_- \cdot Y_{Skin} \cdot Y_{Prox} \tag{3}$$

In this equation, the d.c. resistance of the fuse-link is influenced by two factors. One factor for the skin and one for the proximity effect ($Y_{Skin} \cdot Y_{Prox}$). The values for these correction factors are greater than 1. That means, with higher current frequency the resistance of the conductor increases. Because of the higher resistance, the power dissipation and the temperature rise of the fuse-link will increase.

3. Heating behavior of the fuse-link

Due to the assembly of the fuse-link, the power dissipation of the fuse-link is generally low. In fuse-links with 3 or 4 conductors, the one or two conductors in the center of the fuse-link are having higher temperatures than the two outer ones (see Fig 10).

To obtain more information on the temperature distribution inside the fuse-links, a temperature measurement was taken. For this experiment a fuse-link body was opened and filled by half with sand, leaving the edges if the fusible conductors exposed. After that, the open fuse was subjected to currents of I = 100 A with f = 50 Hz and f = 1.000 Hz.

Fig 10 shows the temperature distribution of a fuse-link with three conductors. The fusible conductor in the center of the fuse heats up to 70°C. The two outer conductors to 60°C. This effect takes place independent on the current frequency.

Due to this effect the solder of the center conductor would melt first and initiate fuse operation.

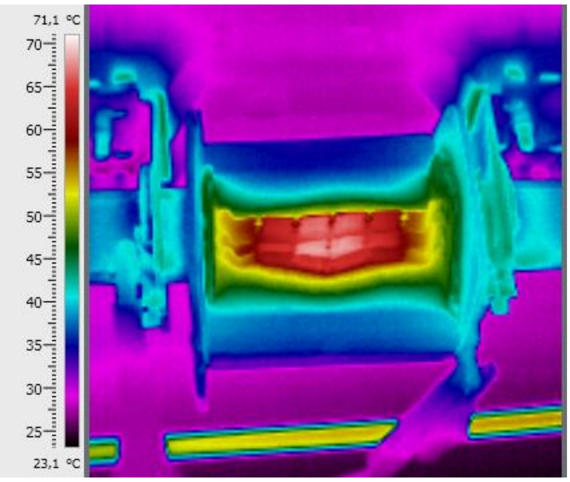

Fig 10: Temperature rise of a fuse-link model with three parallel conductors

4. Power dissipation of the fuse-link

In the experiment, fuse-links with one to four fusible conductors have been investigated. The experiment was split in two steps. In the first step the fuses were fed with their “rated” currents. It was assumed that each conductor can carry a current of I = 100 A. The current frequencies were changed in three steps from f = 50 Hz to 400 Hz and 1.000 Hz.

In the second step the currents were increased to 1,6 times and 2,5 times their “rated” currents.

During the tests, the current, the voltage and the temperature of the fuse-links were recorded every 60 s. The different experimental steps can be seen in Table 1.

Fig 11 shows the power dissipation of a 400 A fuse-link with four fusible conductors at the three different frequencies.

Table 1: Table of the measurements

	Frequency	Fuse type			
Nominal fuse current		100A	200A	300A	400A
Number of fusible conductors		I	II	III	IIII
Heating treatment with hominal fuse current	50Hz	1	1	1	1
	400Hz	1	1	1	1
	1000Hz	1	1	1	1
pre-arching times with 1,6 times the nominal current	50Hz	1	1	1	1
	400Hz	1	1	1	1
	1000Hz	1	1	1	1
pre-arching times with 2,5 times the nominal current	50Hz	1	1		
	400Hz	1	1		
	1000Hz	1	1		

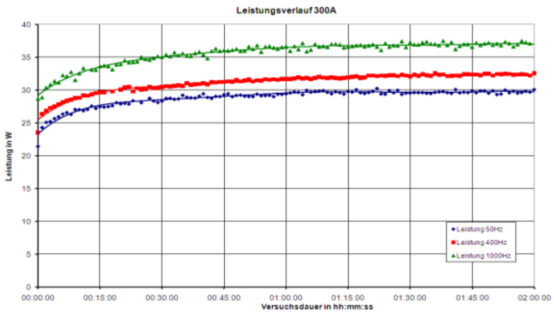

Fig 11: Power dissipation of a fuse-link with 4 fusible conductors at different frequencies

It can be seen that the power dissipation rises with increasing current frequencies. The temperature and power dissipation of the fuse-link changes the same way. After starting the experiment the power dissipation rises and finally reaches a steady state.

Fig 12 shows the steady state values of power dissipation of the fuse-links over the different frequencies. The figure shows a linear rise of power dissipation with increasing current frequencies.

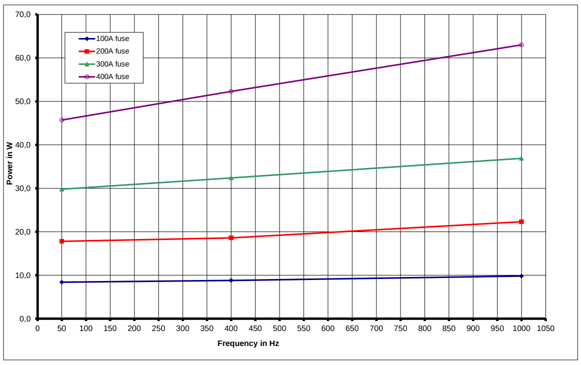

Fig 12: Power dissipation of the fuse-links over the frequency at “rated” currents of the fuse-links

Due to the linear dependence of the power dissipation of the fuse-links and the current frequency, a correction factor for the fuse rated current can be calculated. With this factor the maximum current of a fuse-link can be calculated that results in a similar thermal behavior than a 50 Hz current.

5. Calculation of the correction factors

$$P = I^2 \cdot R \quad (4)$$

Equation (4) shows the power dissipation of the fuse-link in dependence of its resistance R and the current I thru it. The resistance R represents the a.c. resistance in dependence of the skin and proximity effects. The a.c. resistance is independent on the fuse current. To obtain equal power dissipation at high frequency currents, the current thru the fuse-link has to be reduced.

In the next equations, a correction factor for a 400 A fuse-link at f = 1.000 Hz is calculated.

$$P_{50Hz} = I^2 \cdot R_{50Hz} = P_V = I_v^2 \cdot R_{1000Hz} \quad (5)$$

To get the reduced current I_V of the fuse, the power dissipation in the conductors at f = 50 Hz must be the same as the power dissipation with reduced current at f = 1.000 Hz (see equation (5)). After solving equation (5) to the currents, a ratio in dependency of the resistances can be calculated using equation (6).

But there is no information about the a.c. resistances of the fuse-link at any frequency. So equation (6) has to be modified to obtain a suitable correction factor.

$$I_{50Hz}^2 \cdot R_{50Hz} = I_v^2 \cdot R_{1000Hz}$$
$$\rightarrow \frac{I_{50Hz}}{I_v} = \sqrt{\frac{R_{1000Hz}}{R_{50Hz}}} \quad (6)$$

The reduced current through the fuse can be calculated using the measured power dissipation. To obtain an equation for the ratio of the currents in dependency of the power dissipation, the frequency specific equations (5) has to be inserted in equation (6).

$$\frac{I_{50Hz}}{I_v} = \sqrt{\frac{P_{1000Hz}}{P_{50Hz}}} = \frac{1}{k} \quad (7)$$

Equation (7) shows, that the f = 1.000 Hz current has to be reduced, in order to obtain a similar behavior than with the f = 50 Hz current. In equation (8) the correction factor is calculated for a 400 A fuse at a current frequency of f = 1.000 Hz.

The equation shows, using the measured power dissipation of the fuses, the current has to be reduced to $I_V = 341A$.

$$\frac{I_{50Hz}}{I_v} = \sqrt{\frac{P_{1000Hz}}{P_{50Hz}}} = \sqrt{\frac{63W}{45,7W}} = 1,174 = \frac{1}{k}$$
$$k = 0,852 \quad (8)$$
$$I_v = I_{50Hz} \cdot k = 400A \cdot 0,852 = 341A$$

Using the power dissipation of the experiment, the factors for the skin and the proximity effects for higher frequencies can be calculated.

$$R_{1000Hz} = R_{50Hz} \cdot Y_{Skin} \cdot Y_{Prox} = \frac{R_{50Hz}}{k^2} \quad (9)$$

As shown in equation (9), the calculated correction factor k stands for the two factors Y_{Skin} and Y_{Prox} of the fuse with 4 fusible conductors. An emphasis of the skin or the proximity effect can't be seen. The factor for the skin effect can be calculated from the measurement results with one fusible conductor. In this measurement, only the skin effect takes place. It is nearly the same factor for fuse-links with more conductors. Typically, the proximity effect has an increased influence of the power dissipation in the conductors.

$$Y_{Skin} \cdot Y_{Prox} = \frac{1}{k^2} \quad (10)$$

The second step of the experiment shows that the calculated reduction factors for the currents for $I = 1,6 \cdot I_N$ and $I = 2,5 \cdot I_N$ times the nominal current are similar.

As a next step the pre-arcing times of the fuse-links at higher frequency currents were plotted in a time-current characteristic diagram of a standard fuse-link. It has to be considered that the examined model fuse-links had identical parallel fusible conductors taken from a standard 100 A gG fuse-link and therefore had an inferior thermal behavior compared to standard fuse-links. To fit the measured pre-arcing times into a time-current chart of a standard fuse-link the “rated” currents of the fuses had to be adjusted to more realistic values.

The adjustment was based on the power dissipation of the fuse-links. If a standard fuse-link with one single fusible conductor has a power dissipation of $P = 8,4W$ a fuse-link with two fusible conductors should have a power dissipation of $P = 16,8W$. The corresponding model fuse-link tested exhibited a power dissipation of $P = 20W$, which represents a 19% increase Considering equation (4), a standard fuse-link can carry a current increased by 9% of its rated current to dissipate the same power.

To plot the measured results in a time-current diagram of a standard fuse-link the “rated” currents of the tested sample fuses had to be corrected by a factor as shown in Table 2. After adjusting and normalizing the rated currents of the tested fuse-links, the pre-arcing times of the fuses can be plotted in a time-current chart of a standard fuse-link as shown in Fig 13.

Table 2: Adjustment factors for rated currents of the model fuse-links to compare with standard fuse-links

Umrechnung der Stromwerte

		I	II	III	IIII	
P_N	50 Hz	8,4	20,00	33,00	48,00	W
P_N	Faktor	1	1,19	1,31	1,43	W
I_N	Faktor	1	1,09	1,14	1,20	A
P_N	400 Hz	9,5	25,50	38,50	55,00	W
P_N	Faktor	1	1,34	1,35	1,45	W
I_N	Faktor	1	1,16	1,16	1,20	A
P_N	1000 Hz	9,25	25,00	50,00	85,00	W
P_N	Faktor	1	1,35	1,80	2,30	W
I_N	Faktor	1	1,16	1,34	1,52	A

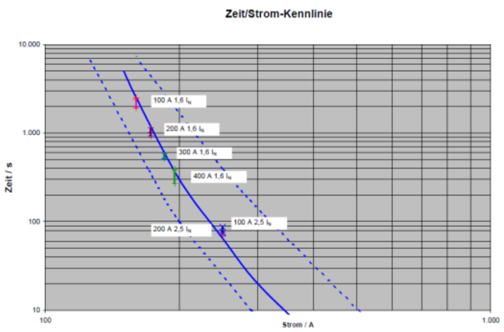

Fig 13: Pre-arcing times of the model fuse-links adjusted to time-current characteristics of standard gG fuse-links

6. Conclusions

By feeding higher frequency currents thru standard NH gG fuse-links, higher power dissipation of the fuses is generated. Due to the higher power dissipation, the temperature-rise of the fuse increases over rated values. After a sufficient temperature-rise, fuse operation will be initiated at rated current or even below.

The two main effects for this rise in power dissipation and temperature are the skin and the proximity effects. They were investigated by calculation and 3D finite element simulation using Maxwell simulation tools.

In an experiment, different fuses with different numbers of parallel fusible conductors were loaded with higher frequency currents. The voltage and currents on the fuses were measured to obtain the power dissipation of the fuse-links. With these power dissipation values, reduction factors for the fuse rated currents are calculated for similar power dissipation of the fuse as at rated frequency currents.

After normalizing the rated currents of the tested model fuse-links with parallel conductors the pre-arcing times of the fuses could be drawn in a standard time-current characteristic and compared to standard characteristics.

Now, the same experiment could be done with standard fuse-links to examine the influence of the proximity effect on the standard fuses. Then modified rated currents and pre-arcing times could be defined too.

It has expired that the thermal effect of higher frequency currents have to be considered and reduction factors applied when calculating the maximum load of fuses and fuse gear. The effects on time-current characteristics, however, appear to be within the limits of normal fuse tolerances.

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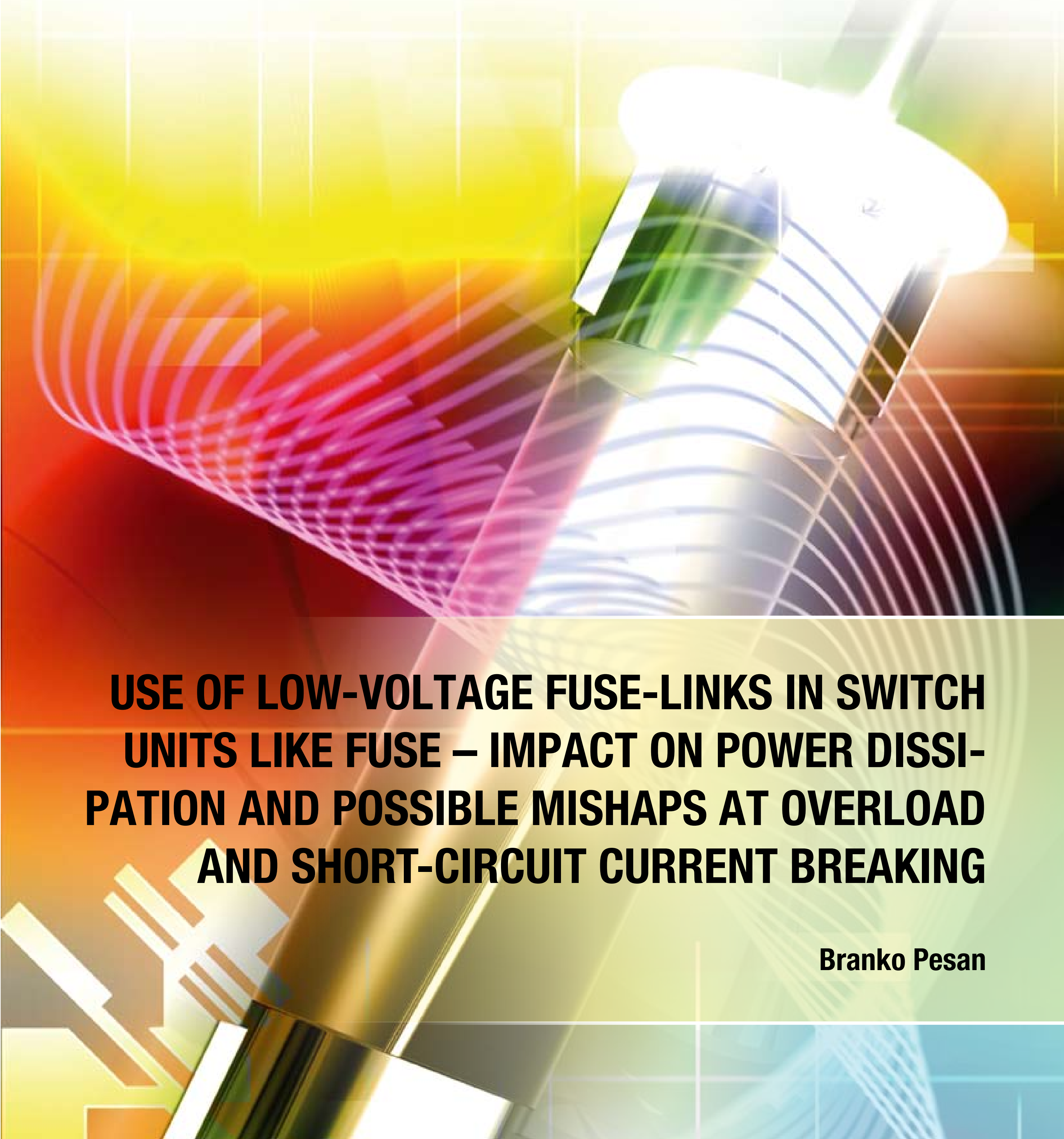

USE OF LOW-VOLTAGE FUSE-LINKS IN SWITCH UNITS LIKE FUSE – IMPACT ON POWER DISSIPATION AND POSSIBLE MISHAPS AT OVERLOAD AND SHORT-CIRCUIT CURRENT BREAKING

Branko Pesan

Use of low-voltage fuse-links in switch units like fuse – impact on power dissipation and possible mishaps at overload and short-circuit current breaking

Branko Pesan

ETI Elektroelement d.d., Obrezija 5, SI-1411 Izlake, Slovenia, branko.pesan@eti.si

Abstract

Low-voltage fuse-link's power dissipation and related temperature rise are prescribed with standard IEC 60269. Standard require measurement of power dissipation and temperature rise in free air.

As the use of fuse switch units, i.e. fuse dissconnectors increases, impact on power dissipation of low voltage fuse-links when used in switches is presented in paper.

Impact on power dissipation and temperature rise of fuse-links as well as fuse switch unit when incorrect connection wire like aluminium connector is used are being presented.

Possible mishaps of incorrect breaking of overload and short-circuit currents when using fuse-links in fuse switch units are being presented.

The paper is focused on use of low voltage cylindrical fuse-links in fuse disconnectors.

Keywords: cylindrical fuse-links (Fuse system F- NF cylindrical fuse system), fuse disconnector, overload, short-circuit, connection wire.

1. Introduction

Fuse-link's power dissipation is according to definition in [1]: "Power released in a fuse-link carrying a stated value of electric current under prescribed conditions of use and behaviour".

The power dissipation is also linked to temperature rise of fuse-link and with it to temperature rise of fuse-base used. This means that higher the power dissipation is more the fuse-base will be heated. To avoid over-heating (in case of rated currents) and thus potential damage to fuse-bases and equipment standards [1], [2], [3] limit the maximum power dissipation allowed on fuse-links (depending on type of fuse-links) to maximum rated current of one type of fuse-link and to rated voltage of the fuse-link. With this it limits also maximum temperature rise and maximum acceptable power dissipation of fuse-base.

As well as fuse-link and its power dissipation influence on temperature rise of fuse-base, the type of fuse-base could influence temperature rise and power dissipation of fuse-links, depending on the type of fuse-base. Types of fuse-bases are open bases (open free-air fuse-base) and closed bases (disconnectors, switch units, etc.). On closed bases the temperature rise and power dissipation of fuse-links will be higher than on open bases due to lower heat convection. This is important in case of cylindrical type fuse-links which are mainly used in fuse disconnectors.

Temperature rise is also dependent on connection conductor used. For connections standard [1] prescribes the use of copper conductors although somewhere the aluminium conductors are used. In case of aluminium conductors special attention at conductor cross-section selection is needed. Incorrect cross-section of aluminium conductor causes higher temperature rise and power dissipation, in some cases overheating which could lead to fuse-base and equipment damage.

2. Power dissipation and temperature rise of fuse-link

According to standard [1] the fuse-link shall be so designed and proportioned as to carry continuously, under standard conditions of service, its rated current without exceeding the rated power dissipation of the fuse-link as indicated by the manufacturer or otherwise specified in subsequent parts of [1].

In case of cylindrical fuse-link of size 22x58 (according to [2]), rated voltage 500V and rated current 100A the maximum power dissipation allowed is 9,5W.

In this section of paper the intention is to experimentally present influence of type of fuse-base and type of connection (copper or aluminium conductor) on power dissipation of fuse-link size 22x58, characteristics gG, rated current 100A. For this purpose 1-pole open fuse-base and 1-pole fuse-disconnector type ETI VLC 22 have been used.

2.1 Influence of fuse-base to fuse-link's power dissipation

First the test of temperature rise and power dissipation measurement according to standard requirements have been made. Open fuse-base in parallel with fuse-disconnector have been used. Copper conductors of cross-section 35mm^2 (according to standard) have been used. Test have been made on fuse-links size 22x58, gG, 100A (2 pcs.) with cold internal resistance of 0,582mΩ each (for comparison purpose fuse-links with equal internal resistance have been used).

Measurement of temperature rise have been made in 5 points for open fuse-base and in 7 points for fuse-disconnector (for details see Fig. 1, Fig. 2 and Table 1).

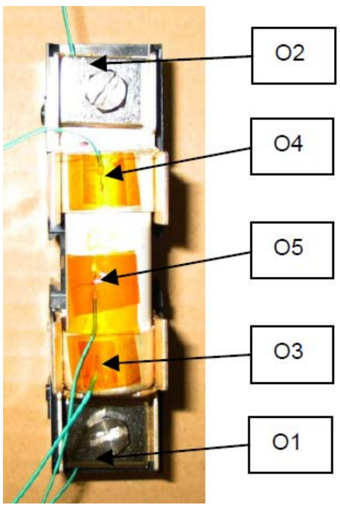

Fig. 1: Temperature rise measuring points on open fuse-base

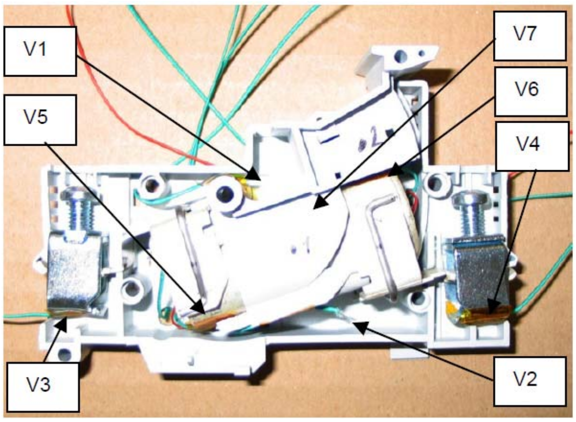

Fig. 2: Temperature rise measuring points on fuse-disconnectors

Table 1: Temperature rise measuring points

Point	Description
O1	Terminal – inbound (open base)
O2	Terminal – outbound (open base)
O3	Contact cap – inbound (open base)
O4	Contact cap – outbound (open base)
O5	Fuse body (open base)
V1	Inside space - up (fuse-disconnector)
V2	Inside space - down (fuse-disconnector)
V3	Terminal – inbound (fuse-disconnector)
V4	Terminal – inbound (fuse-disconnector)
V5	Contact cap – inbound (fuse-disconnector)
V6	Contact cap – inbound (fuse-disconnector)
V7	Fuse body (fuse-disconnector)
A1	Ambient
A2	Ambient

Power dissipation measurement have been done at the end of temperature rise test when the stationary conditions have been reached. Measurement points for both fuse-links (on both fuse bases) were at the end of contact cap according to standard [2] requirements (see Fig. 3).

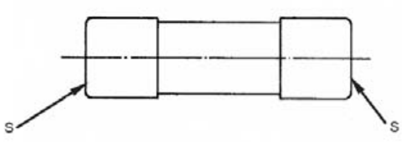

Fig. 3: Measurement points for power dissipation

Test results are presented in Tables 2 and 3 and in figure 4.

Table 2: Temperature rise

Point	T_{max} (°C)	T_{max} (K)
O1	NA*	NA*
O2	NA*	NA*
O3	67,7	44,5
O4	74,6	51,3
O5	76,9	53,2
V3	68,0	44,6
V4	72,5	49,1
V5	90,0	66,7
V6	95,9	72,5
V7	100,1	76,8
A1 (average)	23,1	23,2°C
A2 (average)	23,3	

Table 3: Power dissipation

	ΔU (mV)	P_{diss} (W)
Fuse-link (open base)	79	7,9
Open base	89	8,9
Fuse-link (disconnector)	86	8,6
Disconnector	107	10,7

Remark *: Thermocouple broken/disconnected during test

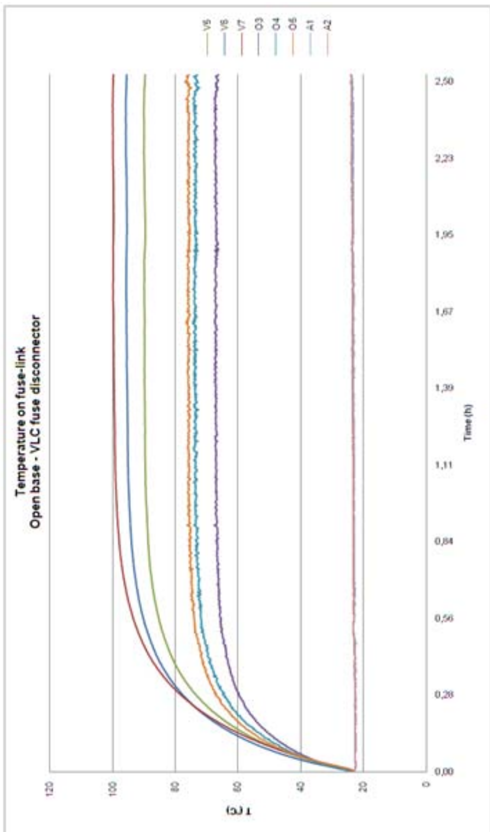

Fig. 4: Temperature rise on fuse-links (copper conductors 35mm^2)

From test results it is clear that fuse-link in fuse disconnector reached significantly higher values at temperature rise than the fuse-link in open fuse-base due to lower heat dissipation in fuse-disconnector. The difference between open fuse-base and fuse-disconnector could be more than 20K. Due to a higher temperature of fuse-link in fuse-disconnector resistance of fuse-link is higher, consequently power dissipation is higher than the power dissipation on fuse-link used in open base.

2.2 Conductor influence on fuse-link's power dissipation

In this case influence of connecting conductor on temperature rise and power dissipation of fuse-links is experimentally presented. Tests have been made the same way as in 2.1. Difference was in connection conductors used. For the first part of test aluminium conductors with cross-section of 35mm^2 have been used. Fuse-links used have had the same internal resistance as in part 2.1. For the second part of test aluminium conductors with cross-section of 70mm^2 have been used. Fuse-links used for test have internal resistance of 0,589mΩ. Results are presented in tables 4, 5, 6, 7 and in figures 5, 6 and 7

Table 4: Temperature rise (conductor Al 35mm^2)

Point	T_{max} (°C)	T_{max} (K)
O1	66,0	42,2
O2	73,6	49,8
O3	71,2	47,4
O4	78,6	54,8
O5	80,0	56,2
V3	NA*	NA*
V4	86,5	62,7
V5	101,3	77,6
V6	109,7	85,8
V7	111,4	87,6
A1 (average)	23,6	23,8°C
A2 (average)	23,9	

Table 5: Power dissipation (conductor Al 35mm^2)

	ΔU (mV)	P_{diss} (W)
Fuse-link (open base)	81	8,1
Open base	92	9,2
Fuse-link (disconnector)	89	8,9
Disconnector	110	11,0

Remark *: Thermocouple broken/disconnected during test

Table 6: Temperature rise (conductor Al 70mm^2)

Point	T_{max} (°C)	T_{max} (K)
O1	NA*	NA*
O2	NA*	NA*
O3	67,5	44,4
O4	70,8	47,3
O5	76,5	53,0
V3	59,2	35,6
V4	64,4	40,9
V5	88,3	64,8
V6	91,0	67,5
V7	103,5	79,9
A1 (average)	22,9	23,0°C
A2 (average)	23,1	

Table 7: dissipation (conductor Al 70mm^2)

	ΔU (mV)	P_{diss} (W)
Fuse-link (open base)	80	8,0
Open base	91	9,1
Fuse-link (disconnector)	86	8,6
Disconnector	106	10,6

Remark *: Thermocouple broken/disconnected during test

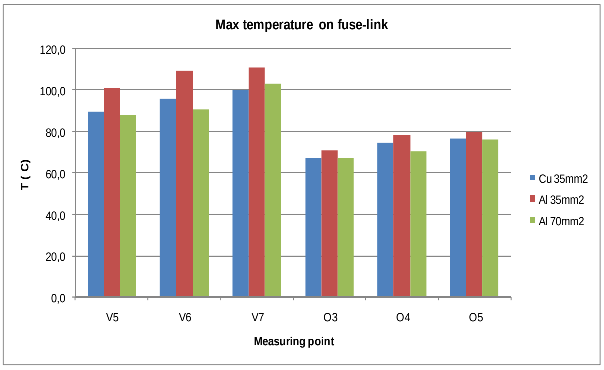

Fig. 5: Temperature rise on fuse-link comparison

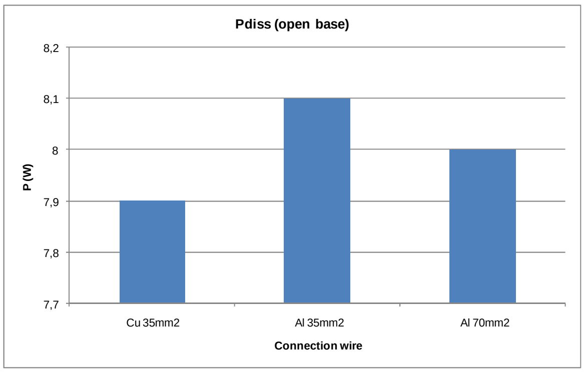

Fig. 6: Power dissipation of fuse-links comparison (open fuse-base)

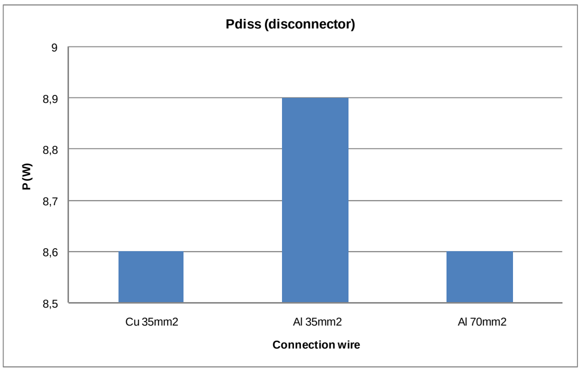

Fig. 7: Power dissipation of fuse-links comparison (fuse-disconnector)

From the results we can determine that type of fuse-base used have a significant impact on power dissipation and temperature rise of fuse-links as well as on fuse-base. Type of conductors also have impact on temperature rise and power dissipation of fuse-links and fuse-bases. If we use aluminium conductor instead of copper conductor with the same cross-section as copper conductor the temperature rise will be higher due higher aluminium conductor resistivity (lower conductivity). This is shown especially in case of use of closed fuse-base where the difference in temperature rise and power dissipation between open fuse-base and closed fuse-base is highest. With use of aluminium conductors with cross-section of two levels higher than copper conductors (according to recommendation/requirements in older standards issues i.e. DIN 57636-21/VDE 0636-21:1984) the impact on temperature rise and power dissipation is minimised.

3. Possible mishaps during fuse-links operation

Like in case of rated currents the choice of fuse base and connecting conductor have in some cases even bigger impact at overload currents. Major defects, fuse-base and equipment damage could occur in connection with incorrect operation of fuse-link or incorrect choice of fuse-link (i.e. fuse-link with higher rated current than fuse-base rated current, fuse-links of unknown origins).

Most defects occur at overloads when overload current occurs and fuse-link starts to operate. In most cases defects occur at 3-phase connections when 3-pole fuse-base is used. In this case the middle pole is heating the most due to both side poles influence (side poles are causing higher temperature rise on middle pole). The most common defect on fuse-bases, especially if closed fuse-bases (i.e. fuse-disconnectors) are used, is when overheated parts become soft, in some cases start to melt, and could bond together. Consequently fuse-base could not be opened (in case of fuse-disconnectors) to replace fuse-links and have to be replaced. In severe cases, when fuse-links for various reasons start to overheat (i.e. incorrect operation during melting time – anomalous M-effect, dispersion of solder into quartz sand, in some cases lack of sand), the consequences are that fuse-base (fuse-disconnector) starts to melt – first the fuse-carrier and then housing. The result is destroyed fuse-base, in most severe cases melting of fuse-base could cause short-circuit between poles. If backup protection does not work or there isn't any, continuous arcing could occur causing fire.

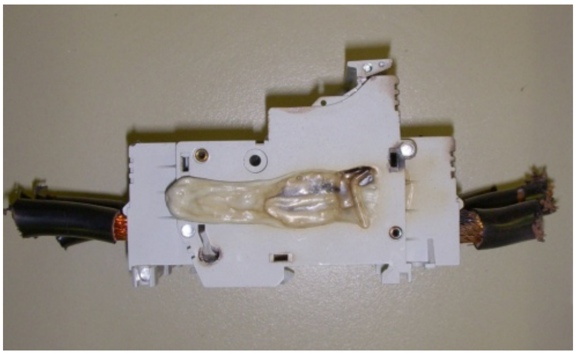

Fig. 8: Damaged fuse-base after incorrect operation of fuse-links at overload currents

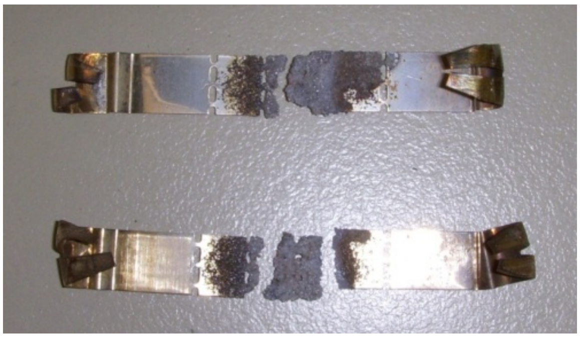

Fig. 9: Melting element after incorrect overload operation

At short-circuit currents most common defect is fuse body breaking. In some cases parts of fuse-link could break apart and stay in fuse-base (especially in closed bases), fuse-base have to be replaced. The worst defect at short-circuit currents is explosion of fuse-link which usually destroys also fuse-base.

The most common cause for fuse body breaking at short-circuits is inability of fuse body to withstand thermal shock that occurs during fuse-link operation. The most common causes for explosions of fuse-links are lack of sand (mostly in fuse-links of unknown origins), insufficient closing of contact caps (in case of cylindrical fuse-links contact cap could slide of the body due to internal pressure during operating causing blow out of arc between the contacts) and weak fuse-body (fuse body could not withstand the internal pressure that occurs during operation).

4. Conclusion

Power dissipation and temperature rise of fuse-links depends on many factors. The choice of fuse-base, open or closed, connecting conductors, use in 1-phase or 3-phase system are some of them.

All these factors influence operation of fuse-links also in case of overload and short-circuit currents causing possible defects and damage on fuse-bases and equipment. The correct choice of fuse-links and its quality also have impact on temperature rise and operation at overload and short-circuit currents. Greater quality of fuse-links means less chance for defects during operation.

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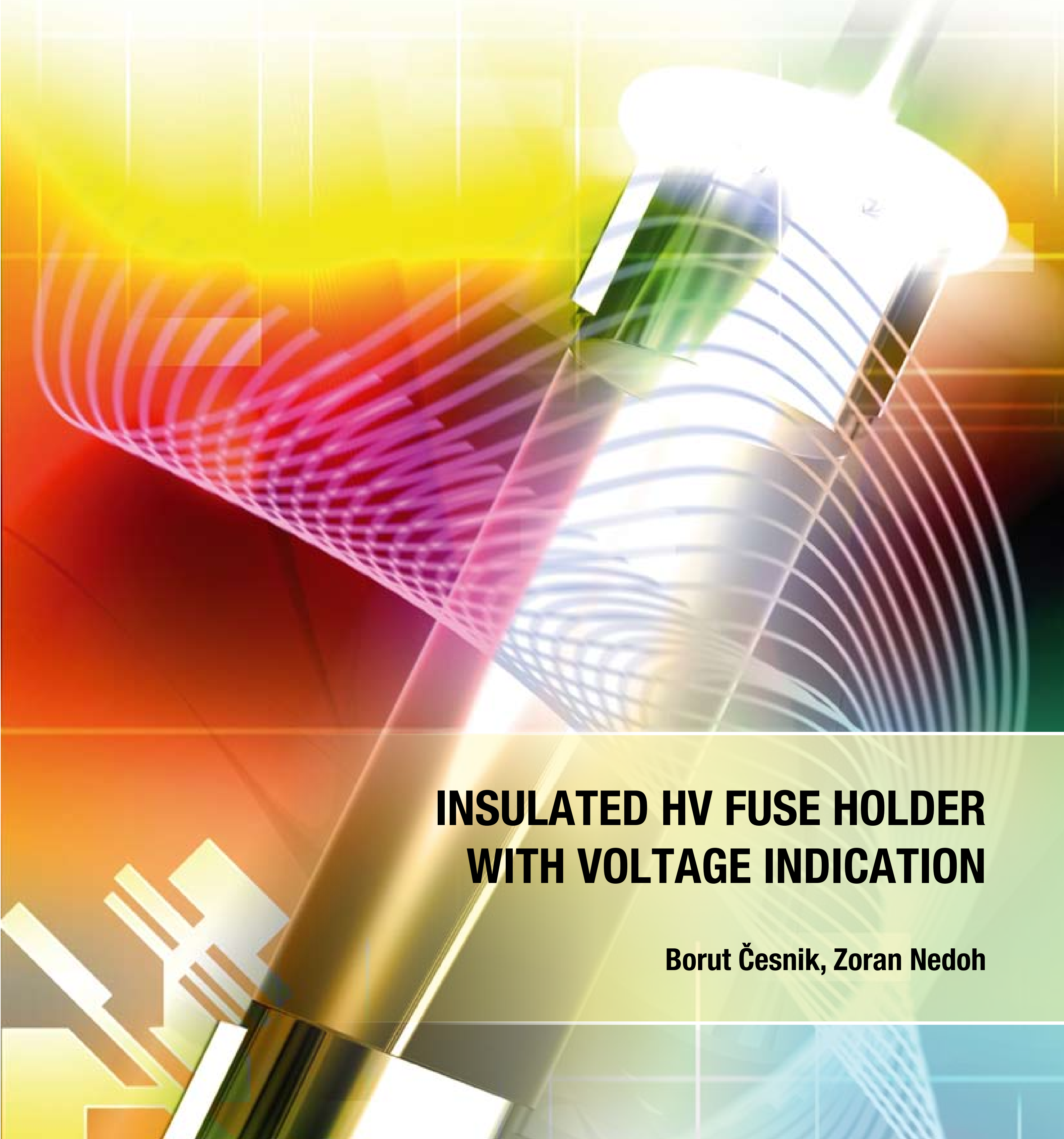

INSULATED HV FUSE HOLDER WITH VOLTAGE INDICATION

Borut Česnik, Zoran Nedoh

Insulated HV fuse holder with voltage indication

Borut Česnik(1), Zoran Nedoh(2)

(1) IMP-tentelekom, d.o.o., Vojkova cesta 58, 1000 Ljubljana, Slovenia, b.cesnik@imp-tentelekom.si
(2) TSN, d.o.o., Šentiljska cesta 49, 2000 Maribor, Slovenia, z.nedoh@tsn.si

Abstract

The most common protection of a power transformer in an end distribution transformer substation are MV fuses on proper fuse holder. Uninsulated parts are weak points of a transformer substation (danger of contact with live parts, wheather influences, little animals etc.). Insulated fuse housing type VOH allows the design of a transformer substation with a completely insulated 20 (10) kV part. Voltage indication offers an additional security to the operator. The fuse housing is manufactured out of high quality insulating material. The fuse holder is covered with earthed metal casing.

Keywords: electric fuse, insulated fuse holder, overvoltage.

1. Introduction

Protection of distribution transformers is often carried out with HRC HV fuses and switches. Distribution transformers of up to 160 kVA rated power are protected against short-circuit current with built-in HRC HV fuses. HV fuse is mounted to the fuse holder which is installed to the transformer. Fuse holder comes in various designs. Common to all fuse holders is that they are not insulated. The fuse itself is also not insulated.

At the mentioned designs of fuse holders exists danger of touching parts under high voltage and malfunction due to access of small animals.

New trends in manufacturing of distribution transformers dictate new designs of HV connection type plug-in.

As example: transformers type HTI3 from manufacturer ETRA33 has HV connections carried out through connector bushings. The construction of such connector allows new solutions which improves safety in transformer substations.

Solution to listed deficiencies is single pole insulated HV fuse holder – VOH.

2. Technical characteristics of VOH

Characteristics of single pole insulated HV fuse holder – VOH.

- Completely insulated design, which allows maintenance of substation without danger of touching parts under high voltage,
- Voltage indication in cable connector (VOH01),
- Electric signalization of fuse operating with possibility to install micro-switch for remote signal transfer of the fuse condition (VOH02),
- Use of standard HRC HV fuse,
- Installation of various designs directly on the transformer's cover,
- Simple manipulation respectively exchange of the fuse,
- Ready for usage on transformers with connector bushings (SIST EN 50181 – design with insulated cable connector),
- Ready for connection with cable connector (interface C-630 A-bolted T plug) according to SIST EN 50181 which also allows installation of surge arrester,
- It does not need any additional maintenance,
- Voltage indication on transformer bushing,
- Possibility of earthing without dismantling cable connector (head) on connection point of the holder

Figure 1: Insulated HV fuse holder VOH 01 (design by TSN) mounted on a transformer's cover (50 kVA).

Rated voltage of the fuse holder is 24 kV, but it can also be used for lower voltages. Rated current is 30 A. Fuse holder with rated current 100 A has a special design of contact connections.

On cable connector is a mechanical signalization of voltage indication (SIST EN 61958:2002; SIST EN 61243-5:2002).

Built-in voltage indicators type IN5 (design by TSN) allow local signalization of voltage indication on cable.

Voltage indicator IN5 (Figure 2) receives the signal from indication on the fixed part of the fuse holder.

The cable is earthed to the earthing screw on the construction. The whole device itself is earthed to the main earthing of the substation.

Figure 2: Voltage indication on VOH 01 carried out with IN5

In case of mounting voltage indicator IN6, an own power supply is necessary (<1W, 24-48V_{DC}; 90-220 $V_{DC,AC}$). This type allows remote signal transfer of presence respectively absence of voltage indication.

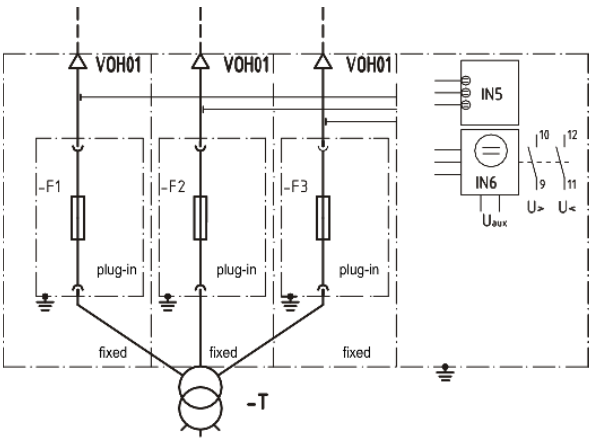

Figure 3: Schematic presentation of fuse holder function type VOH01

Fuse holder type VOH is designed for installation of standard HRC HV fuses with maximum diameter of insulation tube of 85 mm and length of insulation tube of 442 mm. Diameter of fuse connection is 45 mm.

Fuse holder design type VOH 2 is used when one wishes to know the fuse condition. VOH 2 is equipped with voltage indicator on cable connector as well on bushing connector on transformer.

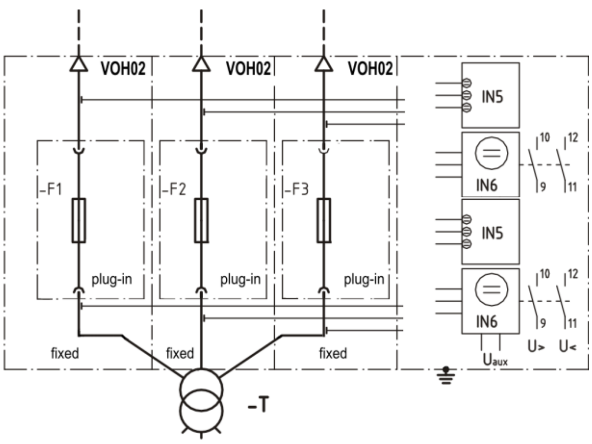

Figure 4: Schematic presentation of fuse holder function type VOH02

TABEL1
TECHNICAL DATA

Type	VOH01 (02)
Rated voltage	24 (12) kV
Rated power frequency withstand voltage	50 kV
Rated lightning impulse withstand voltage	125 kV
Rated current	30 (100) A
Rated peak withstand current	50 kA
Rated short time withstand current	20 kA
Protection degree (IEC 60529)	IP 54
Width	225 mm
Depth	270 mm
Height	725 mm
Fuse characteristics	
-Rated current	up to 100 A
-width of insulation tube	max. 85 mm
- length of insulation tube	442 mm
- diameter of the fuse connection	45 mm
- maximum length	512 mm

The Fuse holder is suitable for areas with polluted atmosphere and areas with danger of touching “live parts” that are under high voltage.

Therefore it perfectly matches for installation in prefabricated compact transformer substation with external manipulation. The exchange of fuses itself is very simple and easy.

3. Design of fuse holder VOH

The installation of fuse holder on the transformer is designed to assure all required electrical characteristics. Fuse holder type VOH consists out of fixed part, which is mounted on the transformer´s cover and withdrawable part, which contains a fuse (Figure 5).

Figure 5: Structure of fuse holder type VOH 01

Fixed part is made out of insulating epoxy resin. With a system of holder it is mounted on the transformer´s cover.

On the holders are earthing elements. When mounting the fuse holder, one presses out all the air between silicon insertion and insulating materials. The mechanical design assures a strong fixation and protects HV connections on transformer against damages.

Into the fixed part the withdrawable part is inserted. In the withdrawable part are jaws of the main withdrawable contacts and contacts which hold the fuse. The withdrawable contacts are designed for a burden of continuous current of 400 A. Because usage in closed housing which disables the air circulation a rated current 30 A (100 A) is defined.

All internal copper connections are over dimensioned to divert the heat as much as possible.

The withdrawable part is made out of insulation material and covered in a earthing metal cover (option). In the interior is a fuse, a system of withdrawable contacts and a silicon washer.

Figure 6: Detail of upper contacts

Figure 7: Fuse holder type VOH01 with elements for installation

Figure 8: Fuse holder type VOH01 with connection Type C (EN5018), bolted T-plug, and mounted surge arresters

4. Application

Single pole insulated fuse holder is designed for installation of HV HRC fuses for transformer protection. It is suitable for installation of HV HRC fuses up to 30 A, but a special design allow also an of HV HRC fuses of 100 A

Fuse holder type VOH is designed for installation on transformer of hermetical type with HV connectors 12(24) kV type plug-in up from 50 to 400 kVA rated power.

The holding construction allows assemblies on the transformer´s cover without reaching into the distribution transformer.

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Figure 9: Holding construction of fuse holder type VOH01

When choosing a type of a fuse holder following data must be specified: size and type of transformer (cover of transformer), voltage indication type (IN5, IN6) and indication design (VOH01, VOH02).

At the assembly of the fuse holder on the transformer´s cover we use the tighten screw to assure the right pressure to the silicon insertion, which is between holder and transformer´s bushing.

We fix the fuse holder to prevent movement when manipulating the withdrawable part. Otherwise damages on the fuse holder and transformer´s bushing can occur.

Figure 10: Silicon insertion, silicon lubricant and tube for silicon venting at installation onto the transformer´s bushing

The installation of the fixed part of the fuse holder on the transformer is now complete. The fuse is inserted into the withdrawable part (cover). The cover is put on the guide rails of the fixed part, then move forward to place the wihdrawable contacts. The final position is fixed with the locking handle.

The procedure is repeated for every phase. The exchange procedure is going backwards. After removing the withdrawable cover one can exchange the fuse outside of the transformer substation.

After the exchange we put the cover on the fixed part.

With this the device is ready for operation.

VOH allows a very simple earthing of the cable connector when operating.

The fixed part with the fuse is dismantled. With the earthing gear we connect to the screw M10 (Figure 9).

In this way we earth the cable without reaching into the cable head.

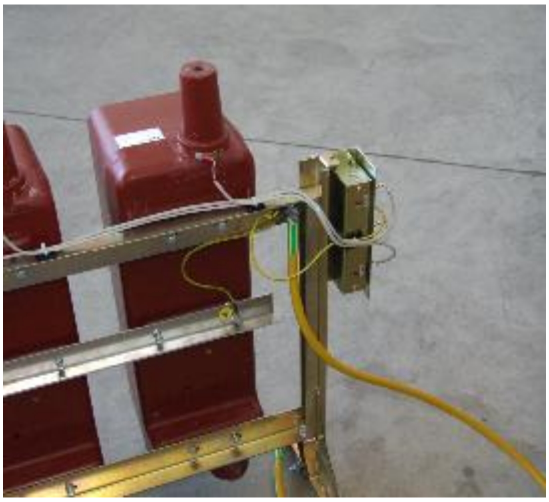

Figure 11: Screw M10 for cable earthing

Figure 13: Example of not insulated places in a transformer substation

Figure 12: Example of fuse holder type VOH 2 with two type of voltage indication.

Figure 14: An example of application of fuse holder type VOH1, which insulates the HV part in a transformer substation

5. Conclusion

After the installation of fuse holder type VOH the prefabricated compact transformer substation has a fully insulated HV part.

Due to the full insulation of voltage and current paths, there is no danger to come to a voltage breaktrough because of the creapage distances.

As example: power company Elektro Celje d.d. (data 2011) has around 55 pcs end transformer substations, where the distribution transformer is protected only by fuses.

The maintenance of the substations would decrease or even drop out by applying the fuse holder. At the same time the possibility of touching "live" parts under high voltage when working on LV side would fall away. The same goes for the HV side

The application of the fuses is the most common transformer protection against the consequences of higher values of primary current and short circuit. This kind of protection is simple, reliable and price affordable.

With application of the fuse holder type VOH we have integrated the traditional solution for transformer protection (HV HRC fuse) into the modern device concepts (transformer bushings). At the same time we have fulfill the required conditions which are stated by the regulations about safe work on the power supply devices.

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EVALUATION OF THE CONTRIBUTION IN ELECTRICITY LOSSES CAUSED BY THE HIGHER RATED VOLTAGE OF NV/NH FUSELINKS IN THE GREEK LOW VOLTAGE DISTRIBUTION NETWORK

Constantinos S. Psomopoulos, George C. Ioannidis, Yannis Karras

Evaluation of the contribution in electricity losses caused by the higher rated voltage of NV/NH fuselinks in the greek low voltage distribution network

Constantinos S. Psomopoulos(1), George C. Ioannidis(2), Yannis Karras(3)

(1) Technical Education Institute of Piraeus, Department of Electrical Engineering, High Voltage Lab, Thivon 250 & P. Ralli, GR-122 44 Egaleo, Greece, cpsomop@teipir.gr

(2) Technical Education Institute of Piraeus, Department of Electrical Engineering, Electrotechnical Applications Lab, Thivon 250 & P. Ralli, GR-122 44 Egaleo, Greece, gioan@teipir.gr

(3) Technical Department, ELMA N. Karras SA, 34a Averof str, GR-14232, N. Ionia, Greece, yannis.karras@elma.gr

Abstract

The Public Power Corporation (PPC), operator of the Greek low voltage electricity distribution network still does not accept LV NH fuses with rated voltage 400VAC which is the network’s nominal operating voltage. Based on a rather old internal standard (a PPC ‘s standard of 1975), PPC is using fuses with 500V AC rated voltage and rejects the fuses with 400V rated voltage. This work is aiming to evaluate the reduction of the low voltage network losses in case that PPC used fuses with rated voltage 400VAC instead of 500-690VAC. The evaluation was based on statistical data since there are no records about the actual number per size of installed fuses, or the average load per fuse. Even though the evaluation presents an uncertainty, the results showed that the electricity losses reduction is not negligible and the use of fuses with rated voltage of 400V instead of 500-690V will increase the network’s efficiency.

Keywords: high-breaking-capacity fuse links, fuses rated voltage, power dissipation, power distribution losses, efficiency in electricity distribution.

1. Introduction

Low voltage (LV) high-breaking-capacity (HRC or most commonly NH) fuse links are mainly used to protect the LV electrical installations of the LV electricity distribution networks, public and private, as well as a significant amount of LV electrical equipment used in industrial, commercial and residential facilities and infrastructures. Being a typical electric device, a fuse is consuming energy which is transformed into heat as long as current flows through its body [1-4]. This power consumption should not exceed specific values depending on the type and fuse's rated voltage, as per IEC 60269-2:2006 [5]. As it can be found in the technical data sheets, the higher the rated voltage is, the higher the fuses' power losses are. It is also true that the previous mentioned consumption or power dissipation, as it is also called, is also increased following the rated current of the fuse link [6-9].

Furthermore, since this consumption is converted into thermal energy, high temperatures are developed inside the IP54 or IP55 enclosures in which the fuses are installed. These high temperatures also affect other electrical equipment's operation in case they are installed in the same enclosure [1-4,5]. The aforementioned overheating problem, which also affects the fuses behaviour, was one of the reasons that electricity distribution companies, nowadays, prefer to use fuses with rated voltage equal to their network's rated voltage [2-4,8,10,11].

In Greece, the Public Power Corporation (PPC) which has the operation of the Greek low voltage electricity distribution network still does not accept LV NH fuses with rated voltage 400VAC which is the network's nominal operation value. Based on a rather old internal standard (a PPC 's standard of 1975), the PPC is using fuses with 500V AC rated voltage in the Greek network and rejects the fuses with 400V rated voltage [12].

In this paper an attempt is made to evaluate the reduction of the low voltage network losses in case that PPC uses fuses with rated voltage 400VAC instead of 500-690VAC. This evaluation was based on statistical data since there are no records about the actual number per size of installed fuses, or the average load per fuse. Even though the evaluation presents an uncertainty, the results showed that the electricity losses reduction is not negligible and the use of fuses with rated voltage of 400V instead of 500-690V will probably affect positively the network efficiency.

2. Electricity Losses in Distribution Networks

Total system losses are the difference between the energy purchased (or produced) and the energy delivered (or sold) to end users. Losses can come from two sources: 1) technical losses, those that result from the heating of conductors and coils and from the excitation of the windings of transformers and other devices, and 2) nontechnical losses, those associated with inadequate or missing revenue metering, with problems with billing and/or collection systems, and/or with consumer pilferage [11, 13-15].

There are two sources of technical losses: a) the load losses, consisting of the I^2R and I^2X losses in the series impedances of the various system elements (e.g., lines and transformers); when the system is unloaded (i.e., I=0), the load losses are obviously nonexistent and b) the no-load losses, which are independent of the actual load served by the system. The majority of the no-load losses are due to the transformer core losses resulting from the excitation current [3, 4, 10, 11, 14,15].

There are both capacity (or demand) losses and energy losses. Capacity losses contribute to the system peak load demand, while energy losses increase the electricity requirements of the system load. Both capacity and energy losses can be subdivided into their active and reactive elements [11,14,15].

Electricity networks allow many diverse points of demand to share access to many generators, thus reducing the cost of the overall system and increasing the security of supply [3,4]. However, an electricity network loses a proportion of the electrical energy passing through it before that energy can be delivered to customers. Energy losses are not measured directly, but calculated in their most simple definition as the difference between electrical energy entering and exiting (distributed by) the network [11, 14, 15].

Losses are a combination of physical technical losses (resistive and transformer losses) and commercial non-technical losses. The non-technical losses include theft and systematic errors in metering, settlements or billing. In some countries, the non-technical losses are likely to dominate the overall losses figure [11, 16]. Losses can be subdivided according to whether or not they depend on power flow. The 'iron' losses in transformers do not vary with power flow, so are considered 'fixed' for a given network. Non-technical losses are likely to be relatively insensitive to total power or energy demands, so can also be classed as 'fixed'. In contrast, the resistive losses vary as the square of the power flow. Thus, electricity transmission and distribution at peak periods lead to a higher loss of power, and over time contributed is proportionately to the variable component of energy losses [10,11]. Any strategy to reduce losses is an opportunity to reduce the environmental impact of the electricity supply system [10, 11, 16, 17].

Figure 1 presents the average transmission and distribution power losses components in European networks. These components include technical and non – technical losses, as these were described above [11].

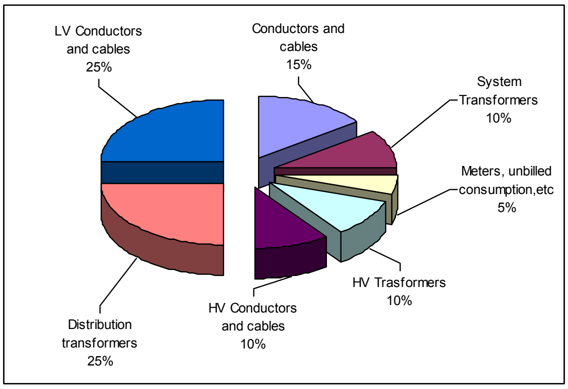

Fig. 1: Transmission and distribution power losses' components in European Networks (average estimations by MMA).

3. The Greek Distribution Network

According to Law 2773/1999, Public Power Corporation through the Distribution Unit constitutes the only power supplier in Greece while acts as the Operator of the Distribution Network. The Distribution Unit is responsible for the power distribution within the whole Greek territory, not only to the interconnected system area but also to the non-interconnected islands. The energy is received from the Transmission Network providing the possibility to supply all Network users with the energy needed [12].

The Greek distribution network is a typical European one. The main quantitative figures of Distribution network for the year 2009 were as follows [12]:

- 7,554,289 Customers (9,772 MV - 7,544,517 LV)
- 47,186 GWh consumptions (11,725 in MV and 35,461 in LV). High voltage consumptions and network leakages are not included.
- 104,415 km Medium Voltage Network (M.V.),
- 117,657 km Low Voltage Network (L.V.)
- Total 227,072 km of Network
- Annual increase of network length up to 1.87%, that is, 4,074 km of Network.
- 149,178 MV/LV Substations Annual increase of 2.23%, that is, 3,254 of new Substations
- 205 km of HV Network and 14 HV/MV Substations in Attica.

Table 1 presents the quantities of transformers used per type of substations in Greece according to 2009 inventory data of PPC. Table 2 shows the number of feeders per size of transformer used by PPC-Distribution Unit, as these were standardized by their internal orders. Depending on the feeding loads the number of feeders could be different than the ones shown on Table 2 [12].

Table 1. Transformers' quantities installed in MV/LV substations in 2009, per substation type.

Transformers in outdoor substations installed over poles (one or two poles)		**Transformers in other type substations (compact type, indoor installed, or installed in ground level)**	
Rated Power (kVA)	**Quantity (pcs)**	**Rated Power (kVA)**	**Quantity (pcs)**
15	38	15	1
25	2,427	25	0
50	38,228	50	8
75	4,291	75	1
100	34,528	100	3
150	3,962	150	1
160	27,394	160	6
200	363	200	2
250	20,000	250	42
300	1	300	10
400	8,630	400	171
500	95	500	206

600	5	600	445
630	1,933	630	6,468
750	0	750	25
1000	10	1000	1,010
20,527,800	141,905	5,557,790	8,399

Table 2. Standardized number of feeders per transformers' size used by PPC-Distribution Unit.

Rated Power (kVA)	Standard number of feeders
15 ÷ 25	1
50	3
75	2 or 4
100	2 or 4
150 or 160*	4
250*	4
400*	6
630*	8
1000	12

* : The rated power values of 200kVA, 500kVA, 600kVA and 750kVA, corresponds to existing transformers on the distribution network. These units are old (over 10 years), while in the new order PPC – Distribution Unit orders standard sizes: 160kVA, 250kVA, 400kVA, 630kVA and 1000kVA.

Figure 2 presents a typical low voltage panel configuration used in the Greek Distribution Network. Typically the low voltage panels of every MV/LV substation, constitutes of a number of 3phase LV feeders protected by High Breaking Capacity fuses (NH-fuses). The usual configuration includes one main switching device for protection of the main panel and an odd number of feeders, five or seven most commonly, with rated currents of 160A, 250A, 315A, 400A usually [10,12].

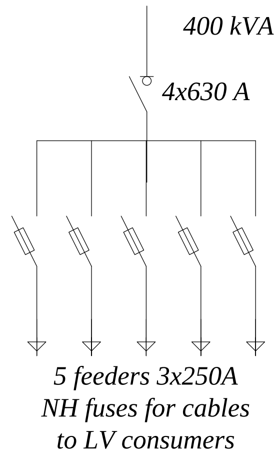

Fig. 2: Typical low voltage panel configuration used by Distribution Unit of PPC (400kVA transformer, 1 3ph disconnector of 630A, 5 3ph rail type fuse-disconnectors of 250A).

Table 3. NH Fuses' quantities used by PPC-Distribution Unit for 3 years (2007 to 2009)

NH Fuses	Quantities used in the years 2007-2009
size 1 63A	12,000
size 1 80A	38,000
size 2 63A	21,000
size 2 80A	18,000
size 2 100A	91,000
size 2 125A	88,000
size 2 160A	76,000
size 2 200A	53,000
size 2 250A	111,000
size 2 315A	24,000
size 2 400A	3,600

The most common magnitude of NH fuses used by PPC-Distribution Unit are "size 2" 250A/500V, 100A/500V, 125A/500V and 150A/500V. Table 3 presents the quantities used by PPC-Distribution Unit for 3 years (2007 to 2009), during scheduled maintenance procedures or after short-circuits. These data was given by the commercial department of ELMA N. Karras S.A. for the aforementioned years.

Figure 3 presents the transmission and distribution losses in Greece, over the last years, and figure 4 the losses as a percentage of the final electricity consumption. As it can be seen, the network losses are increasing through out the years, following the increment of power consumption. It can also be noted that these losses are decreasing in the last three years [16].

In recent years the network's losses seem to become stable around 8% which is close to the EU – 15 mean value of 7%. One important reason is that the main power production units of Greece are lignite fired plants (over 45% the last years, over 60% 15 years ago), and are located near by the existing lignite fields. These fields are located in two areas, one north, in Western Macedonia, where the major lignite mines are operating and one in the south, in Megalopoli – Peloponnese, where the other big lignite mine is operating [12,16].

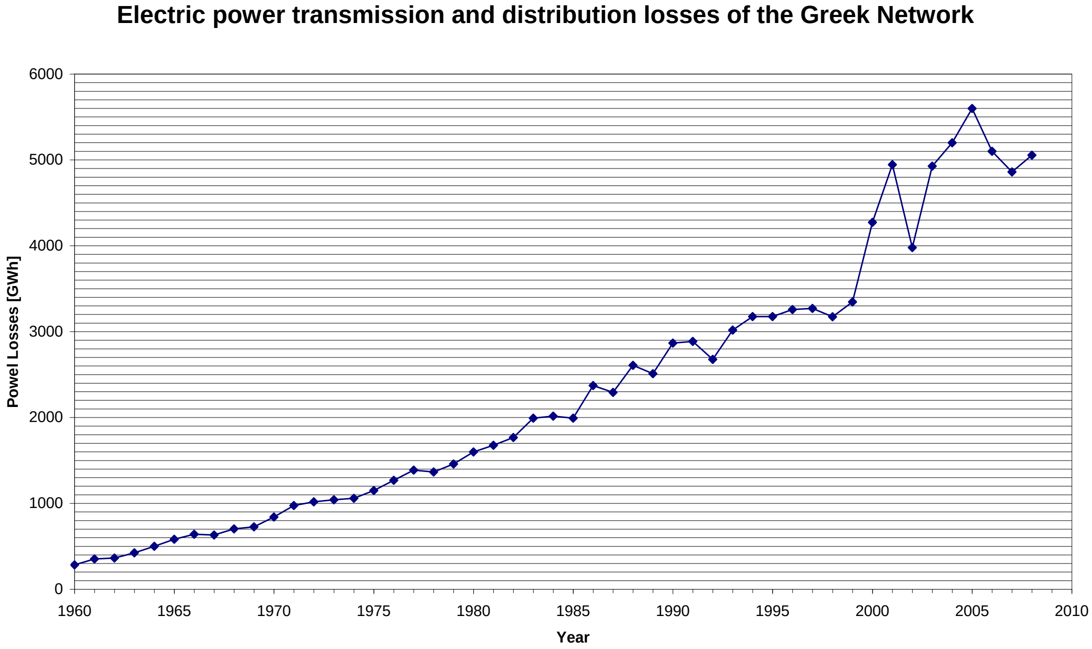

Fig. 3: Transmission and distribution losses of the Greek network for the last fifty years' period.

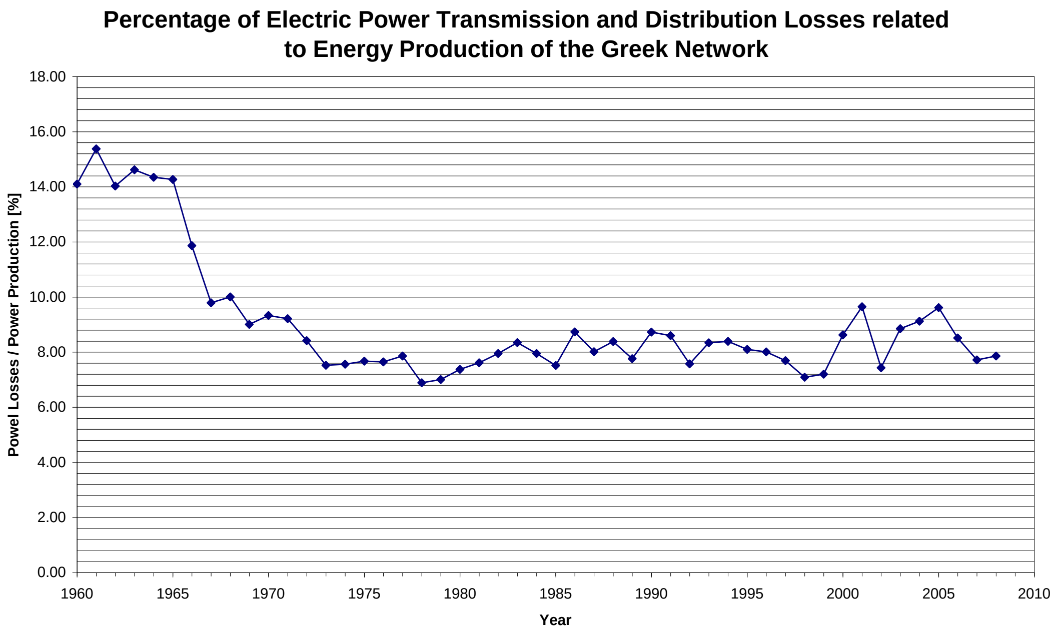

Fig. 4: Transmission and distribution losses of the Greek network as a percentage of the electricity production by for the last fifty years' period.

4. NH-fuses Power Dissipation Evaluation

Fuse, like any other overcurrent protective device, is installed in a circuit and it is flown by the circuit's current. The fuse-elements usually consist of metallic strips with restrictions that melt by electric heat at a certain current value [1,2]. It is obvious that the fuse-element presents electric resistance and hence Joule heating when a current flow through it. Fuse operation is based on a defined temperature rise and melting of the fuse-element by electric heat. The heating process requires electric energy that will be dissipated to the environment [1,2,9, 18-21]

This energy is considered as power loss and is included in the low voltage distribution network, by network operators. This power loss is non-metered energy, but on the other hand is a physical necessity for the fuse operation, and the fuse design engineers have to balance the speed of current interruption against power losses under normal load and design parameters [2,9,19,20]. The common used term "power dissipation" describes fuses power losses under nominal loads [2,9].

Table 4. NH Fuses' maximum permissible "power dissipation" according to IEC60269-2:2006

gG						
Size	400 V a.c.		500 V a.c.		690 V a.c.	
	In A	Pn W	In A	Pn W	In A	Pn W
000	100	5.5	100	7.5	63	12
00	160	12	160	12	100	12
0	160	12	160	16	100	25
1	250	18	250	23	200	32
2	400	28	400	34	315	45
3	630	40	630	48	500	60
4	-	-	1000	90	800	90
4a	1250	90	1250	110	1000	110

The international standards and mainly the IEC60269-2:2006 determine the maximum permitted values of the rated "power dissipation P_n per size and nominal current value. For the "gG" fuses, which are the most common ones in the distribution networks, table 4 present these maximum values for selected sizes and nominal current values [5]. As it can be seen this values could be considered small ones for a single fuse. Furthermore, considering that most of the time the current flow is small comparing to the nominal one, it can be easily concluded that this consumption is usually very small, and occasionally reaches zero (when the circuit 's current is zero) [1,2]. But considering the number of the installed fuses this small consumption seems that should not be neglected. In following paragraphs this will be proven and the current flowing through the fuse will be also considered.

For the evaluation of the power dissipation of the fuses under lower current flow, the following equation could be considered, based on the existing literature [3,4,10]:

$$P = P_n \left(\frac{I_b}{I_n} \right)^2 \quad (1)$$

where :

P is the actual power loss;
P_n is the rated power loss (at I_r)
I_b is the actual current
I_r is the rated current

Based on this equation, figure 5 presents the power losses versus the actual current for two selected fuse cases. Table 5 presents the values of power dissipation as these are presented in the official data sheets of fuse manufacturers. As it can be seen, the power dissipation of fuses is increasing as the nominal operating voltage is increasing. For the lower nominal current and the small sizes these differences are very small, but as the nominal current or the size is increased the difference is increasing significantly [6,7].

Table 5. NH Fuses' "power dissipation" (data from a fuse manufacturer) for the fuses used by PPC – Distribution Unit.

Size	In (A)	400V Pn (W)	500V Pn (W)	690V Pn (W)
1	63	5.1	5.5	6.9
1	80	5.4	7.2	8.9
2	63	5.7	5.5	6.88
2	80	6.4	7.1	8.91
2	100	7.6	8.1	10.5
2	125	8.7	9.5	12.7
2	160	12.3	14.9	15.3
2	200	13.5	16.9	18.5

2	250	17.6	21.8	23.3
2	315	21.9	23.7	29.5
2	400	26.3	30.5	38.2

Based on the above figures, the power losses of the fuses in the electrical network have a wide variation depending on the nominal operating voltage, the load and the number of fuses installed. For the case under examination, since there are no records available to make accurate calculations, the evaluation of the magnitude of power losses will be estimated based on the following considerations:

1. The volume of fuses installed in the Greek distribution network will be estimated using the combination of the data presented in Tables 1 and 2, considering the lowest values. These results can be seen in table 6.
2. The volume of fuses per size and rated current can be estimated considering the data presented in Table 3. These results are presented in table 7.

Table 6. Evaluation of the NH Fuses' installed in the Greek Distribution Network.

Transformers installed in the Greek Distribution Network		**Circuits Feed by Fuses**	
Rated Power (kVA)	**Quantity (pcs)**	**Number of 3 phase Circuits per Transformer**	**Fuses Quantity (pcs)**
15	39	1	117
25	2,427	1	7,281
50	38,236	3	344,124
75	4,292	3	38,628
100	34,531	3	310,779
150	3,963	4	47,556
160	27,400	4	328,800
200	365	4	4,380
250	20,042	4	240,504
300	11	4	132
400	8,801	6	158,418
500	301	6	5,418
600	450	8	10,800
630	8,401	8	201,624
750	25	8	600
1000	1,020	12	36,720
26,085,590	150,304		1,735,881

Since there are no records for the actual current flowing from each 3 phase feeder protected by fuses, the evaluation of these increased losses will be done based on the estimations of table 7, considering the number of fuses per size and rated current installed in the Greek Distribution Network, and typical values for average load factor of the Network. The average load factor multiplied with the rated current will be considered as the actual current flowing through the fuse. This value will be used in the equation (1) in order to evaluate the power dissipation of each fuse for the cases of fuses with rated voltage 400V and 500V. The power dissipation value under rated current was the one mentioned in Table 5. The results of the evaluation can be seen in tables 8, 9 and 10, for average load factors m=0.30, m=0.45 and m=0.65 respectively.

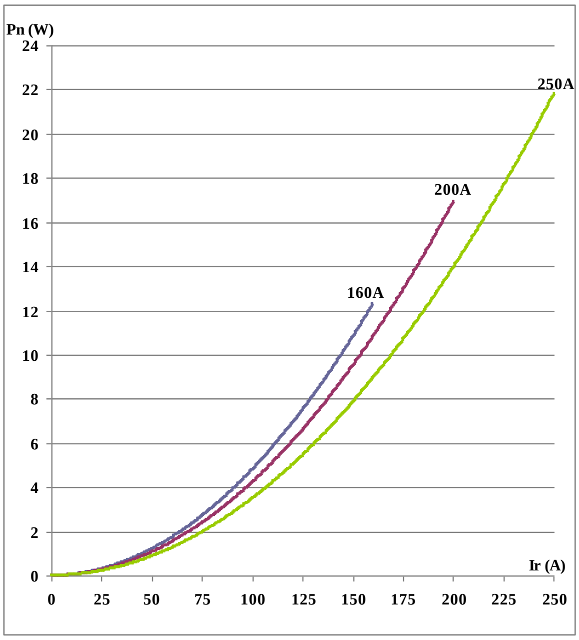

Fig. 5: NH-Fuses power dissipation related to the actual current, for rated current 160A, 200A, 250A.

Table 7. Evaluation of the NH Fuses' installed in the Greek Distribution Network per size and rated current.

NH Fuses	**Quantities per size and rated current**
size 1 63A	38,892

size 1 80A	123,158
size 2 63A	68,061
size 2 80A	58,338
size 2 100A	294,931
size 2 125A	285,208
size 2 160A	246,316
size 2 200A	171,773
size 2 250A	359,751
size 2 315A	77,784
size 2 400A	11,668

Table 8. Evaluation of the increment of the power losses due to higher nominal voltage of NH Fuses' installed in the Greek Distribution Network per size and rated current, for average load factor m=0.30.

Size	In (A)	m=0.30 Ir (A)	400V Pn (W)	500V Pn (W)	ΔPn (W)	ΣΔPn (kW)
1	63	18.9	0.46	0.50	0.04	1.40
1	80	24.0	0.49	0.65	0.16	19.95
2	63	18.9	0.51	0.50	-0.02	-1.23
2	80	24.0	0.58	0.64	0.06	3.68
2	100	30.0	0.68	0.73	0.05	13.27
2	125	37.5	0.78	0.86	0.07	20.53
2	160	48.0	1.11	1.34	0.23	57.64
2	200	60.0	1.22	1.52	0.31	52.56
2	250	75.0	1.58	1.96	0.38	135.99
2	315	94.5	1.97	2.13	0.16	12.60
2	400	120.0	2.37	2.75	0.38	4.41
Total NH-fuses Increment in Power Dissipation with load factor m=0.30						***320.81***

Table 9. Evaluation of the increment of the power losses due to higher nominal voltage of NH Fuses' installed in the Greek Distribution Network per size and rated current, for average load factor m=0.45.

Size	In (A)	m=0.45 Ir (A)	400V Pn (W)	500V Pn (W)	ΔPn (W)	ΣΔPn (kW)
1	63	28.35	1.03	1.11	0.08	3.15
1	80	36.00	1.09	1.46	0.36	44.89
2	63	28.35	1.15	1.11	-0.04	-2.76
2	80	36.00	1.30	1.44	0.14	8.27
2	100	45.00	1.54	1.64	0.10	29.86
2	125	56.25	1.76	1.92	0.16	46.20
2	160	72.00	2.49	3.02	0.53	129.69
2	200	90.00	2.73	3.42	0.69	118.27
2	250	112.50	3.56	4.41	0.85	305.97
2	315	141.75	4.43	4.80	0.36	28.35
2	400	180.00	5.33	6.18	0.85	9.92
Total NH-fuses Increment in Power Dissipation with load factor m=0.45						***721.82***

As it can bee seen from these tables the increment in the distribution losses cannot be neglected even in small network loads, like the ones represented by an average load factor m=0.30. In that case the distribution network losses are increased by 320.81kW and if a higher average load factor is considered, such as m=0.45, then these losses are increased significantly to 721.82kW. If the average load factor is even higher, like m=0.65, then the increment is higher reaching 1506kW. These differences correspond to significant power losses if the operating hours under these conditions are included in the calculations. The resulting values for the energy losses are as follows:

- m=0.30, ΔPn=320.81kW and energy losses E=320.81kW x 8760h = 2.81GWh
- m=0.45, ΔPn=721.82kW and energy losses E=721.82kW x 8760h = 6.32GWh
- m=0.65, ΔPn=1506.01kW and energy losses E=1506.01kW x 8760h = 13.19GWh

Table 10. Evaluation of the increment of the power losses due to higher nominal voltage of NH Fuses' installed in the Greek Distribution Network per size and rated current, for average load factor m=0.65.

Size	In (A)	m=0.65 Ir (A)	400V Pn (W)	500V Pn (W)	ΔPn (W)	ΣΔPn (kW)
1	63	40.95	2.15	2.32	0.17	6.57
1	80	52.00	2.28	3.04	0.76	93.66
2	63	40.95	2.41	2.32	-0.08	-5.75
2	80	52.00	2.70	3.00	0.30	17.25
2	100	65.00	3.21	3.42	0.21	62.30
2	125	81.25	3.68	4.01	0.34	96.40

2	160	104.00	5.20	6.30	1.10	270.58
2	200	130.00	5.70	7.14	1.44	246.75
2	250	162.50	7.44	9.21	1.77	638.38
2	315	204.75	9.25	10.01	0.76	59.15
2	400	260.00	11.11	12.89	1.77	20.70
Total NH-fuses Increment in Power Dissipation with load factor m=0.65						***1506.01***

The results even though present inaccuracy due to the lack of measured values of the loading curves for each feeder in the low voltage distribution network of Greece, clearly show that the procurement policy followed by the PPC – Distribution Unit for the NH-fuses, correspond to higher power losses which cannot be neglected. It is rather obvious that the PPC-Distribution Unit should replace the old internal PPC standard No 75, which rejects fuses with rated voltage of 400V, and replace gradually all installed fuses with rated voltage of 500V and 690V with new ones having 400V rated voltage in order to reduce the distribution network's losses and increase its efficiency. In this way, as it has already been stated before, the equipment installed in the same panels with fuses will suffer less thermal stress as the NH-fuses will produce less thermal power. This will affect positively the operation of the whole equipment installed in the panel and reduced consequently the faults related to thermal stress. Furthermore, as it is well known, the life expectancy of the equipment and especially the insulations will not be reduced.

5. Conclusions

In this paper the potentially reduction of power losses in the Greek low voltage distribution network is explored. Fuses due to their operating characteristics present power losses widely known as "power dissipation". One important parameter that affects the volume of losses is the rated voltage. The higher the operating voltage is the higher the losses are. The low voltage power distribution network and especially the distribution power lines is the main application of NH fuses. In every distribution network several hundreds of thousands NH-fuses are installed and operating continuously. In Greece, the PPC utilizes 500 V or even 690V fuses for the 400V low voltage network, rejecting the 400V counterparts according to an old internal standard. This practise is directly related with increased power losses as it can be seen from presented results. Due to lack of accurate data concerning the actual number per size of installed fuses and the average load per fuse, the analysis is based on statistical data. Although this approach is not very accurate, shows clearly that the power losses of the low voltage distribution network can be sufficiently reduced and thus improving its capacity. Therefore, it is suggested that the Distribution Unit of PPC should reject its old internal standard and proceed as the other Electric Power Distribution Companies in EU Member States to accept and widely utilise NH-fuses with rated voltage of 400V.

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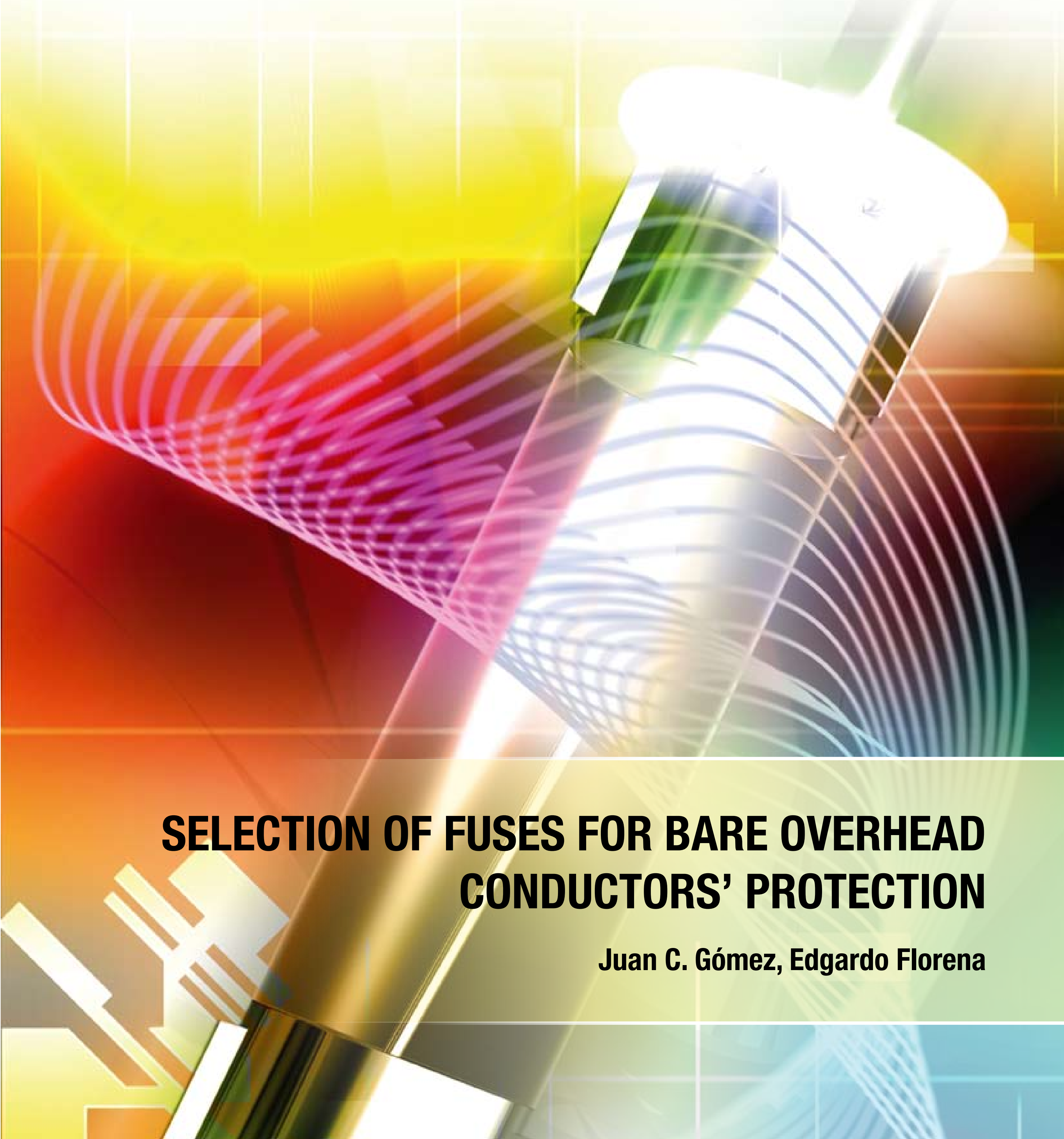

SELECTION OF FUSES FOR BARE OVERHEAD CONDUCTORS' PROTECTION

Juan C. Gómez, Edgardo Florena

Selection of fuses for bare overhead conductors' protection

Juan C. Gómez, Edgardo Florena

IPSEP, Rio Cuarto National University, Argentine, jcgomez@ing.unrc.edu.ar

Abstract

One of the most widespread applications of fuses in medium voltage distribution systems is the overhead lines protection, but unfortunately and very frequently the people on charge of the fuse selection leave aside important facts of the protection. Usually the fuse is selected taking into account only the selective coordination with other up-stream and down-stream protective devices. Due to this procedure, really the overhead line is not protected against its main problem, the overheating. This over-heating is the cause of the two bare overhead conductors application limits, a. the mechanical strength weakening (annealing), and b. the minimum distance to earth (maximum sag). The paper firstly presents a summarized study of the thermal behavior of bare overhead conductors, under steady-state condition and also for transient conditions after a step change in current, analyzing the heat losses and gains, due to conduction, radiation, convection, overcurrent flow, sun effect, etc. The conductor over-temperature for steady-state conditions can be easily assessed by using a simple exponential equation, after doing two o three iterative temperature estimations and the corresponding recalculations. This analysis allows the determination of the conductor rated current, based on the maximum steady-state temperature normally recommended by the conductor manufacturers. The relationship between the conductor temperature and conductor lengthening and thus sag, is shortly explained. The general equation for transient condition after a current jump is given, explaining the temperature dependence of part of its terms and the difficulties for finding the accurate solution. A simplified solution by linearizing the non-linear equation terms is proposed, which is of easy application and also allows determining for each current value the time needed to reach the limit temperature. With the described methodology a time-current characteristic for the conductor could be draw which can be directly compared with the fuse characteristic in order to assess the protected and not-protected zones. By applying the cooling equation, the over-temperature as time function was assessed, in order to calculate the useful life lost and the conductor creep. This simple methodology allows a more rational fuse selection for the bare overhead conductor protection.

Keywords: overhead conductor, conductor ampacity, conductor sag, alloy annealing, medium voltage fuses, expulsion fuses.

1. Introduction

One of the most widespread applications of fuses in medium voltage distribution systems is the overhead lines protection, but unfortunately and very frequently the people on charge of the fuse selection leave aside important facts of the protection. Usually the fuse is selected taking into account only the selective coordination with other up-stream and down-stream protective devices.

The more used fuse for this application is the expulsion type, which due to its operation principle have the particularities of not being current limiter (low breaking capacity) and its overload protection is not accumulative on time due to the lack of M effect [1].

Elsewhere a thermal model designed for this type of fuse has been presented which has been successfully applied during many years exclusively to the coordination of expulsion fuses and reclosers [2].

Frequently, the fuse protective task is left aside or forgotten. The fuse must protect the overhead conductor against overloads and short-circuits. The overcurrents cause two phenomena, thermal and electro-dynamical stresses, which are the origin of conductor overheating and conductor movement that for the last phenomenon could produce a new up-stream short-circuit.

Due to electro-dynamical forces the conductors can slap together violently and traveling waves moving longitudinally along the line can be also generated. Experience and testing have shown that this action is not damaging to the mechanical strength of conductors or insulators, but it must be carefully considered in the design and selection of spacers and dampers [3]. Thus, if the conductor distances have been properly considered during the line design and construction, the only remaining aspect to be take into account is the overheating; besides, in the medium voltage distribution systems where expulsion fuses are used short-circuit currents are of low magnitude as to produce significant conductor movements or displacement.

The conductor overheating determines the maximum temperature limit that will cause damaging annealing or excessive conductor sag (violating the minimum conductor – earth distance).

There are numerous antecedents of complex studies over bare conductors, for fundamentally determine their ampacity based on the actual current, solar radiation and wind speed and wind direction. The objective of such studies is the determination of the conditions of maximum current capacity to allow the system operator of taking suitable operating decisions. These studies can extend from permanent régime to transients (including short circuits) [4].

The ampacity factors such as current, wind characteristics and solar radiation can be measured, by using expensive and complex equipment in order to extend ampacity of transmission lines, but due to its cost it is not usually applicable to distribution lines protected by expulsion fuses [5].

The conductor, depending of the conductor type, is named:

- AAC All Aluminum Conductor
- ACSR Aluminum Conductor Steel Reinforced
- ACAR Aluminum Conductor Alloy Reinforced

Due to this erroneous procedure of studying only the selective coordination and not the conductor protection, really the overhead line is not protected against its main problem, the overheating. This overheating is the cause of the two bare overhead conductors application limits, a. the mechanical strength weakening (annealing), and b. the minimum distance to earth (maximum sag).

2. Conductor temperature limits

Firstly, it is necessary to present some very important definitions related to overhead conductor applications [3]:

Thermal Limit (as associated with steady-state overload conditions): The maximum temperature at which a conductor can operate continuously yet maintain the minimum tensile properties established by the manufacturer or the user.

Fault-Current Burndown: Failure caused by overheating as a result of a current overload. The conductor strength decreases sufficiently to cause tension failure.

For the present study it is necessary to consider the worst load and ambient conditions as well for the conductor as for the fuse, taking into account pre-load, ambient temperature, sun radiation and wind speed.

The ampacity information generally applies to steady-state normal operation for bare ACSR and all-aluminum conductors for temperatures up to 100ºC (60ºC rise over 40ºC ambient). Each country has its own regulations about critical conditions related to temperature, sun radiation, wind speed, ice covering, etc. This temperature, 100 °C is frequently adopted since the aluminum conductor strands retain approximately 90 percent of rated strength after 10,000 hours at this temperature. For ACSR the strength is even less affected because the steel core is essentially unaffected at these temperatures [3].

2.1. Temperature limit based on mechanical strength weakening (annealing)

- *Under emergency conditions*

The question of what maximum conductor temperatures should be permitted for emergency operation depends on how much loss of strength is allowable and how long the emergency-load temperature continues. The effect of heating is cumulative. As an example, if a conductor is heated under emergency loading for ten hours each year for a period of ten years, the total effect is nearly the same as heating the conductor continuously at that temperature for 100 hours [3].

As explained, the loss of conductor strength due to time at temperature is a cumulative effect, thus heating due to short circuit occurrence should therefore be added to heating due to other circumstances to estimate the condition of the conductor. In actual practice, however, the total time of fault currents is usually very small relative to emergency operating time and is therefore ignored as an effect on conductor strength. A typical practice is to limit emergency load temperatures to a maximum of 125ºC.

The temperature-time strength loss relationship is elsewhere covered in more detail [6].

Figure 1 delineates the effect of time on a type of aluminum conductor strand strength at three temperatures which are of interest to power engineers [3]. The curves permit estimates the change in strength of conductors which have carried emergency overloads.

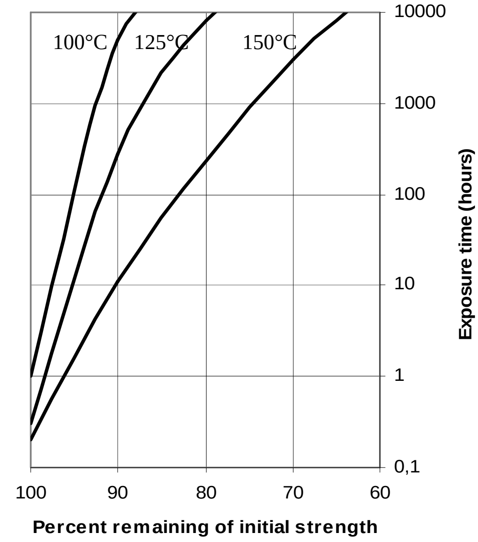

Fig. 1: Time-temperature percent strength remaining (tensile tests made at room temperature after wire exposure to the given temperatures) [3].

- *Under overload and short-circuit conditions*

In establishing suitable fault-current limits, 340ºC has been selected as the maximum temperature for all-aluminum conductors since momentary exposure to this temperature does not result in a significant loss of strength. For ACSR or AWAC conductors with sizeable steel content an upper limit of 645ºC represents the threshold of melting for aluminum with the steel expected to supply the needed mechanical strength [3].

The curves of Figure 2 and 3 apply this criterion to typical bare conductors, using an average specific heat and assuming no heat loss from the aluminum strands during the short duration of the fault current, for 340ºC and 645ºC limits respectively [3].

There are conditions where a lower temperature, limit could be advisable, such as when the bare cable is confined in switchgear or in switching compartments. Other condition such as the use of soldered, copper terminal pads; also may warrant a lower temperature limit.

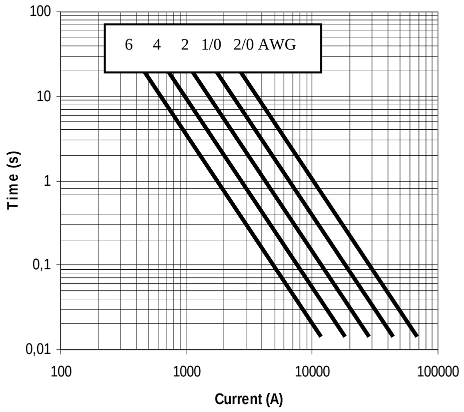

Fig. 2: Maximum fault-current operating limit for stranded aluminum conductor, Upper temperature limit 340°C, ambient temperature 40°C. Note: Time plotted is that required for a given rms fault current to cause conductor damage due to annealing [3].

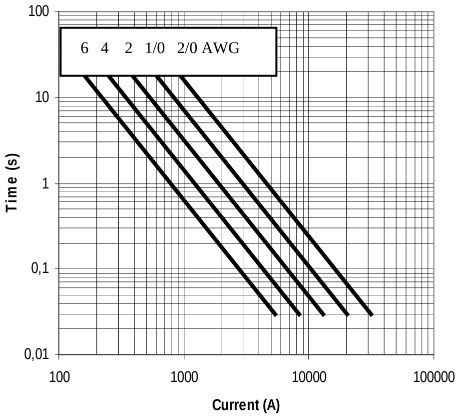

Fig. 3: Maximum fault-current operating limit for stranded aluminum conductor, Upper temperature limit 645ºC, ambient temperature 40°C. Note: Time plotted is that required for a given rms fault current to bring aluminum strands to the threshold of melting [3].

While arcing failure times are so short that little if any change in tension can occur prior to failure, high fault currents can heat the entire line. With modern relaying, the duration of the 60 Hz fault current is usually only from 3 to 20 cycles for transmission circuits but may be longer for distribution lines protected by expulsion fuses.

The resulting increase in sag can establish contact with ground or other conductor, initiating an arcing problem. Clearances can, therefore, be as significant a constraint on maximum acceptable current as is conductor strength.

2.2. Temperature limits based on the minimum distance to ground (maximum sag).

The energized conductors of distribution lines must be placed to totally eliminate the possibility of injury to people. Overhead conductors, however, elongate with time, temperature, and tension, thereby changing their original positions after installation. Despite the effects of weather and loading on a line, the conductors must remain at safe distances from buildings, objects, and people or vehicles passing beneath the line at all times. To ensure this safety, the shape of the terrain along the right-of-way, the height and lateral position of the conductor support points, and the position of the conductor between support points under all wind, ice, and temperature conditions must be known.

Bare overhead transmission or distribution conductors are typically quite flexible and uniform in weight along their length. Because of these characteristics, they take the form of a catenary between support points. The shape of the catenary changes with conductor temperature, ice and wind loading, and also is time function [7].

To ensure adequate vertical and horizontal clearance under all weather and electrical loadings, and to ensure that the breaking strength of the conductor is not exceeded, the behavior of the conductor catenary under all conditions must be known before the line is designed. The future behavior of the conductor is determined through calculations commonly referred to as “sag-tension calculations”.

Sag-tension calculations predict the behavior of conductors based on recommended tension limits under varying loading conditions. These tension limits specify certain percentages of the conductor’s rated breaking strength that are not to be exceeded upon installation or during the life of the line. These conditions, along with the elastic and permanent elongation properties of the conductor, provide the basis for the determination of the amount of resulting sag during installation and long-term operation of the line.

Besides, not all the line spans have the same mechanical tension, neither length nor geographical direction, thus there are too much uncertainties for the precise study.

Accurately determined initial sag limits are essential in the line design process. Final sags and tensions depend on initial installed sags and tensions and on proper handling during installation. The final sag shape of conductors is used to select support point heights and span lengths so that the minimum clearances will be maintained over the life of the line. If the conductor is damaged or the initial sags are incorrect, the line clearances may be violated or the conductor may break during heavy ice or wind loadings.

- *Catenary conductors*

A bare-stranded overhead conductor is normally held clear of objects, people, and other conductors by periodic attachment to insulators. The elevation differences between the supporting structures affect the shape of the conductor catenary. The catenary's shape has a distinct effect on the sag and tension of the conductor, and therefore, must be determined using well-defined mathematical equations.

For level span, the shape of a catenary is a function of the conductor weight per unit length, w, the horizontal component of tension, H, span length, S, and the maximum sag of the conductor, D.

Conductor sag and span length are illustrated in Figure 4, for a level span.

The exact catenary equation uses hyperbolic functions. Relative to the low point of the catenary curve shown in Figure 4, the height of the conductor, y(x), above this low point is given by the following equation (1):

$$y(x)=\frac{H}{w}\cosh\left(\left(\frac{w}{H}x\right)-1\right)=\frac{w(x^2)}{2H} \quad (1)$$

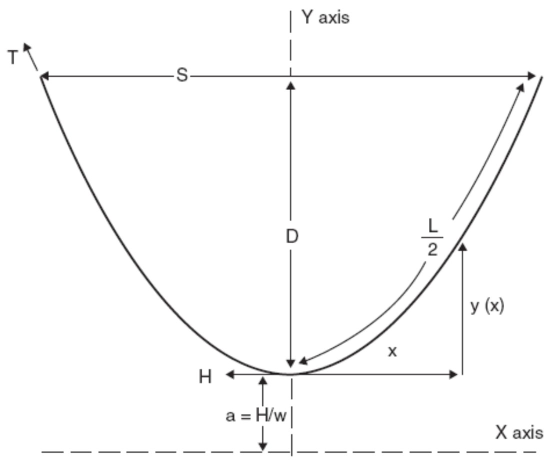

Fig. 4: Catenary curve for level spans.

For a level span, the low point is in the center, and the sag, D, is found by substituting x=S/2 in the preceding equations. The exact and approximate parabolic equations for sag become the following:

$$D=\frac{H}{w}\left(\cosh\left(\frac{wS}{2H}\right)-1\right)=\frac{w(S^2)}{8H} \quad (2)$$

Doing some changes into the catenary equation it allows the calculation of the conductor length, L(x), measured along the conductor from the low point of the catenary in either direction.

The resulting equation becomes:

$$L(x)=\frac{H}{w}\sinh\left(\frac{wx}{H}\right)=x\left(1+\frac{x^2(w^2)}{6H^2}\right) \quad (3)$$

For a level span, the conductor length corresponding to x=S/2 is half of the total conductor length and the total length, L, is:

$$L=\left(\frac{2H}{w}\right)\sinh\left(\frac{Sw}{2H}\right)=S\left(1+\frac{S^2(w^2)}{24H^2}\right) \quad (4)$$

The parabolic equation for conductor length can also be expressed as a function of sag, D, by substitution of the sag parabolic equation, giving:

$$L=S+\frac{8D^2}{3S} \quad (5)$$

The difference between the conductor length, L, and the span length, S, is called slack. The parabolic equations for slack may be found by combining the preceding parabolic equations for conductor length, L, and sag, D:

$$L-S=S^3\left(\frac{w^2}{24H^2}\right)=D^2\left(\frac{8}{3S}\right) \quad (6)$$

While slack has units of length, it is often expressed as the percentage of slack relative to the span length. Note that slack is related to the cube of span length for a given H/w ratio and to the square of sag for a given span. For a series of spans having the same H/w ratio, the total slack is largely determined by the longest spans. It is for this reason that the ruling span is nearly equal to the longest span rather than the average span in a series of suspension spans.

The previous equation can be changed in order to obtain a more interesting relationship showing the dependence of sag, D, upon slack, L-S:

$$D = \sqrt{\frac{3S(L-S)}{8}} \quad (7)$$

As can be seen from the preceding equation, small changes in slack typically yield large changes in conductor sag.

- *Effect of the temperature change on conductor sag*

If the conductor temperature changes from a reference temperature, TREF , to another temperature, T, the conductor length, L, changes in proportion to the product of the conductor's effective thermal elongation coefficient, α_{AS}, and the change in temperature, T – TREF , as shown below:

$$L_T = L_{T_{REF}}\left(1 + \alpha_{AS}\left(T - T_{REF}\right)\right) \quad (8)$$

For example, if the temperature of the certain conductor increases from 15ºC to 75ºC, then the length at 15ºC increases by 0.21 m from 182.96 m to 183.17 m:

$$L_{(75°C)} = 182.96\left(1 + \left(19.13*10^{-6}\right)\left(75-15\right)\right) = 183.17m$$

Ignoring for the moment any change in length due to change in tension, the sag at 75ºC may be calculated for the conductor length of 183.17 m using Equation (7), resulting:

$$D = 4.456m$$

Using a rearrangement of Equation (6), this increased sag is found to correspond to a decreased tension of:

$$H = 1{,}527kg$$

If the conductor were inextensible, that is, if it had an infinite modulus of elasticity, then these values of sag and tension for a conductor temperature of 75ºC would be correct. For any real conductor, however, the elastic modulus of the conductor is finite and changes in tension do change the conductor length. Use of the preceding calculation, therefore, will overstate the increase in sag.

For the present study, it is not worthwhile to consider the change in H and of there to recalculate the new change in D.

The analysis of the interaction of the thermal expansion rates, component stress levels and differing creep rates at elevated temperatures to determine the effect of high temperatures on final sags is very complex. High temperatures for time periods which may seem short in terms of the life of the conductor can result in significant changes in sag, especially for the conductor constructions which do not have significant proportions of steel. A method of practical calculations has been presented elsewhere [6].

3. Conductor thermal analysis

A detailed and justified analysis of the aluminum conductor thermal calculation can be seen in specific publications [8].

The conductor over-temperature for steady-state conditions can be easily assessed by using a simple exponential equation, after doing two o three iterative temperature estimations and the corresponding recalculations. This analysis allows the determination of the conductor rated current, based on the maximum steady-state temperature normally recommended by the conductor manufacturers. Here the simple analysis is presented to solve the general equation for transient condition after a current jump, explaining the temperature dependence of part of its terms and the difficulties for finding the accurate solution.

3.1. Simplified solution

A simplified solution by linearizing the non-linear equation terms follows which is of easy application and also allows determining for each current value the time needed to reach the limit temperature.

The conductor surface temperatures are a function of the following properties [9]:

- Conductor material properties
- Conductor diameter
- Conductor surface conditions
- Ambient weather conditions
- Conductor electrical current

The first two of these properties are specific chemical and physical properties. The third may vary with time and be dependent upon ambient atmospheric conditions other than weather. The fourth, weather, varies greatly with the hour and season. The fifth, conductor electrical current, may be constant or may vary with power system loading, generation dispatch, and other factors.

The equations relating electrical current to conductor temperature may be used in either of the following two ways:

- To calculate the conductor temperature when the electrical current is known.
- To calculate the current that yields a given maximum allowable conductor temperature.
- To select the more suitable overcurrent protection

For the purposes of this article, either the electrical current is assumed constant for all time or it is assumed to undergo a step change from an initial current to a final current. The ambient weather conditions are assumed to be constant with time in both the steady-state and transient calculation methods described in this standard [9].

Maximum allowable conductor temperature: The maximum temperature limit that is selected in order to minimize loss of strength, sag, line losses, or a combination of the above.

The non-steady-state heat balance of the bare conductor is as follows:

$$q_c + q_r + mC_p \frac{dT_c}{dt} = q_s + I^2 R(T_c) \qquad (9)$$

Where

q_c	Convected heat loss
q_r	Radiated heat loss
q_s	Solar gain
mC_p	Total conductor heat capacity
$R(T_c)$	Conductor electrical resistance

Once the steady-state conditions are reached (the term of temperature variation on time disappears), the previous equation becomes:

$$q_c + q_r = q_s + I^2 R(T_c) \qquad (10)$$

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \qquad (11)$$

The non-steady-state heat balance Equation (9) cannot be solved analytically for conductor temperature as a function of time since certain of its terms are non-linear [9].

Considering the equation term by term, it may be seen that the ohmic heating term, and the forced convection equation term are linear in conductor temperature. The solar heating term is also linear since it is independent of conductor temperature. The radiation heat loss term and the natural convection (zero wind speed) term are both non-linear in conductor temperature.

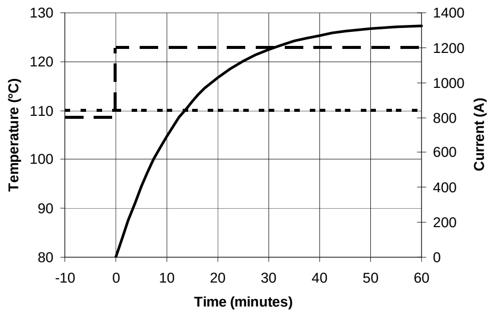

Fig. 5: Step change in current.

A method of approximating the radiation cooling equation as a linear function of temperature has been described. Doing so yields a linear non-steady-state heat balance equation of the form shown in Equation (12) [10]:

$$\frac{d}{dt}(T_c - T_a) = K_1(T_c - T_a) + K_2 I^2 \qquad (12)$$

For a step change in electrical current, the solution of the linearized non-steady-state heat balance equation is shown in Equation 13.

$$T_c(t) = T_i + (T_f - T_i)(1 - e^{-t/\tau}) \qquad (13)$$

The steady-state conductor temperature prior to the step increase in current is Ti. The steady-state conductor temperature which occurs long after the step increase in current is Tf. The thermal time constant, τ, may be calculated by use of Equation (14).

$$\tau = (T_f - T_i)\, m\, C_p \,/\, (R(T_c)\, (I_f^2 - I_i^2)) \qquad (14)$$

Where the conductor resistance is that corresponding to the average conductor temperature, that is $(T_i + T_f)/2$.

Consider the exponential change in conductor temperature shown in Figure 5, due to a current step change. The initial conductor temperature is 80

°C. The final conductor temperature is 128 °C. The current undergoes a step change from 800 to 1200 amperes. If the average conductor temperature is taken as 100 °C, the resistance of the conductor is 9.38 × 10-5 ohms/m and the heat capacity of the conductor is 984 W-s/m-°C. The time constant calculated by applying equation (14) results:

τ = 13.8 min

Alternatively, the temperature change reaches 63% of its final value at a conductor temperature of:

80 °C + (128 – 80) × 0.63 = 110 °C.

From Figure 5, this corresponds to a time of about 14 min.

4. Conductor time – current characteristic

With the described methodology, from the temperature – time graph a time-current characteristic for the conductor could be draw which can be directly compared with the fuse characteristic in order to assess the protected and not-protected zones. For each current value the crossing point of the corresponding curve and the 110ºC horizontal line (figure 6) indicate the time for the time – current characteristic curve of figure 7.

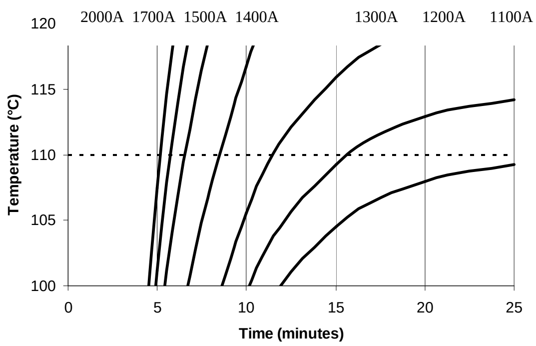

Fig. 6: Time for reaching the limit temperature as function of overload current.

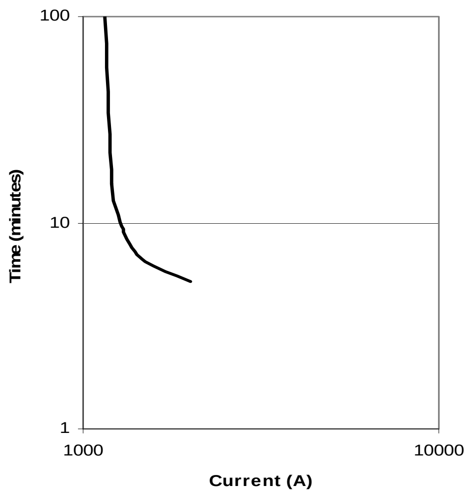

Fig. 7: Time – current characteristic obtained from figure 6.

5. Useful life lost

The permanent elongation caused by everyday tension levels is called creep, which is plastic deformation that occurs in metal at stresses below its yield strength. Creep elongation in aluminum conductors is quite predictable as a function of time and obeys a simple exponential relationship. Creep is assumed exponential with time. Thus, conductor elongation during the first day under tension is equal to elongation over the next week (first six months equals to the next 9 ½ years). Using creep estimation formulas, the creep strain can be estimated and adjustments made to the stringing sag tables in terms of an equivalent temperature.

Thus, the permanent elongation due to creep at everyday tension can be found for any period of time after initial installation. Creep elongation of copper and steel conductors is much less and is normally ignored [7]. It must be remembered that the aluminum conductors loss useful life or in other words suffer of an accumulative phenomenon called “creep”, which is due to the time, tension, temperature. Besides, creep of an overhead conductor at high temperature is a single-valued function of the sum of the time the conductor was operated at the elevated temperature [6].

As previously mentioned, expulsion fuse has not the ability to “accumulate or remember” the duration of damaging conditions unlikely the high breaking capacity fuse provided with M effect. In spite of its low application in this type of distribution systems, fuses provided with M effect can consider or represent the conductor “useful life lost” by the increase of the main fuse element dissolution due to the low melting temperature component diffusion into it. The coordination or protection selection is given by using thermal models including this diffusion [11].

6. Conductor – fuse coordination

Having the conductor behavior represented by a simple exponential equation and by a time-current characteristic, the conductor – fuse coordination can be given by direct comparison of the homologues curves. Normally it is chosen to work on the time-current characteristics due to the other protective devices characteristics are given in this way.

7. Conclusions

A simple methodology has been presented, which allows a more rational fuse selection for the bare overhead conductor protection. The methodology permits to carry out the bare conductor protection against over-temperature considering conductors annealing and maximum sag (or minimum conductor – soil distance).

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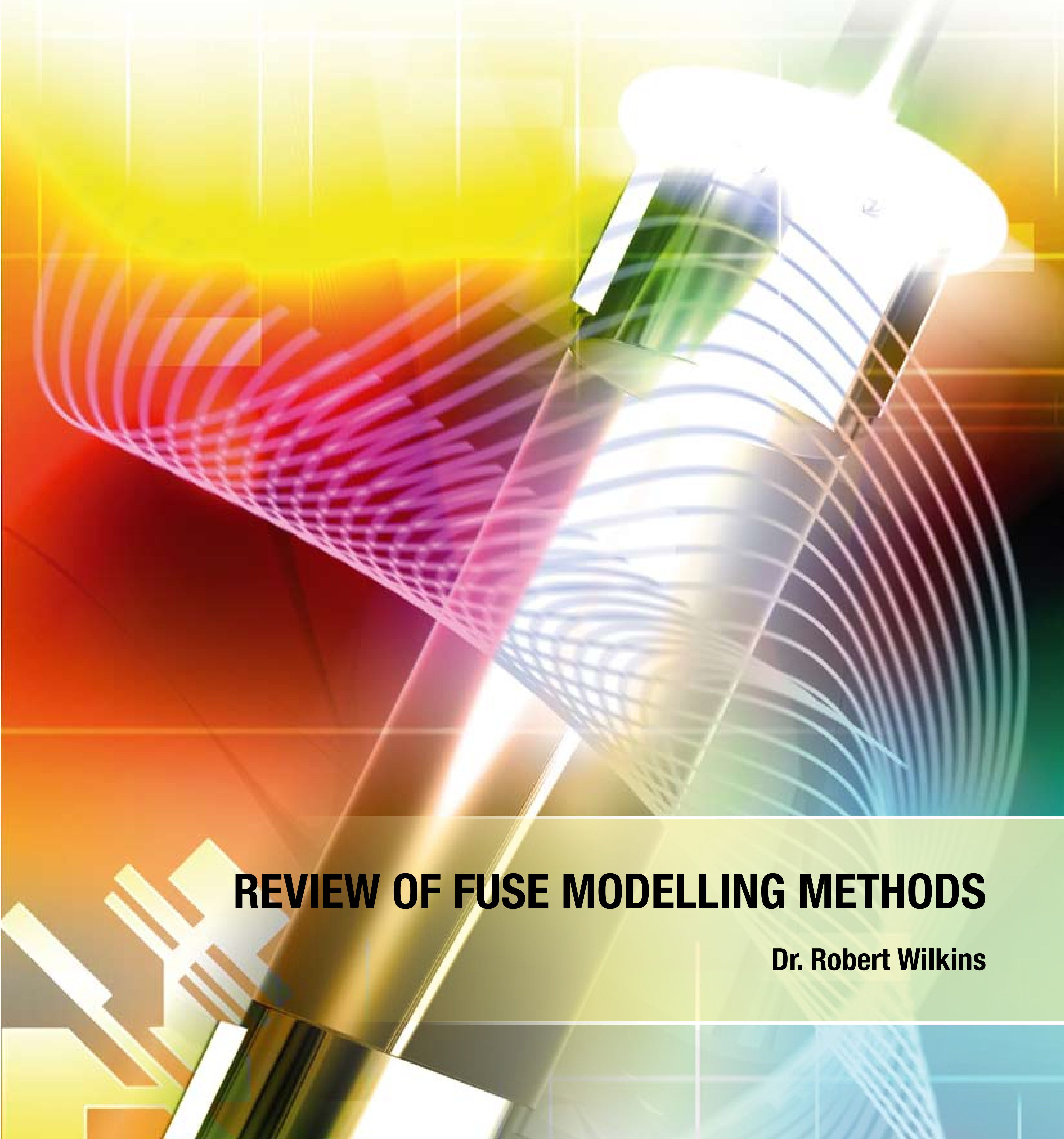
ICEFA 2011

9th INTERNATIONAL CONFERENCE ON ELECTRICAL FUSES AND THEIR APPLICATIONS



REVIEW OF FUSE MODELLING METHODS

Dr. Robert Wilkins

OPENING LECTURE

Review of Fuse Modelling Methods

Dr. Robert Wilkins

Consultant – Heswall, UK, bob@overdee.demon.co.uk

Abstract

Many people think that the fuse is a simple device. However this review shows that modelling fuse behaviour can be very complex, involving electrical circuits, electromagnetics, heat transfer, materials science, mechanical engineering, plasma physics and numerical methods. The review is restricted to those modelling methods which can be directly put to practical use in fuse design and applications. The key issues are highlighted, and significant progress is reported, when compared with the situation which existed at the time of the first ICEFA in 1976. A list of key reference is provided to accompany the review.

Keywords: electric fuses, modelling methods.

Review of Fuse Modelling Methods

R. Wilkins

Consultant, UK

Why Model ?

- Education & research – better understanding
- As a design aid – reduces time & cost of testing
- Fuse applications – conditions differ from those used for type tests

progress made since 1st ICEFA (1976)

ICEFA 1976

- “why have you done this work”?
- “what was the motivation”
- “fuses are not produced as an academic exercise, they are produced for a job of work in the world outside”

Eric Jacks, ICEFA 1976 (transcipt of discussion)

Types of Fuse

- Current-limiting fuses (LV/MV) for many different applications and standards
  - Motor, transformers, capacitors, distribution systems, power electronics, traction ....
- Explusion fuses
- Miniature fuses
- Substrate / microfuses

Types of Model

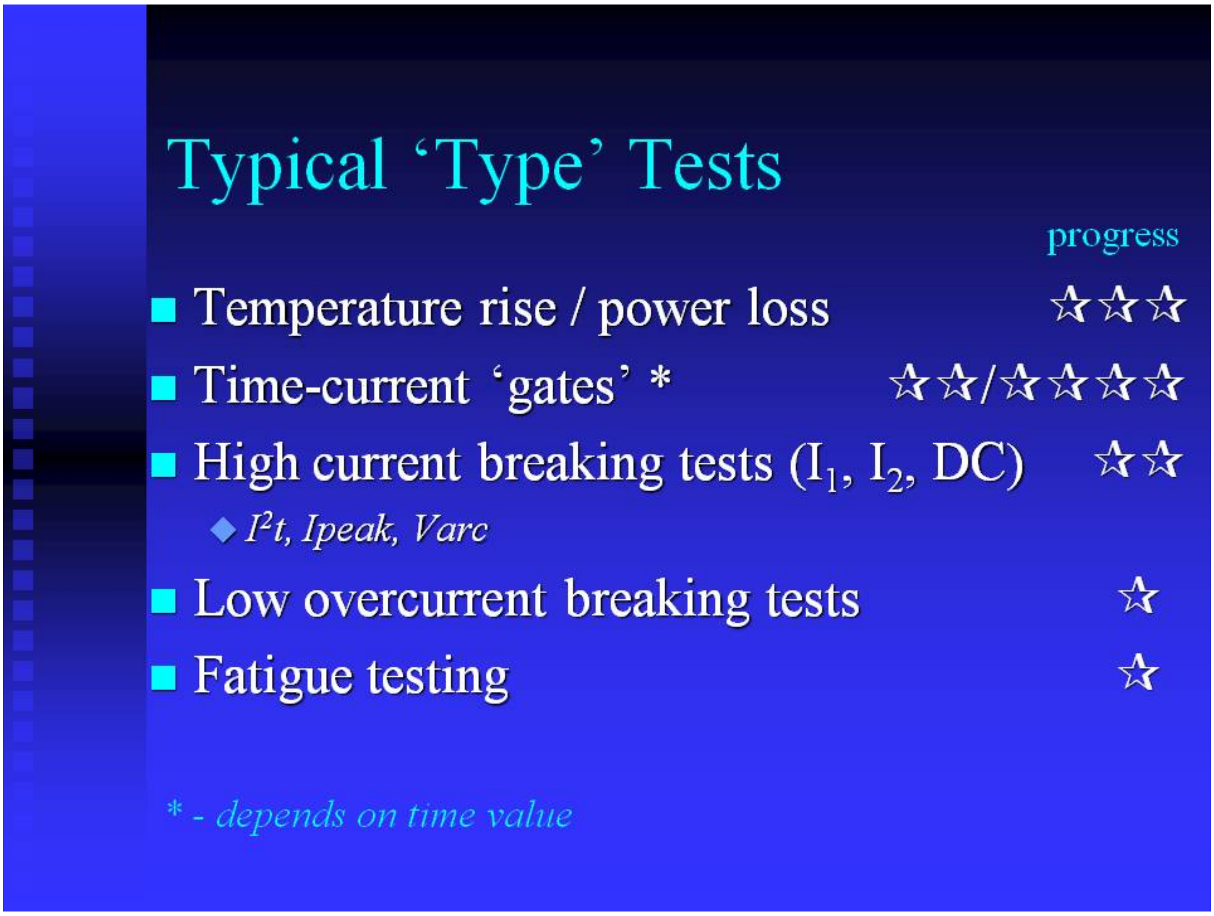
(only those with direct practical applicability reviewed here)

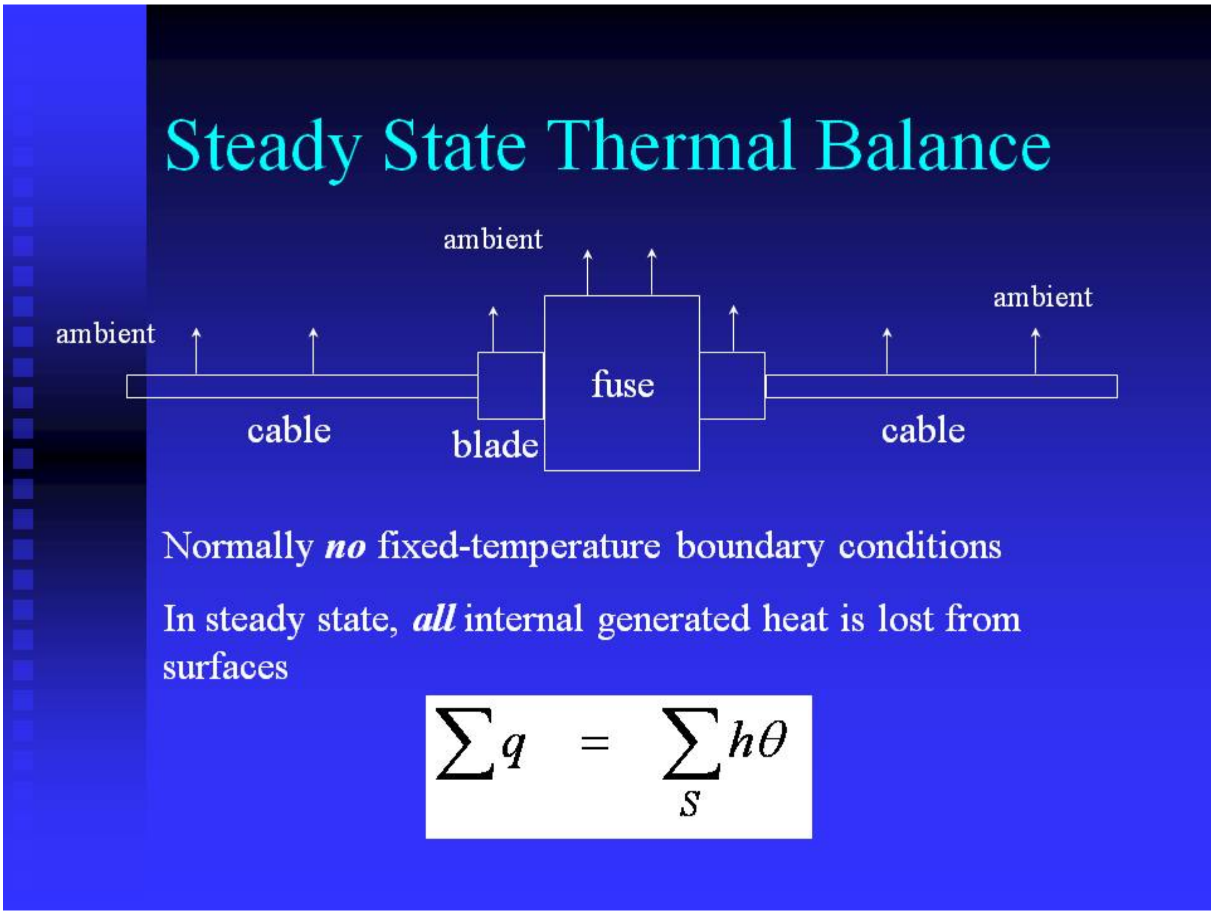
- Simple formulae, e.g. $[I^2t] = K_m S^2$
  - Adiabatic melting of a conductor
- Full 3-D Finite Element or Finite Difference Models of Heating
- Arcing in sand filler / failure criteria
- Metallurgical diffusion (M-effect)
- Simplified models – range of applicability
- Generic models for system studies

Why So Difficult?

not just a bit of wire that melts

- Multidisciplinary – electrical circuits, electromagnetics, heat transfer, materials science, mechanical engieerning, plasma physics, numerical methods ..
- Steady state and long-duration thermal balance governed by non-linear convection and radiation losses from surfaces
- Granulated filler – properties changes with thermal expansion
- Explosive disinegration processes for wire and notched fuse elements
- High-current arc development in sand – followed by possible restriking
- Thermal fatigue processes


Typical 'Type' Tests
progress
Temperature rise / power loss ☆☆☆
Time-current 'gates' * ☆☆/☆☆☆☆
High current breaking tests (I_1, I_2, DC) ☆☆
I^2t, Ipeak, Varc
Low overcurrent breaking tests ☆
Fatigue testing ☆
* - depends on time value


Steady State Thermal Balance
ambient
ambient
ambient
fuse
cable
blade
cable
Normally no fixed-temperature boundary conditions
In steady state, all internal generated heat is lost from surfaces
$\sum q = \sum_S h\theta$

Boundary conditions

$$h = C_B\,(\theta / D)^{0.25} + \varepsilon\,\sigma\,[(Ta+\theta)^4 - Ta^4]\,/\,\theta$$

natural convection + radiation

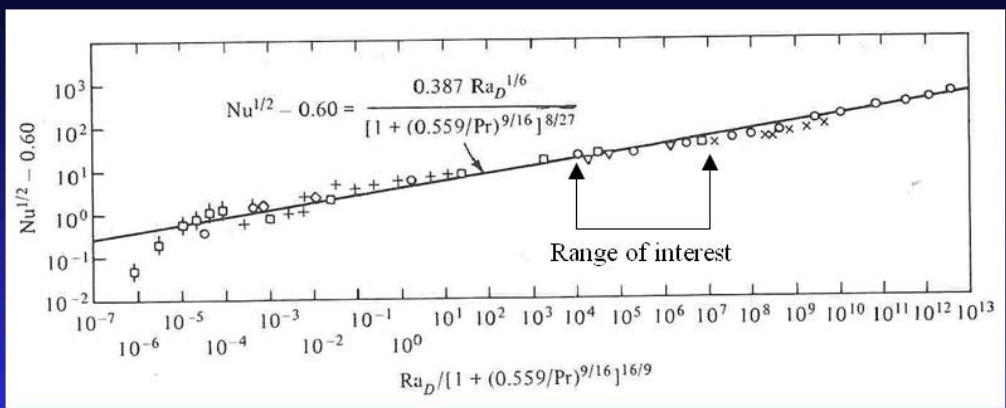
D = characteristic distance

ε = emissivity

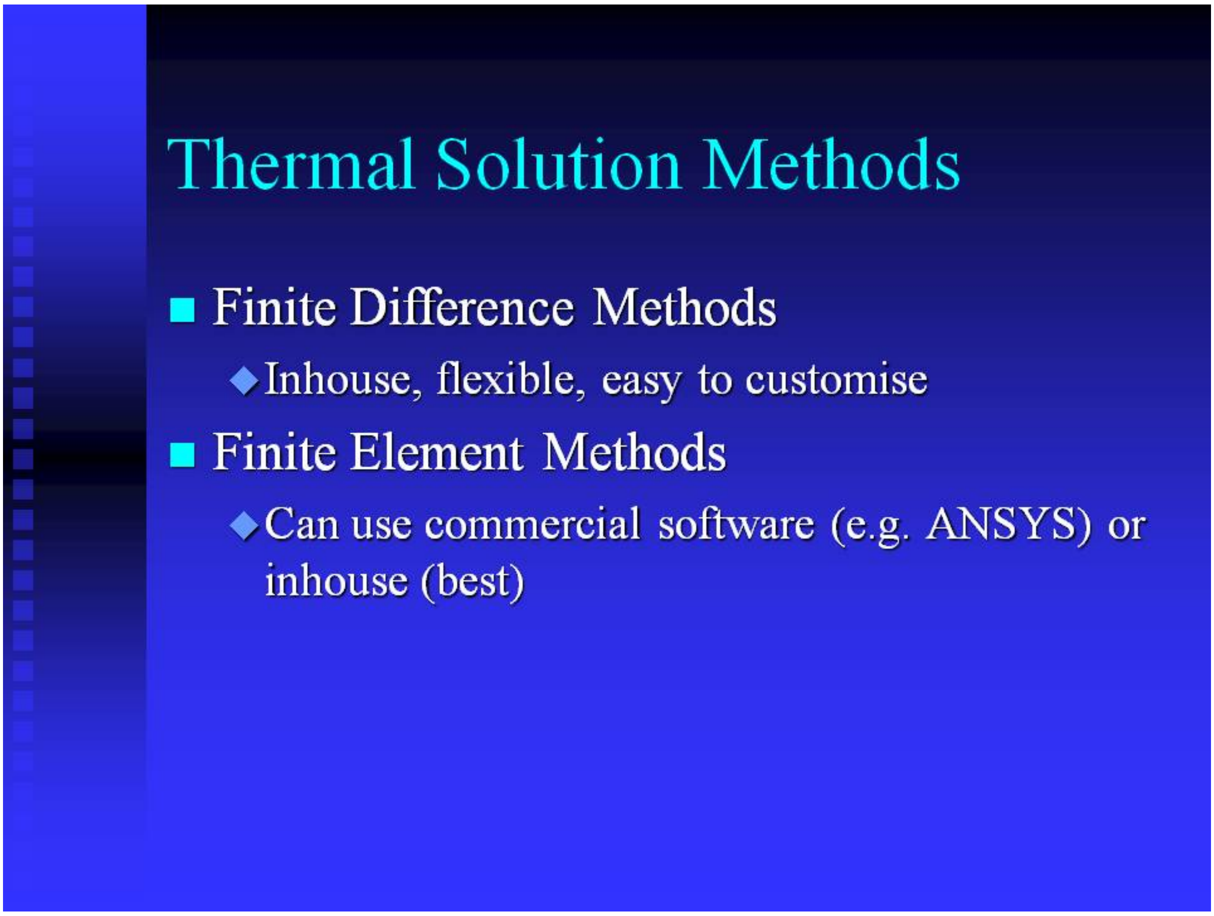
σ = Stefan-Boltzmann constant

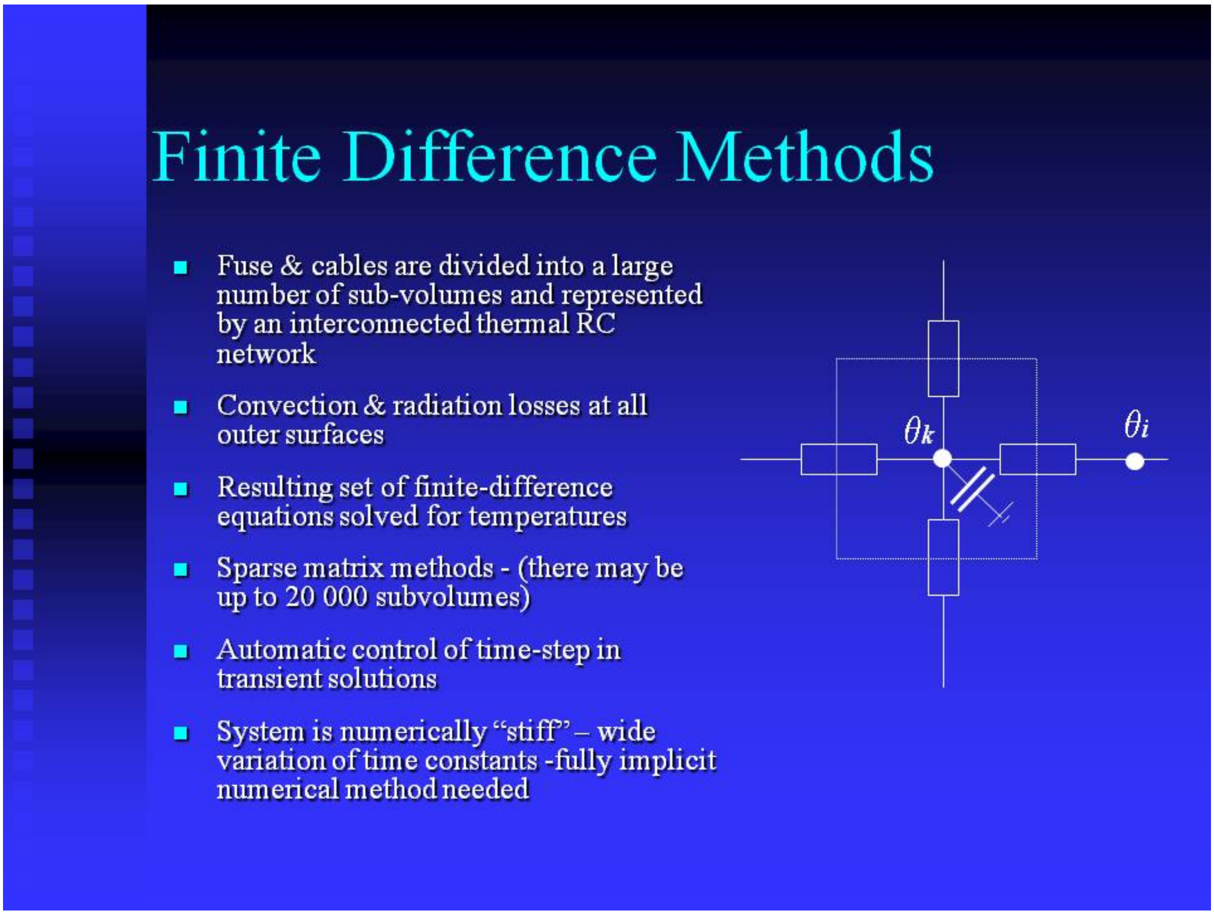
Ta = ambient temperature

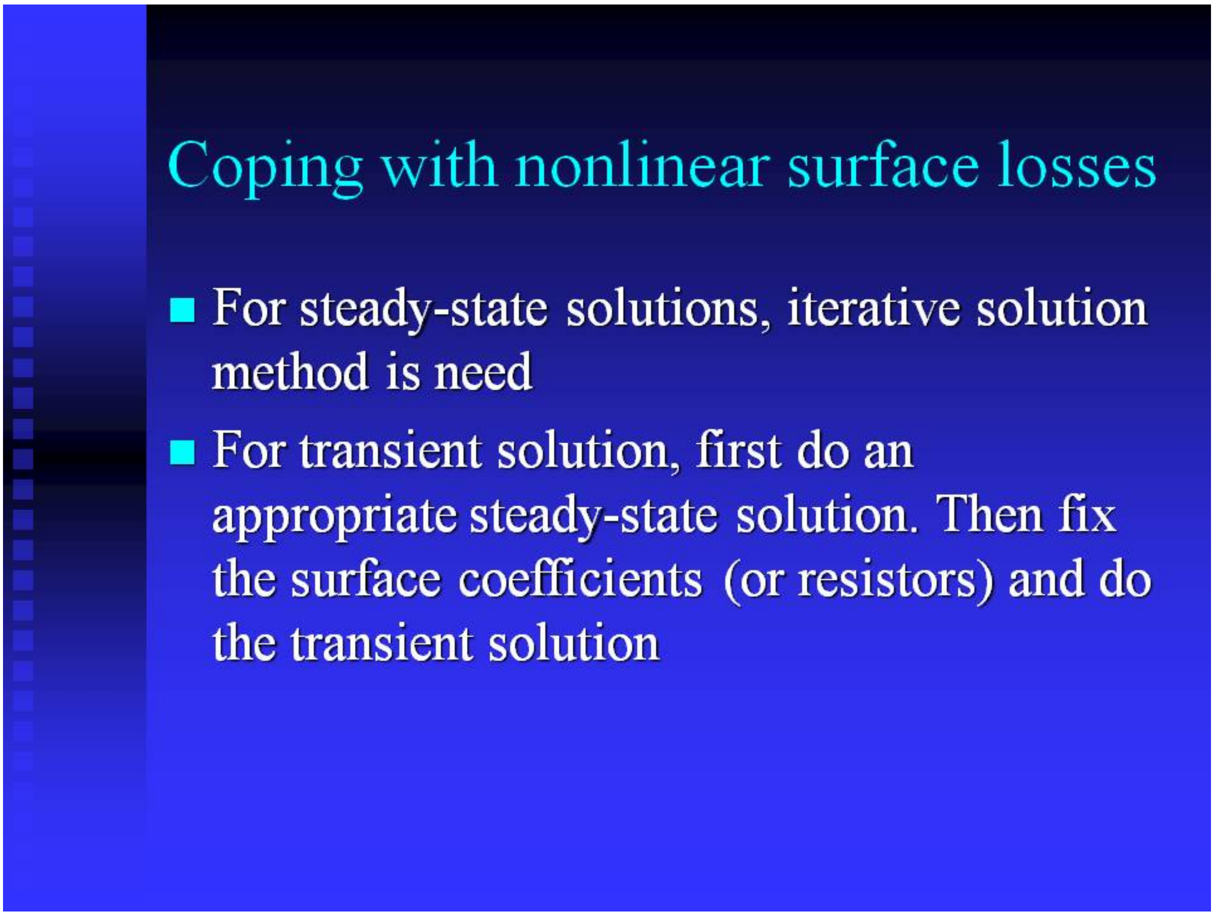
Natural Convection from Long Horizontal Cylinder

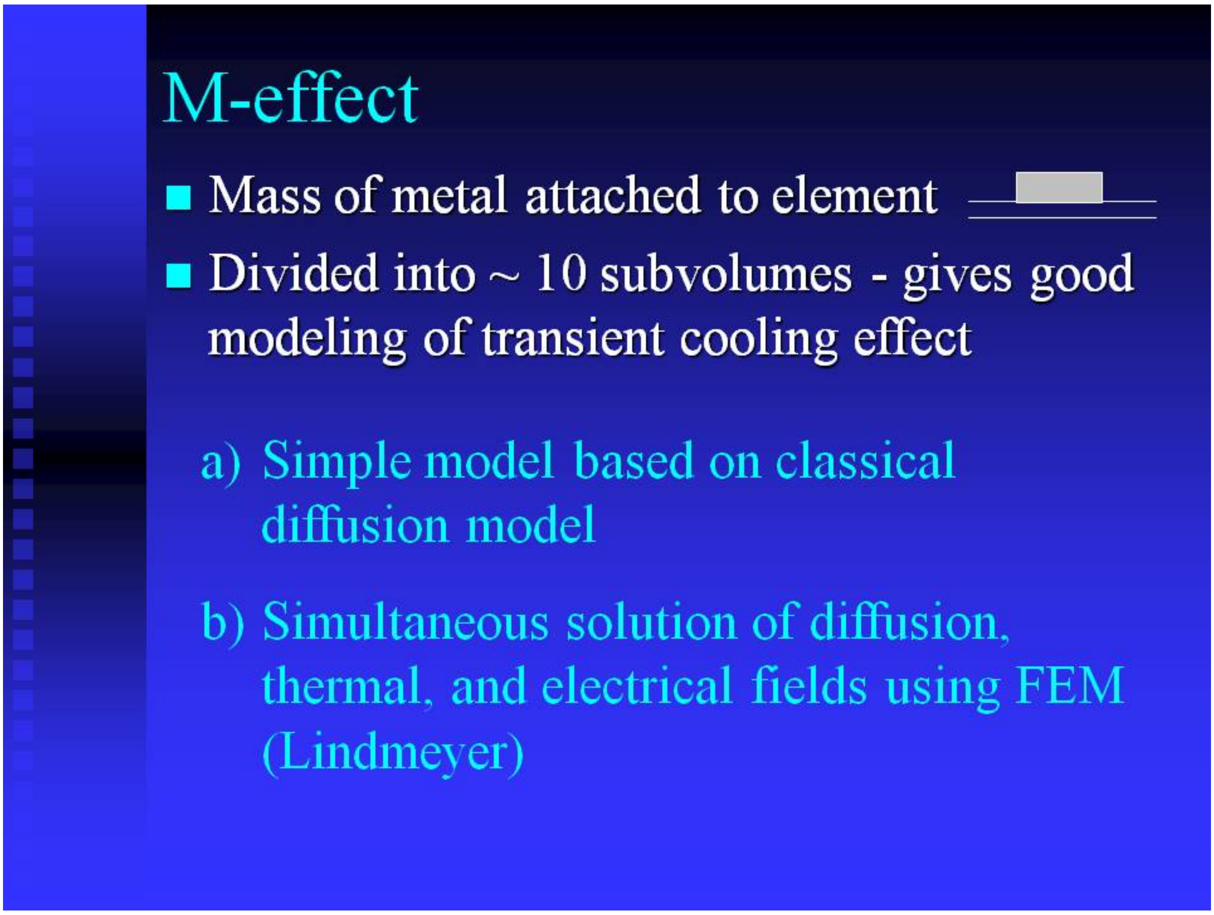


- Not an exact science!
- For air at 25C, $h_C = C_B(\theta/D)^{0.25}$
- C_B must be determined by test
- Emissivity ~ 0.35 (dull metal) – 0.9 (polished ceramic)
- Sometimes *h (total)* is taken to be constant (Newton's Law)


Thermal Solution Methods
Finite Difference Methods
Inhouse, flexible, easy to customise
Finite Element Methods
Can use commercial software (e.g. ANSYS) or inhouse (best)

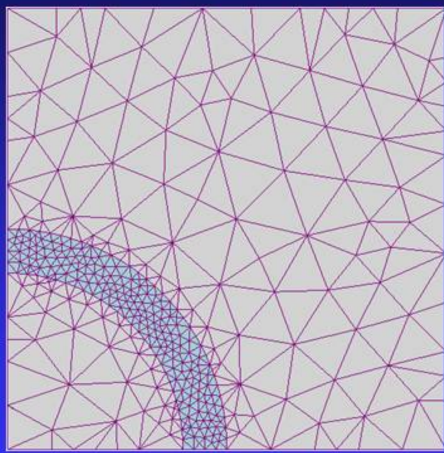

Finite Difference Methods
Fuse & cables are divided into a large number of sub-volumes and represented by an interconnected thermal RC network
Convection & radiation losses at all outer surfaces
Resulting set of finite-difference equations solved for temperatures
Sparse matrix methods - (there may be up to 20 000 subvolumes)
Automatic control of time-step in transient solutions
System is numerically "stiff" – wide variation of time constants -fully implicit numerical method needed
θk
θi


Coping with nonlinear surface losses
For steady-state solutions, iterative solution method is need
For transient solution, first do an appropriate steady-state solution. Then fix the surface coefficients (or resistors) and do the transient solution

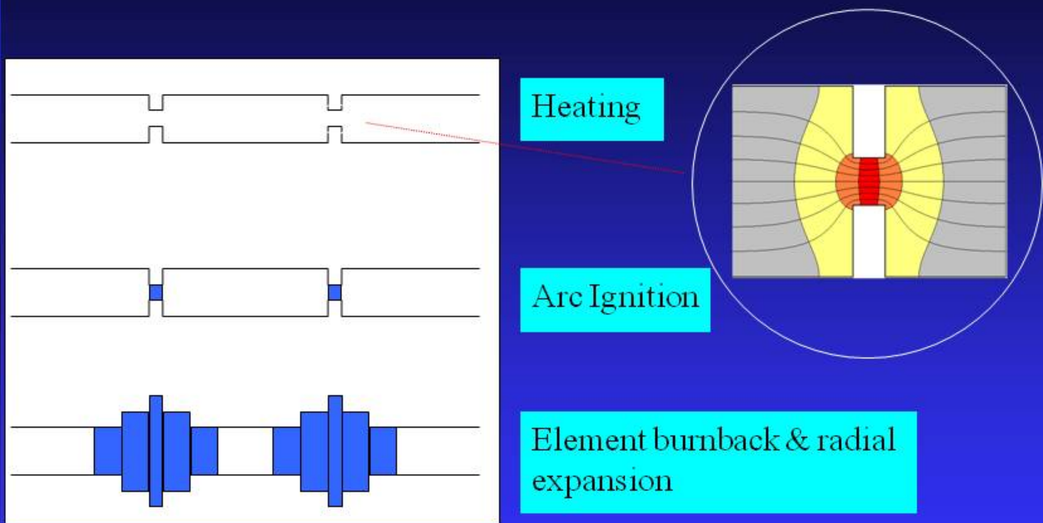

M-effect
Mass of metal attached to element
Divided into ~ 10 subvolumes - gives good modeling of transient cooling effect
a) Simple model based on classical diffusion model
b) Simultaneous solution of diffusion, thermal, and electrical fields using FEM (Lindmeyer)

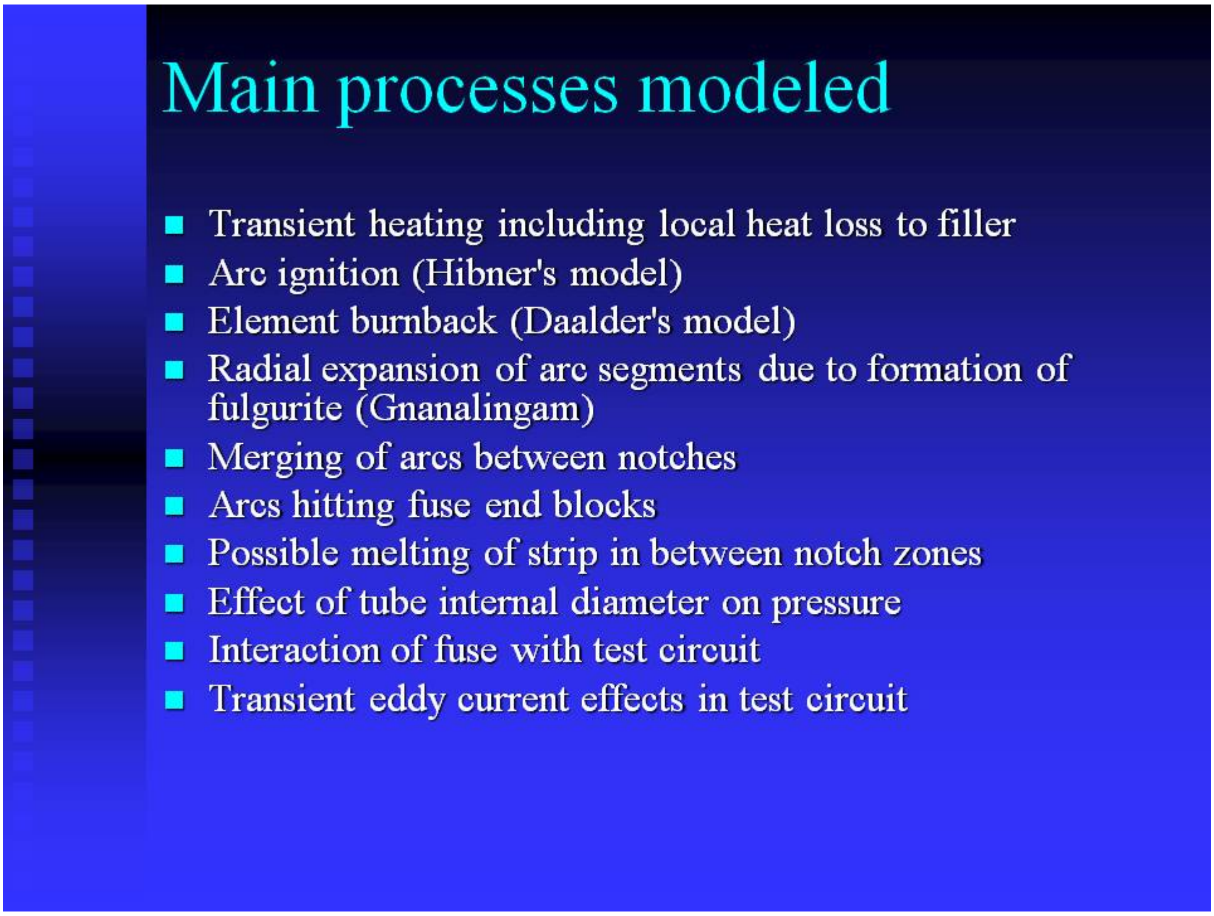
Finite Element Methods

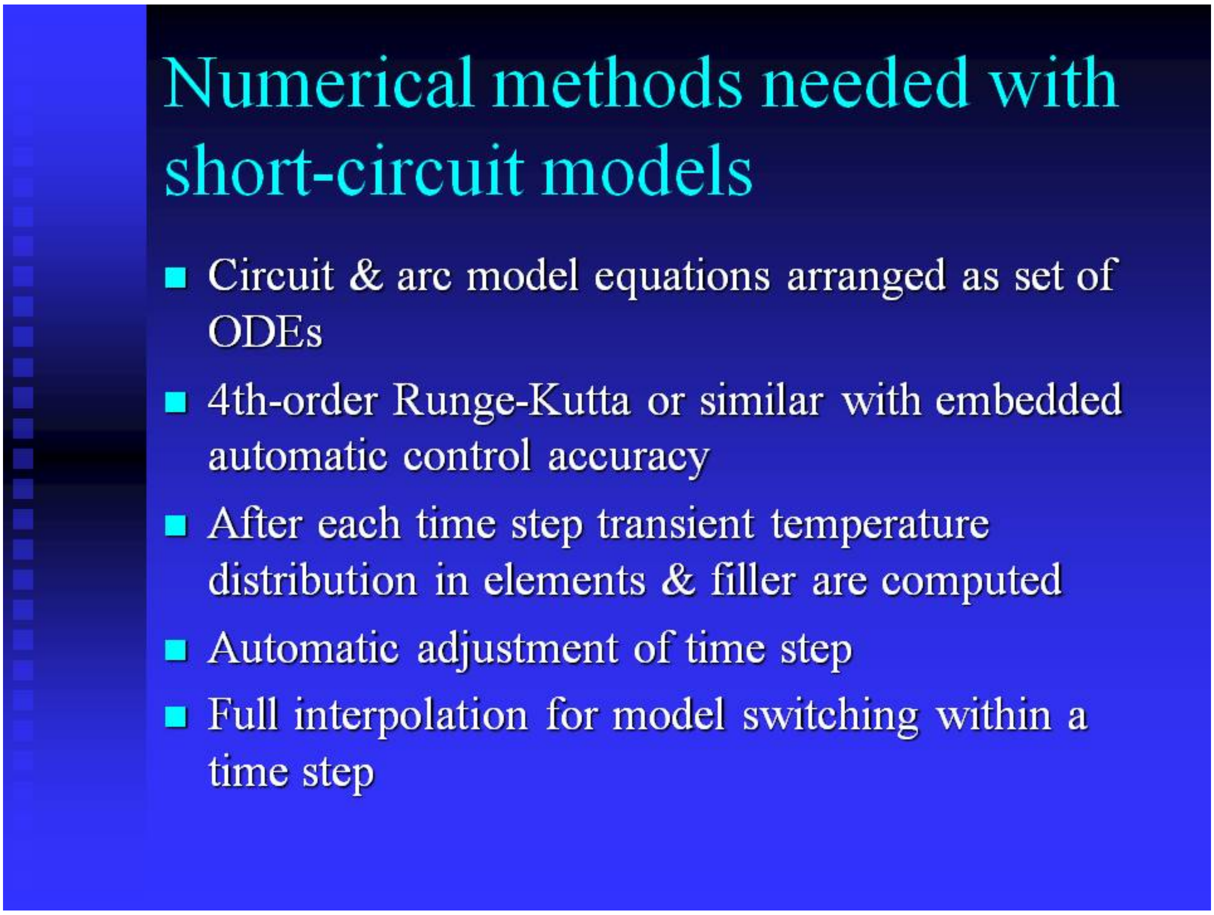
- Temperature assumed to vary within each element according to some function
- Solved for in conjunction with field equations to gives temperatures
- More commonly used for solving fuse heating than FDM
- Key issues the same as with FDM
  - Non-linear losses at surfaces
  - Need to use implicit method for numerical stability



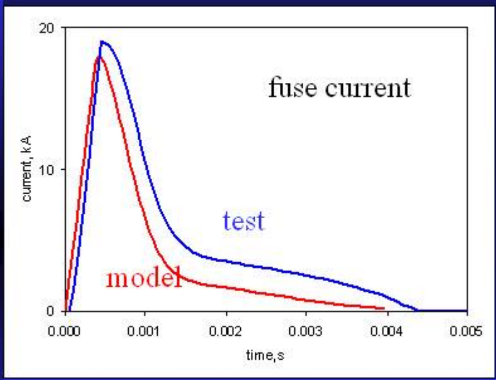
Short-circuit model

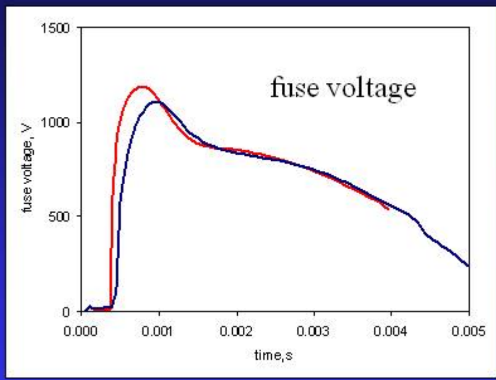



Main processes modeled
Transient heating including local heat loss to filler
Arc ignition (Hibner's model)
Element burnback (Daalder's model)
Radial expansion of arc segments due to formation of fulgurite (Gnanalingam)
Merging of arcs between notches
Arcs hitting fuse end blocks
Possible melting of strip in between notch zones
Effect of tube internal diameter on pressure
Interaction of fuse with test circuit
Transient eddy current effects in test circuit


Numerical methods needed with short-circuit models
Circuit & arc model equations arranged as set of ODEs
4th-order Runge-Kutta or similar with embedded automatic control accuracy
After each time step transient temperature distribution in elements & filler are computed
Automatic adjustment of time step
Full interpolation for model switching within a time step

Typical Results, 200A fuse @ 100kA





Cyclic Loading

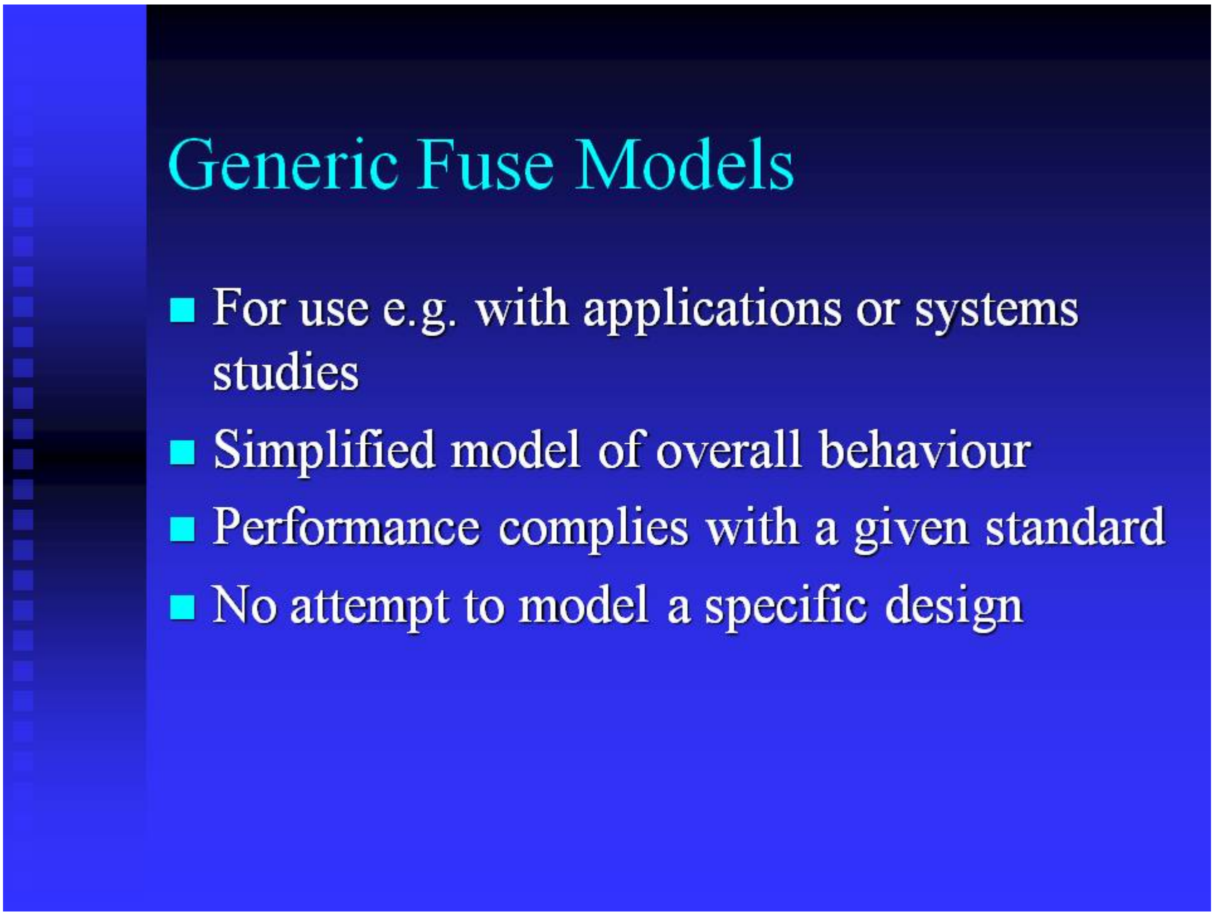
Manson-Coffin Law
(non-ferrous metals)

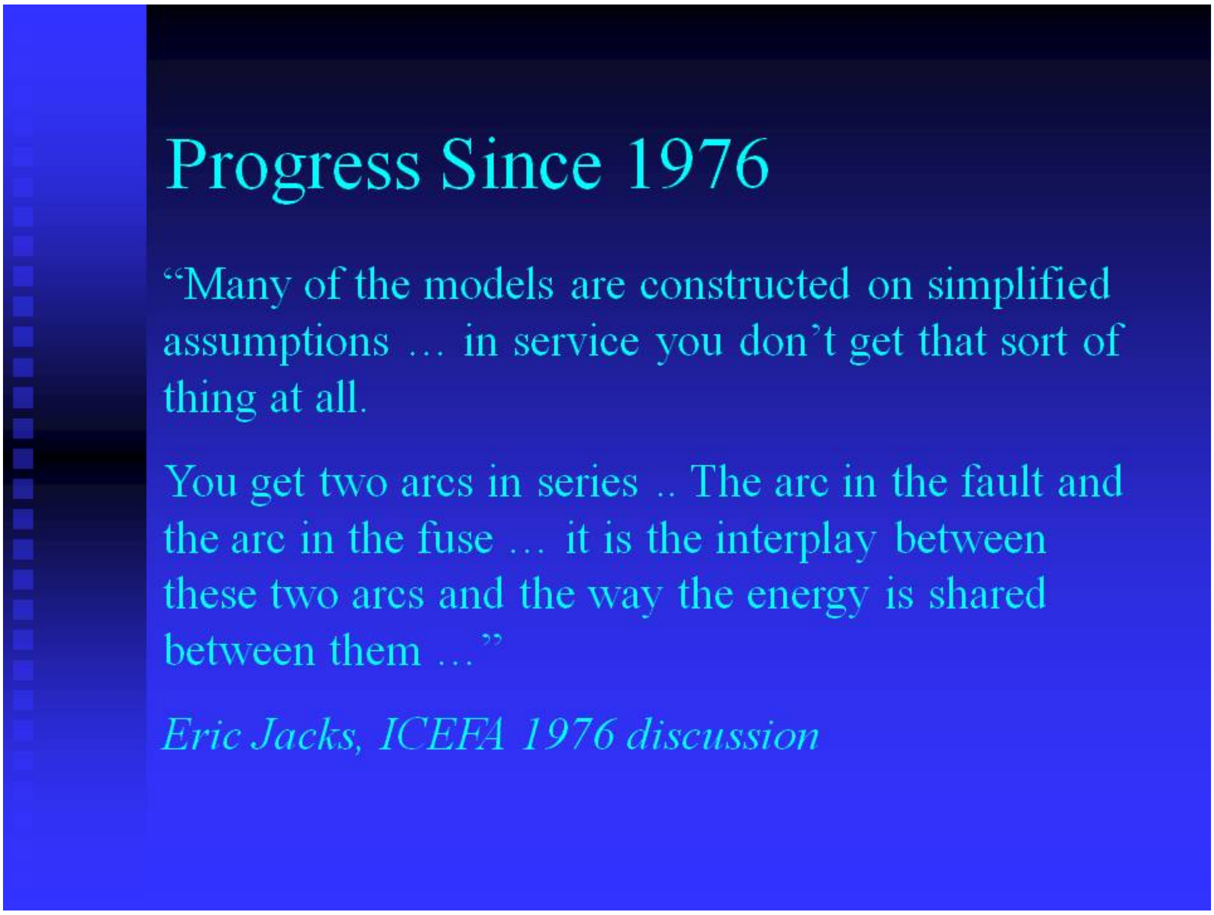
Depends on mechanical construction

$$N = \frac{K}{\Delta\vartheta^{P}\,\vartheta_{av}{}^{Q}}$$

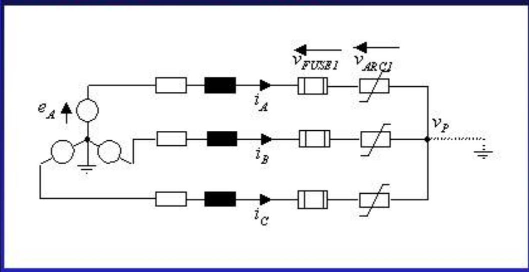
Peak-to-peak temperature fluctation

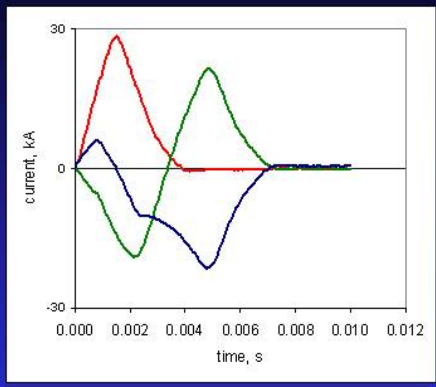
Average temperature

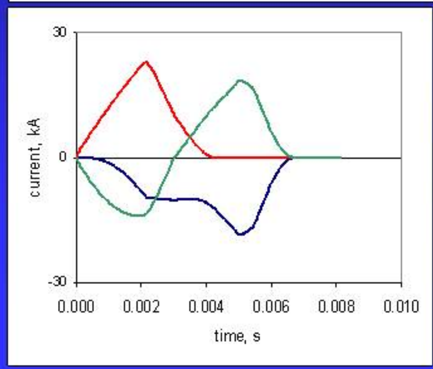

Generic Fuse Models
For use e.g. with applications or systems studies
Simplified model of overall behaviour
Performance complies with a given standard
No attempt to model a specific design


Progress Since 1976
“Many of the models are constructed on simplified assumptions … in service you don’t get that sort of thing at all.
You get two arcs in series .. The arc in the fault and the arc in the fuse … it is the interplay between these two arcs and the way the energy is shared between them …”
Eric Jacks, ICEFA 1976 discussion

3-phase Arc Flash Event with C-L Fuses



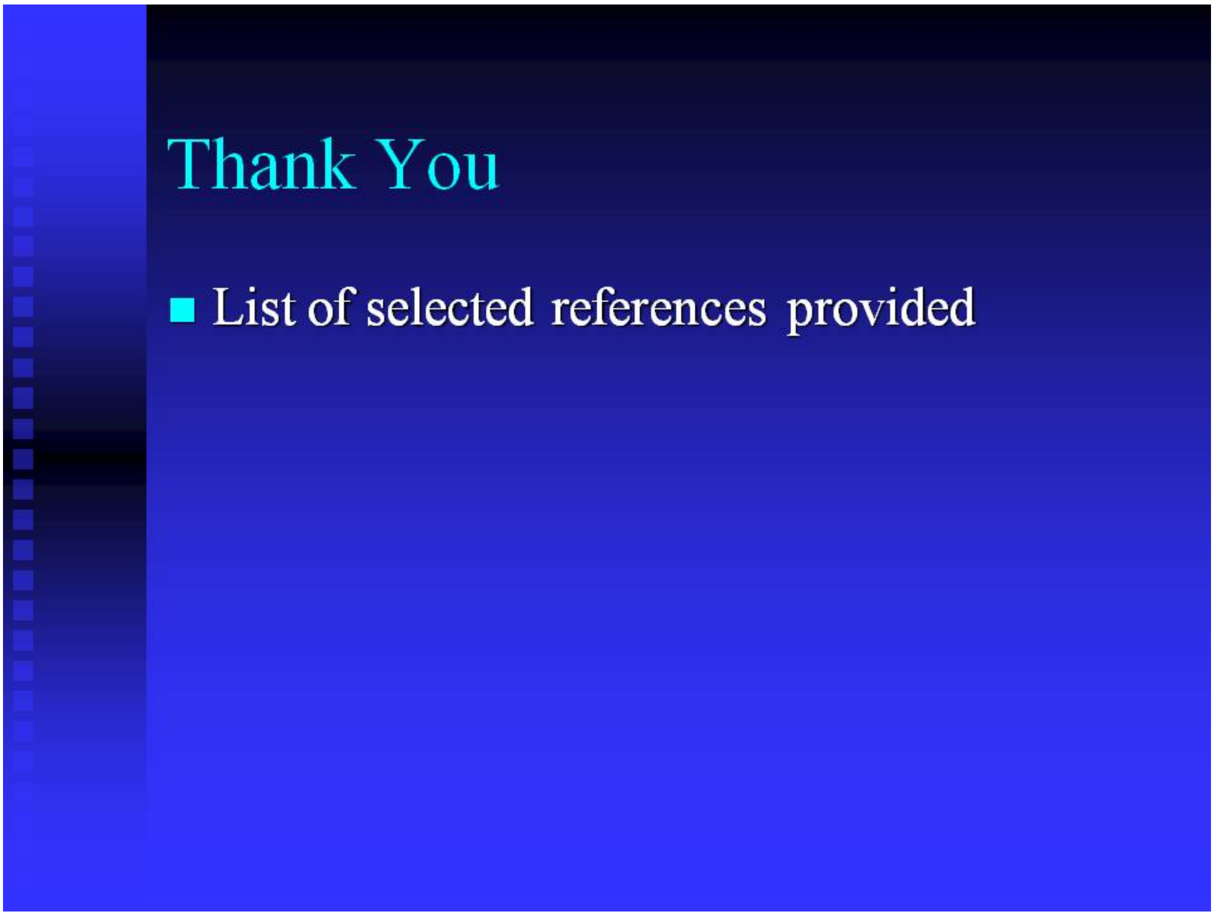




Ungrounded 3-phase arcing fault. Appearance of arc voltage of 1st fuse to melt changes *di/dt* in all phases … and so on.

Practical Implementation

- User Friendly
- Building a Design from Components
- Components Database
- Materials (metals, alloys, body materials, sands)
- Standard Test Set-ups (IEC, UL, etc)
- Simulation of Type Tests & Other Tests
- Report Generation & Output
- Graphic Output
- Control of Settings


Thank You
List of selected references provided

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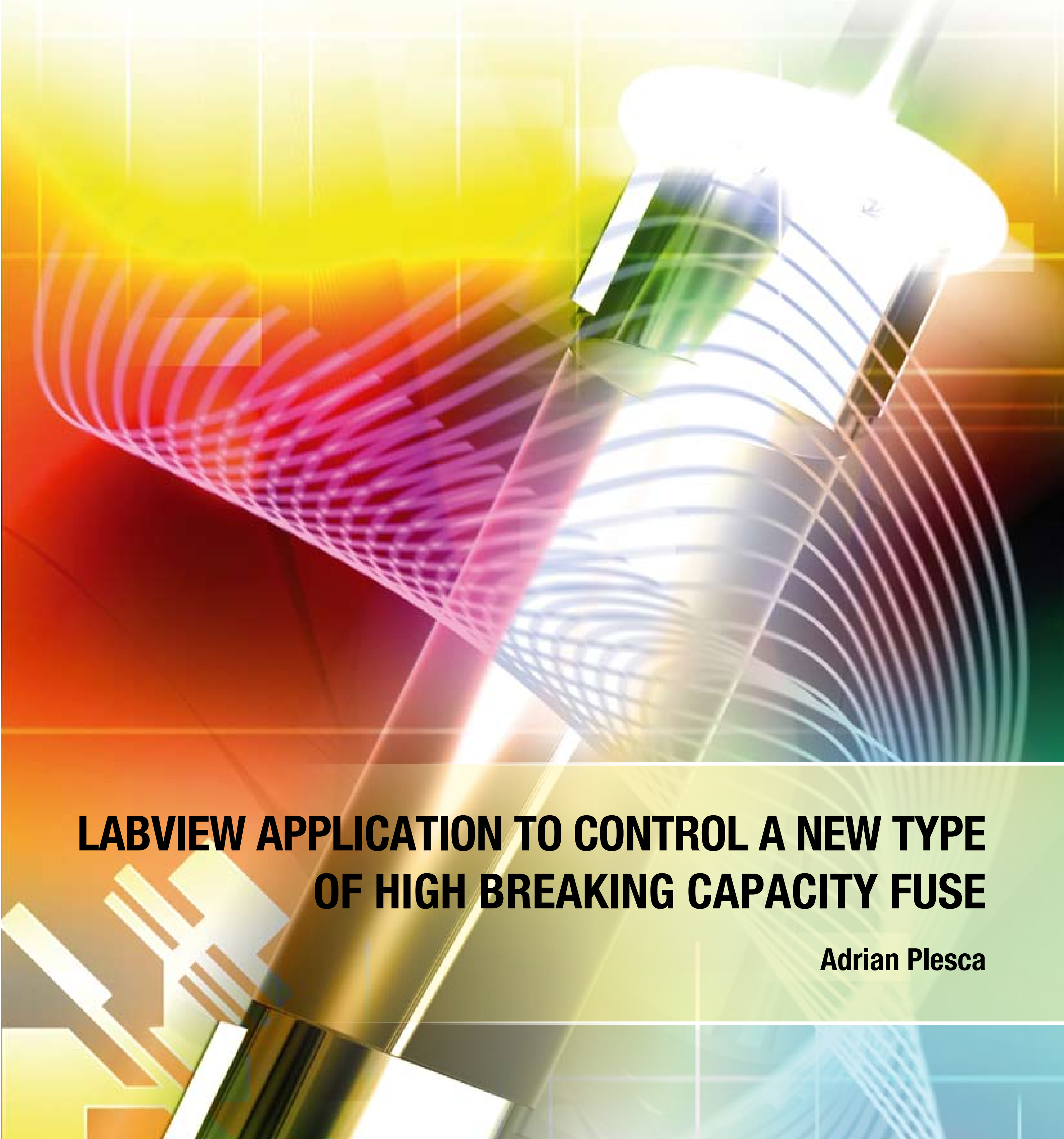

LABVIEW APPLICATION TO CONTROL A NEW TYPE OF HIGH BREAKING CAPACITY FUSE

Adrian Plesca

Labview application to control a new type of high breaking capacity fuse

Adrian Plesca

Gheorghe Asachi Technical University of Iasi, Blvd. Dimitrie Mangeron, 21-23, Iasi – 700050, Romania, aplesca@ee.tuiasi.ro

Abstract

One of the most widespread applications of fuses in medium voltage distribution systems is the overhead lines protection, but unfortunately and very frequently the people on charge of the fuse selection leave aside important facts of the protection. Usually the fuse is selected taking into account only the selective coordination with other up-stream and down-stream protective devices. Due to this procedure, really the overhead line is not protected against its main problem, the overheating. This over-heating is the cause of the two bare overhead conductors application limits, a. the mechanical strength weakening (annealing), and b. the minimum distance to earth (maximum sag). The paper firstly presents a summarized study of the thermal behavior of bare overhead conductors, under steady-state condition and also for transient conditions after a step change in current, analyzing the heat losses and gains, due to conduction, radiation, convection, overcurrent flow, sun effect, etc. The conductor over-temperature for steady-state conditions can be easily assessed by using a simple exponential equation, after doing two o three iterative temperature estimations and the corresponding recalculations. This analysis allows the determination of the conductor rated current, based on the maximum steady-state temperature normally recommended by the conductor manufacturers. The relationship between the conductor temperature and conductor lengthening and thus sag, is shortly explained. The general equation for transient condition after a current jump is given, explaining the temperature dependence of part of its terms and the difficulties for finding the accurate solution. A simplified solution by linearizing the non-linear equation terms is proposed, which is of easy application and also allows determining for each current value the time needed to reach the limit temperature. With the described methodology a time-current characteristic for the conductor could be draw which can be directly compared with the fuse characteristic in order to assess the protected and not-protected zones. By applying the cooling equation, the over-temperature as time function was assessed, in order to calculate the useful life lost and the conductor creep. This simple methodology allows a more rational fuse selection for the bare overhead conductor protection.

Keywords: high breaking capacity fuse, new fuse, LabVIEW application.

1. Introduction

The simplest overcurrent protection device is the fuse, which is used in vast numbers throughout the circuit operating voltage range 415V to as high as 66 kV. The basic principle involves connecting a fuse directly in series with the protected equipment so that, when a given current is exceeded a metallic fuse element(s) melts and thereby breaks the circuit. In this way, fuses both detect and directly isolate faulted equipment from the network, [1].

The term fuse is used in national and international standards to describe a complete assembly. In its simplest form, this consists of a piece of metal wire connected between two terminals on a suitable support; and at its most complex as a cartridge fuse-link mounted in a carrier and fuse base. Modern cartridge fuse-links contain fusible elements mounted in rigid housings of insulating material. The housings are filled with suitable exothermal and arc-quenching powders, such as silica, and they are sealed by metal endcaps which carry the conducting tags or end connections. The metal parts, other than the fusible elements, are invariably of copper, brass, steel or composites and they must be capable of operating under the exacting thermal, mechanical and electrical conditions which may arise in service. A fuse must be able to carry normal load currents and even transient overloads (and the thermal cycling which accompanies them) for a service life of at least 20 years, without any change of state that might affect its electrical performance. This property of non-deterioration requires that the fusible element be both thermally and chemically compatible with the ambient media. It must also respond thermally to overcurrents by melting and subsequently interrupting its circuits. The melting of an element is followed by a period of arcing during which the electrical energy input can be very high, its magnitude and the duration of arcing being dependent on the protected circuit. Successful fault interruption implies that the arcing is wholly contained within the fuselink and the level at which this can be achieved is termed the breaking or rupturing capacity of the fuselink. The operating time of a fuselink varies inversely with the level of an overcurrent and discrimination is obtained in networks by choosing fuses with the necessary time/current characteristics and current ratings, [2-3].

Considerations of fuse component properties are important when designing a fuse to operate and efficiently clear fault currents for particular applications. Therefore, many improvements have been made into the original fuse design in order to extend the low current interruption capability, such as: using of non-traditional fuse element metals, like aluminium or cadmium [4], use of bounded silica sand [5], use of two dissimilar bounded or unbounded metals [6], current limiting and expulsion elements put together inside a single fuse body [7], paralleled combination of high-voltage fuse and Z_nO varistors [8-10], hybrid fuse using SF_6 or vacuum fuse in series with traditional high current part [11, 12], repetition fuse and self-healing or permanent fuse using high pressure sodium and mercury as fuse elements [13-14].

From the literature survey of the main fuse intelligence adding and innovations, the idea of Muth and Zimmermann by 1938 [15], had come out. Afterwards the same idea was developed, especially on the ignition control system, introducing in the market by 1963 the device called *limiter* [16]. By 1990 a technical paper has been presenting a new design applying this concept to low voltage DC systems, called Smart Fuse [17]. During the seventies an interesting idea was proposed, related to the availability in a single fuse cutout of a double fuse time-current-characteristics which was obtained by using a current transformer which working zone included the saturated and non-saturated areas, changing the two paths current sharing depending on the overcurrent level, [18-20].

2. The concept of controllable fusing

With the aim to improve the fuse features, a new concept of controllable fusing has been patented, [21-22]. The controllable fusing means the possibility of fuse to operate at certain time moments when an external command is activated. The key element of the controllable fusing is an electrode which is placed on the fuselink element, as shown in Fig. 1, [23-24].

The electrode E, is made from graphite and is pressed on the copper strip of the fuse element F. The electrode terminal is made from brass in order to allow a good contact with the supply conductor. With the aim to supply this electrode, a detachable contact Cd, or a plug device is used in the case of more parallel fuselink elements, [25-26].

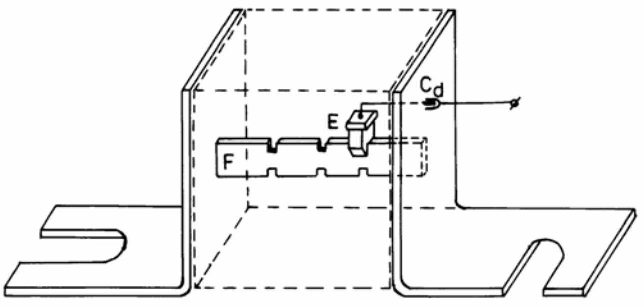

Fig. 1: Details of the new fuse cartridge based on the controllable fusing effect.

Thus, when an overcurrent occurs within an electric circuit where a high breaking capacity fuse is mounted to protect a device against overcurrents, especially shortcircuits, some transducers which are sensitive at current value, di/dt, temperature, etc., will provide a command signal for a power switch. This switch will supply with the necessary power the electrode E, Fig. 1, which finally will interrupt the fuse element F, through an auxiliary electric arc. Therefore, the fuse will turn off the main electric circuit.

3. Experimental tests

In order to test the new type of high breaking capacity fuse a test circuit has been used as shown in Fig. 2, based on a data acquisition board DAQ, programmed using LabVIEW software.

From the diagram of the power circuit used for experimental tests, we can observe the main circuit where the fuse under test SF, Fig. 2, is supplied from a high power current source TC. This is an electromagnetic device built on the principle of power transformers with a primary winding made with many turns and small cross-section, and the secondary winding has a few turns but with high cross-section proper for high currents. Thus, the current source is supplied with variable input voltage from the autotransformer ATR and provides high variable output current which flows through the fuse under test SF.

In order to obtain the controllable fusing an auxiliary energy is provided from the auxiliary transformer TA which is supplied by the autotransformer A-ATR. At the moment when we wish to test the fuse, the power electronic switch K, made with two thyristors mounted in antiparallel, which is controlled by the data acquisition board DAQ, will turn on and the supplementary energy from the auxiliary transformer TA, through the electrode E, will blow the fuse SF.

An adequate current transducer THC, type HTA 1000S using the construction principle of Hall effect, allows to record the prospective current.

The experimental tests have been done at different prospective current values. It has been tested high breaking capacity fuses with the rated current of 100A, a rated voltage of 690V, gG operating class and the supplementary current of the auxiliary source was about 20A. The fuse element is made from copper and has the following overall dimensions: length of 68mm, width by 18mm and thickness of 0.12mm. Silica sand used in the tests is the same as the industrial one.

Actually, the new fuse using the input data such as current, di/dt, temperature, etc., will process data with data acquisition board DAQ and provide the commands for an efficiently and safety circuit interruption.

Further on, the LabVIEW application’s front panels are shown in Fig. 3-5. The virtual instrument has been designed on the basis of tabs’ principle graphical programming. Thus, the first tab, Fig. 3, means the configuration module where the following parameters are specified: number of the device (data acquisition board), number of the analog input and digital output channel, scan rate and the signal limits (high and low) for analog input channel.

The second tab, Fig. 4 and 5, includes data processing and on the front panel there are the prescribed limits’button, the waveform of acquired prospective current, the desired time-current characteristic and a digital flag which indicates the status of the digital output channel (green – no digital output signal; red – digital output signal provided).

For normal operating conditions, Fig. 4, the acquired current value is under the low limit respect to time-current characteristic, thus the data acquisition board DAQ, will not provide digital output signal and the digital flag status has green colour.

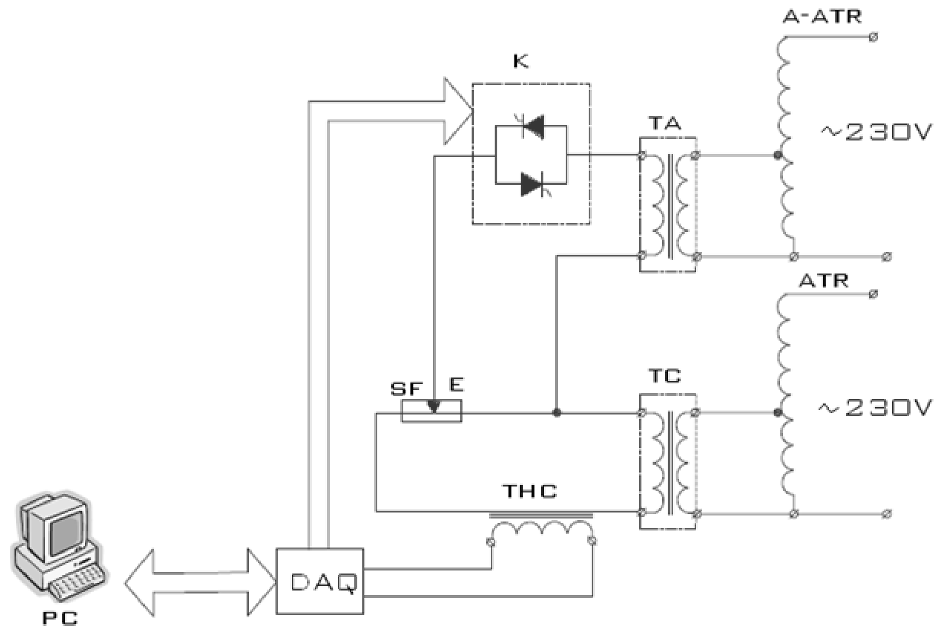

Fig. 2: Diagram of the power circuit for experimental tests of the new fuse.

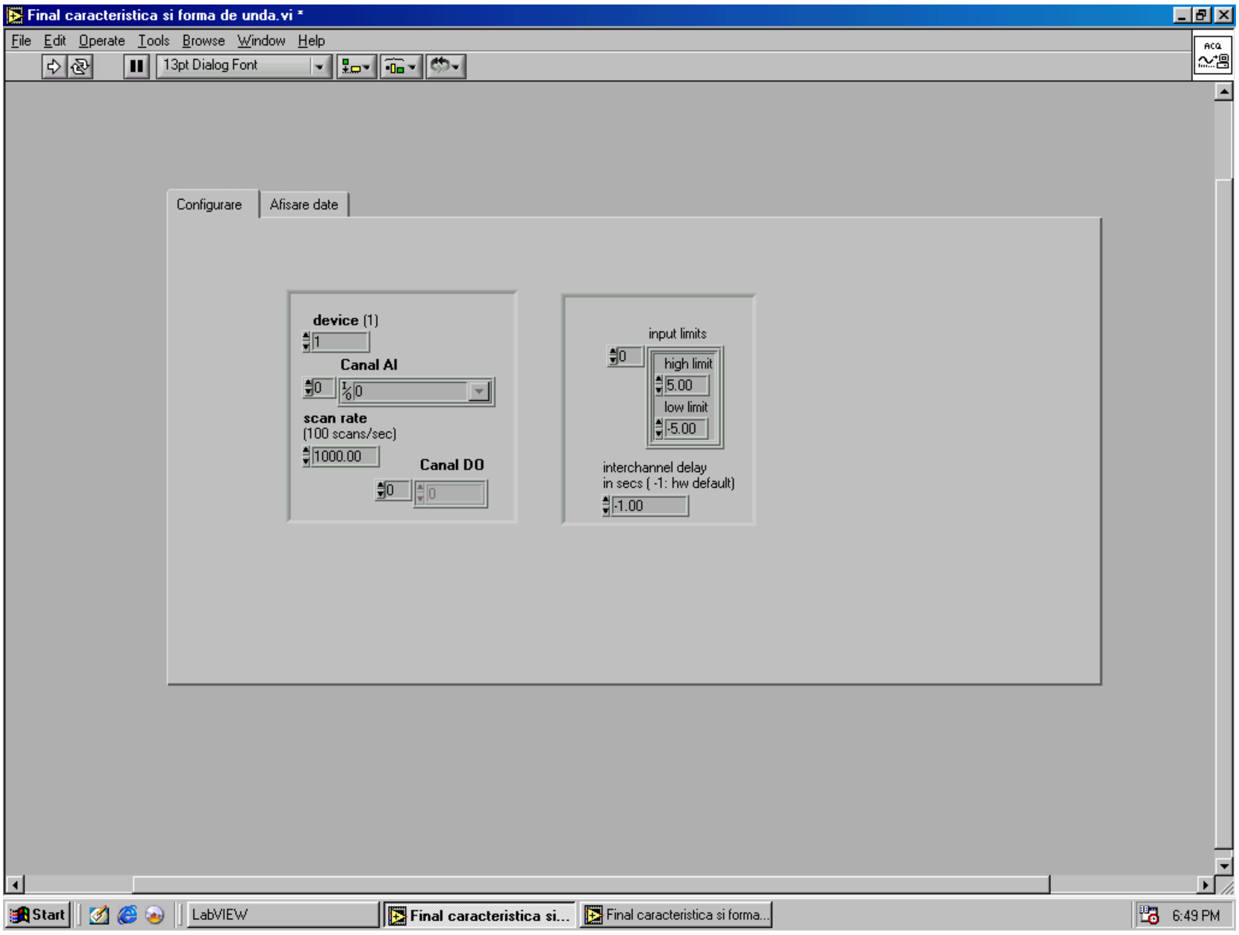

Fig. 3: Front Panel of the LabVIEW application: configuration of the data aquisition board parameters.

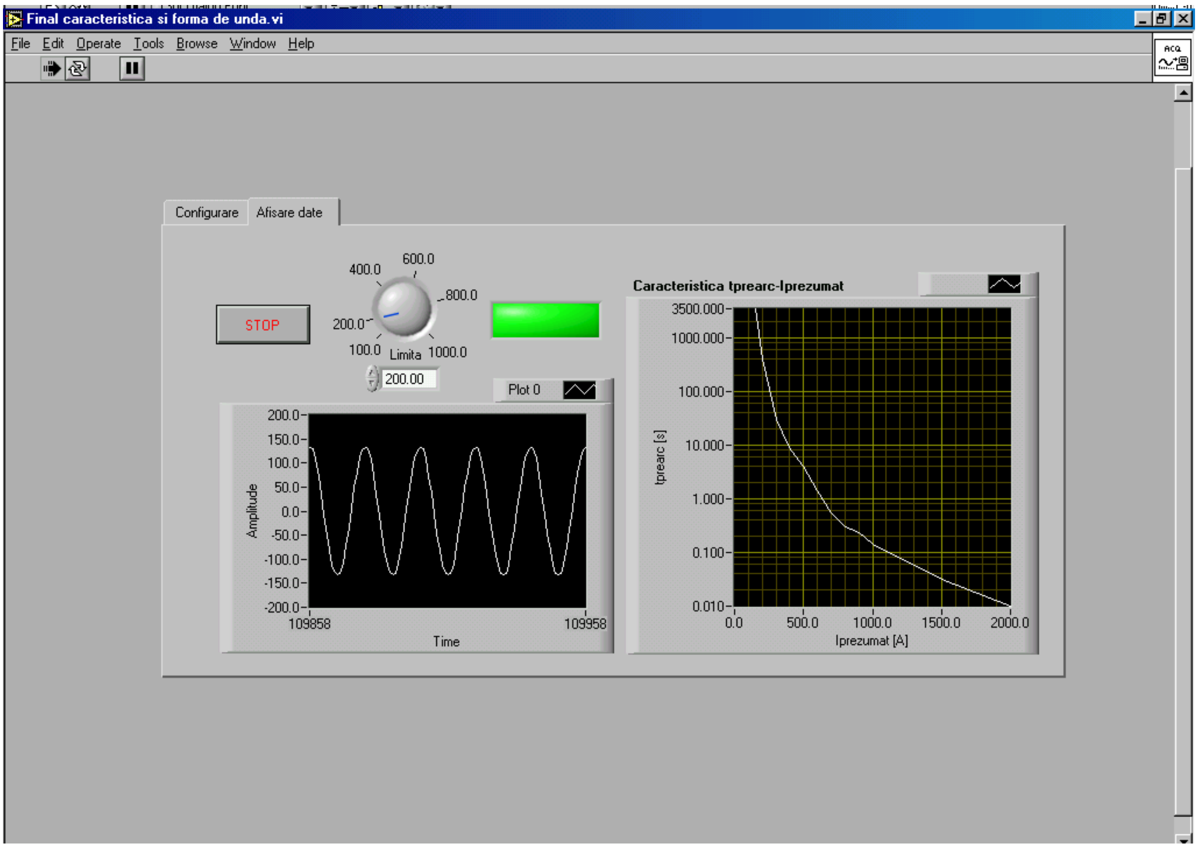

Fig. 4: Front Panel of the LabVIEW application: normal operating.

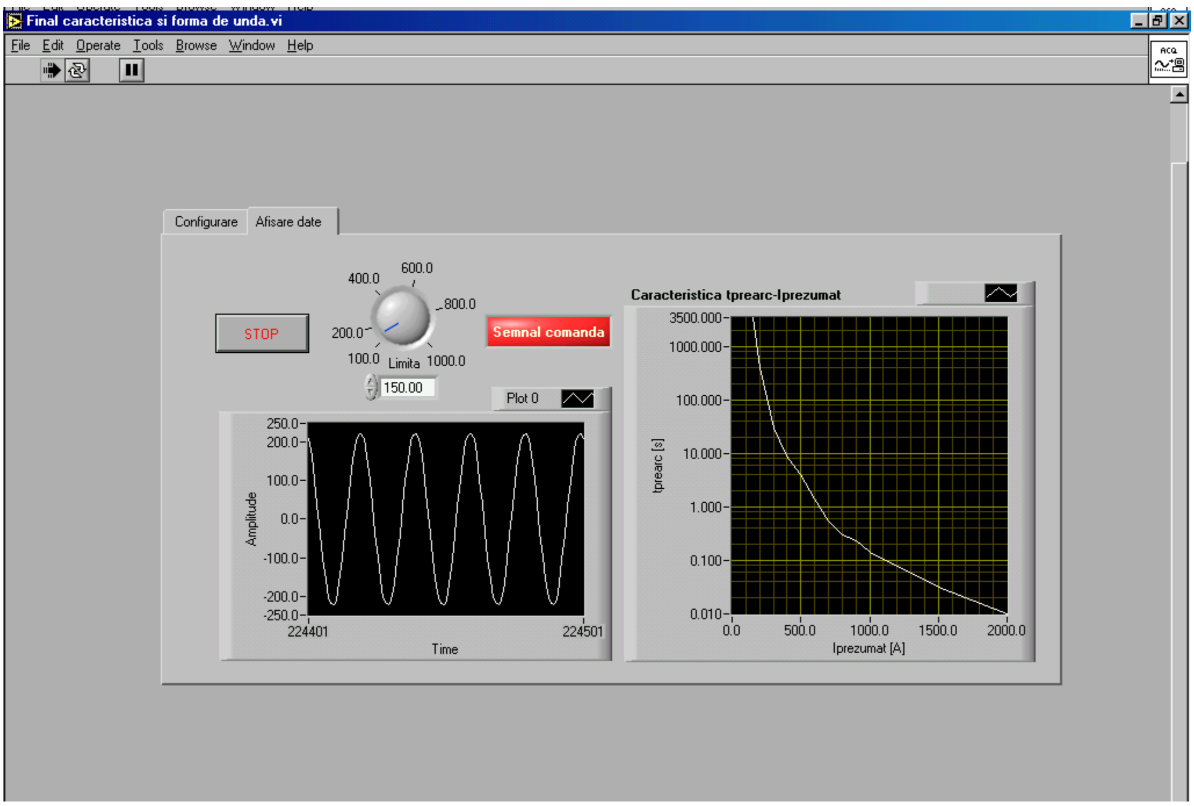

Fig. 5: Front Panel of the LabVIEW application: overload.

When the prospective current acquired value is over the low limit, then this value is compared with the values of the time-current characteristic and after a certain delay, the data acquisition board DAQ, will provide a digital output signal to turn on the power electronic switch K, and finally the fuse will blow. During this time, the digital flag status has red colour, Fig. 5.

The desired time-current characteristic is included as a fitted curve in the virtual instrument programmed with LabVIEW software. For instance, if the desired time-current characteristic is the catalogue one, for a 100A rated current and 690V rated voltage, this characteristic can be fitted by the equation below,

$$t(i) = \frac{a + c \cdot i^2}{1 + b \cdot i^2 + d \cdot i^4} \qquad (1)$$

where the parameters a, b, c and d have the following values:
a = 246.75;
b = $8.534 \cdot 10^{-5}$;
c = $1.952 \cdot 10^{-5}$;
d = $1.915 \cdot 10^{-9}$;

The fitted curve with the above parameters' values have been obtained using a specific fitting software. The comparison between the catalogue characteristic and the fitted one is shown in the figure below, Fig. 6.

Thus, there is the possibility to implement into the virtual instrument made with LabVIEW software, any desired time-current characteristic depending on the application where the fuse is mounted.

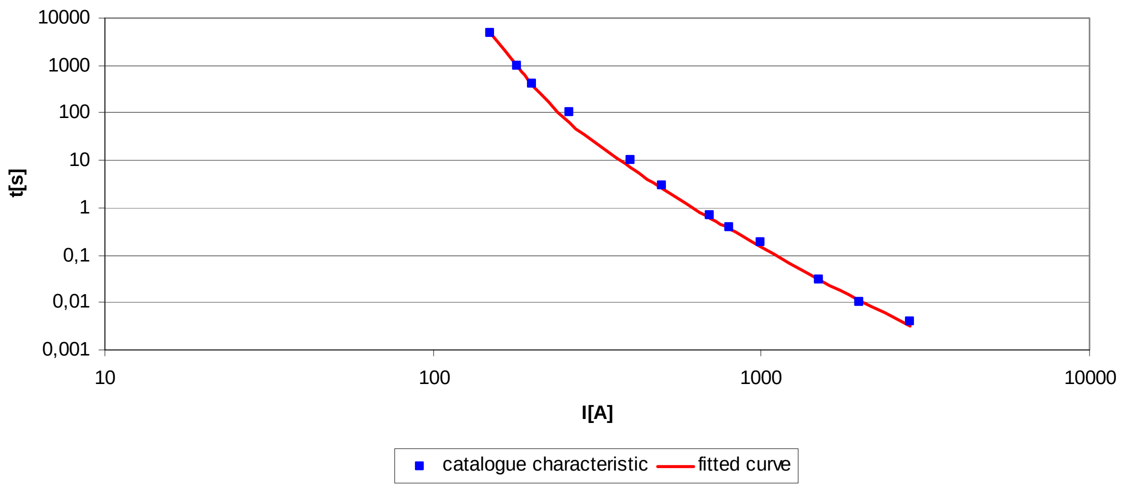

Fig. 6: Comparison between catalogue characteristic and the fitted one.

4. Conclusions

The theoretical aspects related to the new type of high breaking capacity fuse based on the controllable fusing effect and all the experimental tests outline that there is the possibility to extend the current protection range both to overloads and shortcircuits. Thus, the traditional passive overcurrent protection becomes an active one enhanced with new features such:

- controllable fusing level;
- controllable current-limiting effect;
- adjusted time-current characteristics;
- protection possibilities from overload to shortcircuits;
- protection to direct current sense and power line sense at AC applications;
- protection to di/dt.

Acknowledgements

This work was supported by CNCSIS – UEFISCDI, project number 706 PNII – IDEI code 352/2009.

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NEW SOLUTIONS FOR OVERCURRENT PROTECTIVE DEVICE DISCRIMINATION REQUIREMENTS

Matt Darr, Robert Douglass, Vince Saporita

New Solutions for Overcurrent Protective Device Discrimination Requirements

Matt Darr, Robert Douglass, Vince Saporita

Cooper Bussmann, P.O. Box 14460, St. Louis, MO 63178 USA

Abstract

The US National Electrical Code® (NEC®) [1] has initiated requirements for discrimination (selective coordination) in emergency, legally required, and critical operations power systems. While this required discrimination increases the reliability of critical, life-safety-related loads, it has been a challenge to design and install systems that discriminate with currently available fusible and circuit breaker equipment. Challenges included equipment footprint (size), interrupting rating, short-circuit current rating, and cost. Solutions led to a new UL Class fuse, a new load-break disconnect switch with the footprint of an MCCB, and a new MCCB-sized panelboard , all specifically designed to meet the discrimination requirements.

Keywords: overcurrent protective device.

Introduction

There are certain life-safety-related loads that are so critical, so important, that we go to great lengths to make sure that they are not interrupted. Examples of these life-safety-related loads are egress lighting for evacuation of a building, exit signs, fire detection and alarm systems, elevators, fire pumps, and many health care loads. We take special care of these systems/loads. Periodic testing, maintenance and record retention is required. Alternate power sources must be utilized. Emergency wiring must be kept separate from non-emergency wiring. Automatic transfer switches with sophisticated sensors, monitors, and controls are utilized.

Fig. 1: The NEC® requires discrimination for life-safety-related loads, such as for the emergency lighting for evacuation of this arena.

However, before adoption of the 1993 National Electrical Code®, there were no requirements for discrimination for any critical life-safety-related loads, even where large crowds gathered, such as stadiums, arenas (Fig. 1), high-rise office buildings, universities, and hospitals. So, there was no NEC® requirement, for example, that prohibited a short-circuit in a light fixture in the basement of a sports arena from opening overcurrent devices all the way up to and including the main for the entire arena. See Fig. 2.

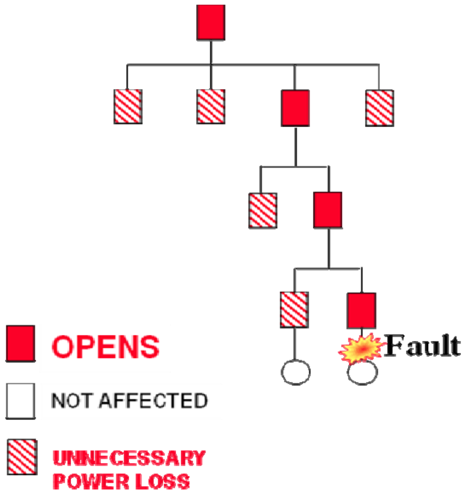

Fig. 2: This one-line diagram shows a fault on a branch circuit opening not only the branch overcurrent protective device, but also the sub-feeder, feeder, and main devices (solid boxes). There is an unnecessary power loss to numerous other loads (hashed boxes)

And, if an emergency generator and transfer switch were utilized, the transfer switch could switch the load to the emergency generator, but if the short still existed, a similar cascading of overcurrent devices could occur, again blacking out the entire building.

The 1993 National Electrical Code® initiated the concept of required discrimination.[2] It began with a requirement for complete discrimination of elevator circuits. In essence, an overcurrent in one elevator circuit is not allowed to open any other elevator circuits. So, an overcurrent in one elevator will not take out any other or even all the elevators. See Fig. 3.

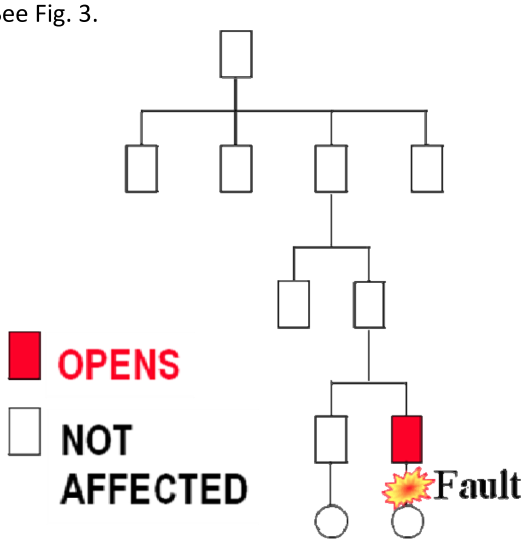

Fig. 3: This one-line diagram shows a fault in one elevator circuit opening only one elevator branch circuit overcurrent device. No other elevators are affected.

The 1993 National Electrical Code® change resulted in development, by at least four manufacturers, of elevator control panels utilizing fusible disconnect switches with shunt-trip capability. See Figure 4.

Fig. 4: This figure shows a fusible disconnect switch with shunt-trip capability so that all power to the elevator can be removed before the application of water in the elevator shaft.

The fuses in a traditional fused switch could, of course, easily discriminate with upstream subfeeder, feeder, and main fuses. The novel twist however was that shunt-trip capability was necessary to meet Mechanical Code requirements that all power be removed from the elevator shaft before the application of water (sprinklers) in the shaft. (So, if there were ever a fire in the elevator shaft, the elevator would travel to a "safe" floor, the doors would open, a signal would be sent to the shunt-trip switch, opening the shunt-trip switch, and then water would be released to douse the fire in the elevator shaft.)

Shunt-trip circuit breakers are available, but it is very difficult, or expensive to get them to discriminate with larger, upstream circuit breakers. As a result, the fused shunt-trip switch elevator panels have now become the standard design throughout the country.

In the 2005 National Electrical Code® requirements were introduced for complete discrimination of emergency[3] and legally required standby system[4] overcurrent protective devices. The emergency and legally required standby loads, typically served out of standard circuit breaker panelboards, include emergency lighting, smoke evacuation, exit signs, fire detection and alarm systems, and fire pumps.

While it was fairly easy to implement complete discrimination for elevator circuits, because the elevator circuit switch was typically a stand-alone unit, mounted in the elevator room, implementing complete discrimination for emergency and legally required standby systems was an interesting challenge. The challenge wasn't whether or not it could be accomplished from an engineering perspective, for it has been standard practice for military, business centers, and banking centers for decades. It was whether or not it could be accomplished in the same amount of space and without adding considerable cost as compared to non-discriminating systems.

The Challenge

For those wishing to meet the discrimination requirements by utilizing an all fusible system, panel size was an issue. A panelboard utilizing fusible switches has always been larger than panelboards utilizing circuit breakers. See Fig. 5. For example a 200 ampere, 480 volt, molded case circuit breaker panel is typically 50 cm (20") wide by 14.6 cm (5.75") deep. The typical fusible panelboard is 91.4-111.8 cm (36"-44") wide by 26.4 cm (10.4") deep. It is a difficult "sell" to convince an architect or consulting engineer to allow so much more room in their building.

Fig. 5: These pictures illustrate the typical difference in size that existed between a fusible panelboard on the left and a molded case circuit breaker panelboard on the right.

Some designers prefer to use thermal-magnetic molded case circuit breakers wherever possible. One method available to them that is often utilized to obtain or improve the discrimination of circuit breakers is to increase the case size of the larger, upstream circuit breaker, while keeping the trip rating the same. For example, if a 400 amp frame, 400 amp trip feeder circuit breaker were supplying a 20 ampere circuit breaker, the two would discriminate to about 4,000 amperes, (assuming the 400 ampere circuit breaker's instantaneous trip is about 10 times the frame rating of the circuit breaker). If an 800 amp frame circuit breaker were to utilize a 400 ampere trip, the 20 amp branch circuit breaker and the 800 amp frame/400 amp trip would discriminate to about 8,000 amperes. Such an increase is often all that it takes to obtain the necessary discrimination. The problem is that the 800 amp frame circuit breaker is considerably more expensive than the 400 amp frame circuit breaker, and it takes up more space in a panelboard.

Another method that is very often utilized is to remove the instantaneous trip on upstream circuit breakers and adjust their short-time delay settings to provide the required discrimination.

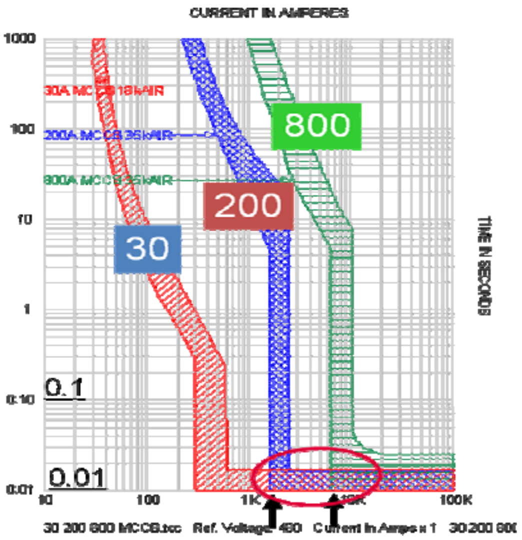

Fig. 6: This figure shows the overlap of three thermal-magnetic circuit breakers employing an instantaneous trip. A fault on the load side of the 30 ampere branch circuit overcurrent device exceeding about 7,000 amperes will open the 30 amp, the 200 amp, and the 800 ampere devices, for a total system blackout.

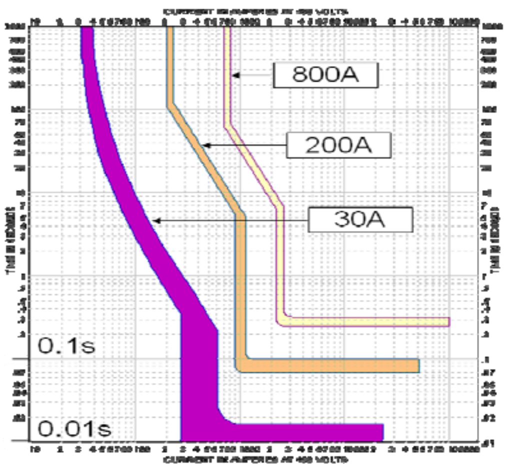

Fig. 7: This figure shows the affect of utilizing short-time delay on the 200 amp and 800 amp upstream circuit breakers. With clear "light" between the circuit breaker curves, discrimination is achieved up through the interrupting ratings of the devices.

Figures 6 and 7 illustrate the benefits of employing short-time delay to achieve discrimination. Fig. 6 shows the overlap of three thermal-magnetic circuit breakers employing an instantaneous trip. A fault on the load side of the 30 ampere branch circuit overcurrent device exceeding about 7,000 amperes will open the 30 amp, the 200 amp, and the 800 ampere devices, for a total system blackout. Fig. 7 shows the affect of utilizing short-time delay on the 200 amp and 800 amp upstream circuit breakers. With clear "light" between the circuit breaker curves, discrimination is achieved up through the interrupting ratings of the devices. Unfortunately, on the negative side, circuit breakers with no instantaneous, and without an instantaneous override, but having short-time delay are often quite expensive as compared to standard thermal-magnetic molded case circuit breakers. These types of circuit breakers, often air-frame or power circuit breakers, are usually much larger than their molded case cousins. Finally, when short-time delay is utilized, (and it is used every day for hospitals, banking and money centers, continuous process industrials, military bases, etc.) the equipment it is protecting must be short-circuit rated for the length of the short-time delay. For example, if a 800 ampere power circuit breaker, with a short-time delay set at 30 cycles, is protecting a transfer switch, that transfer switch must be able to withstand the full available short-circuit current for the full 30 cycles. This may result in the upsizing of the transfer switch so that it is capable of handling the available fault current for the extended period of time.

To summarize the "Challenge", discrimination can be achieved, using both fused systems and circuit breakers systems, but achieving discrimination resulted in larger and very often more costly equipment than is required for systems without discrimination.

The Solution

It became obvious that a different kind of fusible solution was needed for those designers that preferred fuses, (and maybe some designers that prefer circuit breakers would be willing to switch to fusible designs?). Before starting the design however, visits with users and specifiers determined that they wanted (1) Everything to be IP2X (fingersafe). (2) To make sure that fuses couldn't be removed while they were energized. (3) High short-circuit current ratings. (4) Fusible switch panelboards with the size, look and feel of circuit breaker panelboards. (5) Ampere rating rejection so that a 30 ampere fuse could not be replaced into a circuit calling for a 20 ampere fuse. And (6) Full discrimination must be achieved.

The need to meet the requirements for discrimination in the NEC® and the desire to provide users/designers with the features/benefits that they wanted resulted in new designs for fusible switches and panelboards that would accept them. The fuses that were chosen were UL Class CF.[5] They are current-limiting (Class J[6] current limitation requirements), finger-safe fuses rated for 600 volts AC with interrupting rating of 300,000 amperes (at 600 volts AC). The first family of Class CF fuses had time-delay characteristics and was introduced with yellow labels. Another family of Class CF fuses has since been introduced (with a blue label) that is fast-acting, with a 600 volt DC rating (in addition to the 600 volt AC rating). (It is especially useful when used on the load side of UPS systems, providing very quick isolation of a problem circuit before the UPS system shuts down.) Fig. 8 shows the three "case" sizes of time-delay Class CF fuses, 100A, 60A, and 30 A. Two fuses of each case size are shown. The one on the left is an indicating version, while the one on the right is non-indicating. Fig. 9 shows the top, side, and front views of the fuse. The "D" dimension changes with the ampere rating so that ampere rating rejection can be accomplished.

Fig. 8: This figure shows time-delay Class CF fuses in three case sizes, 100, 60, and 30 amperes.

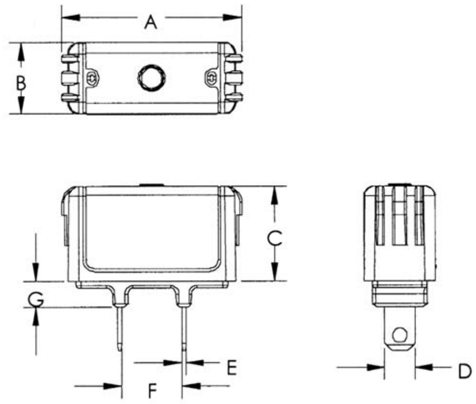

Fig. 9: This Figure shows the top, side and front views of the Class CF fuse. The "D" dimension increases with the ampere rating of the fuse in order to provide ampere rating rejection.

The Class CF fuse now needed a UL 98 disconnect switch [7] that could accommodate its IP2X rating. Fig. 10 shows the side view of the resulting disconnect switch and its matching time-delay Class CF fuse. Fig. 11 shows a 3-pole configuration of the fused switch with time-delay Class CF fuses and a 1-pole configuration with a fast-acting Class CF fuse. As the switch is closed, an internal pin drops down through the hole in the blade of the fuse. (See Fig. 9 for the location of the hole.) This prevents the fuse from being removed while the switch is energized. As the switch is being turned to the off position, the internal pin is removed, making it possible for the fuse to be removed in the de-energized (off) position.

Fig. 10: This figure shows the UL 98 disconnect switch matched up with the Class CF fuse.

Fig. 11:. The UL 98 disconnect switch is available in 1, 2, and 3 pole configurations. The 3-pole switch is shown with time-delay Class CF fuses while the 1-pole switch is shown with a fast-acting Class CF fuse

The switches include an open fuse indication light as an aid for maintenance personnel, as well as provisions for installing a lock to meet lock-out-tag-out safety requirements. See Fig. 12. Of great significance is that these switches are "load break" with horsepower ratings. They are full UL 98 disconnect switches. Another key point is that they are 25 mm (1") wide, to match up with circuit breakers.

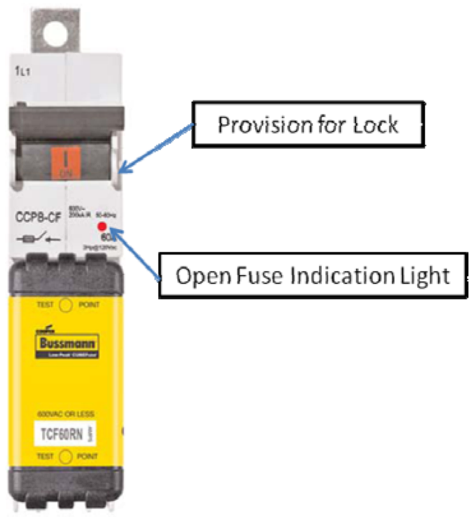

Fig.12: The disconnect switch for Class CF fuses has a built-in open fuse indicator light as well as provisions for installing a lock to meet lock-out-tag-out safety requirements.

With fusible disconnects available in a 25 mm (1") width, a panelboard was developed with dimensions to match competitive circuit breaker panels. 600 volt panels, up through 400 amperes are 50 cm (20") wide by 14.6 cm (5.75") deep. Fig. 13 shows a 200 ampere, 600 volt panelboard with a fused switch main. These panelboards are available with short-circuit current ratings of either 50kA or 200kA. There are provisions for storing spares. See the row of spare time delay Class CF fuses across the bottom of the panel.

Fig. 13: This figure shows a 200 ampere, 600 volt panelboard with a 200 ampere main fused switch with 200 ampere Class J time-delay fuses. Spare fuses are located in the horizontal row across the bottom of the panel. Panel can have either a 50kA or 200kA short-circuit current rating.

This panelboard makes it easy for the designer/installer to achieve discrimination (simply maintain a 2:1 ratio between line side fuse and load side fuse) with the same look, feel, and footprint (size) of a circuit breaker panel.

Conclusion

Changes to the NEC® to require full discrimination for certain life-safety-related loads in places of assembly, such as hotels, stadiums, arenas, universities, and high rise office buildings created a challenge for engineers/installers. They were able to achieve full discrimination using both fuses and circuit breakers, but the available solutions were generally larger and more costly than similar systems that did not achieve full discrimination.

A new UL fuse Class was developed (Class CF), along with a 25 mm (1") wide, UL 98, load break disconnect switch that would fit into a 50 cm (20") wide by 14.6 cm (5.75") deep panelboard. This combination met the demands of the engineers/installers which were (1) Everything had to be IP2X (fingersafe). (2) Fuses couldn't be removed while they were energized. (3) High short-circuit current ratings. (4) Fusible switch panelboards with the size, look and feel of circuit breaker panelboards. (5) Ampere rating rejection so that a 30 ampere fuse could not be replaced into a circuit calling for a 20 ampere fuse. And (6) Full discrimination must be achieved.

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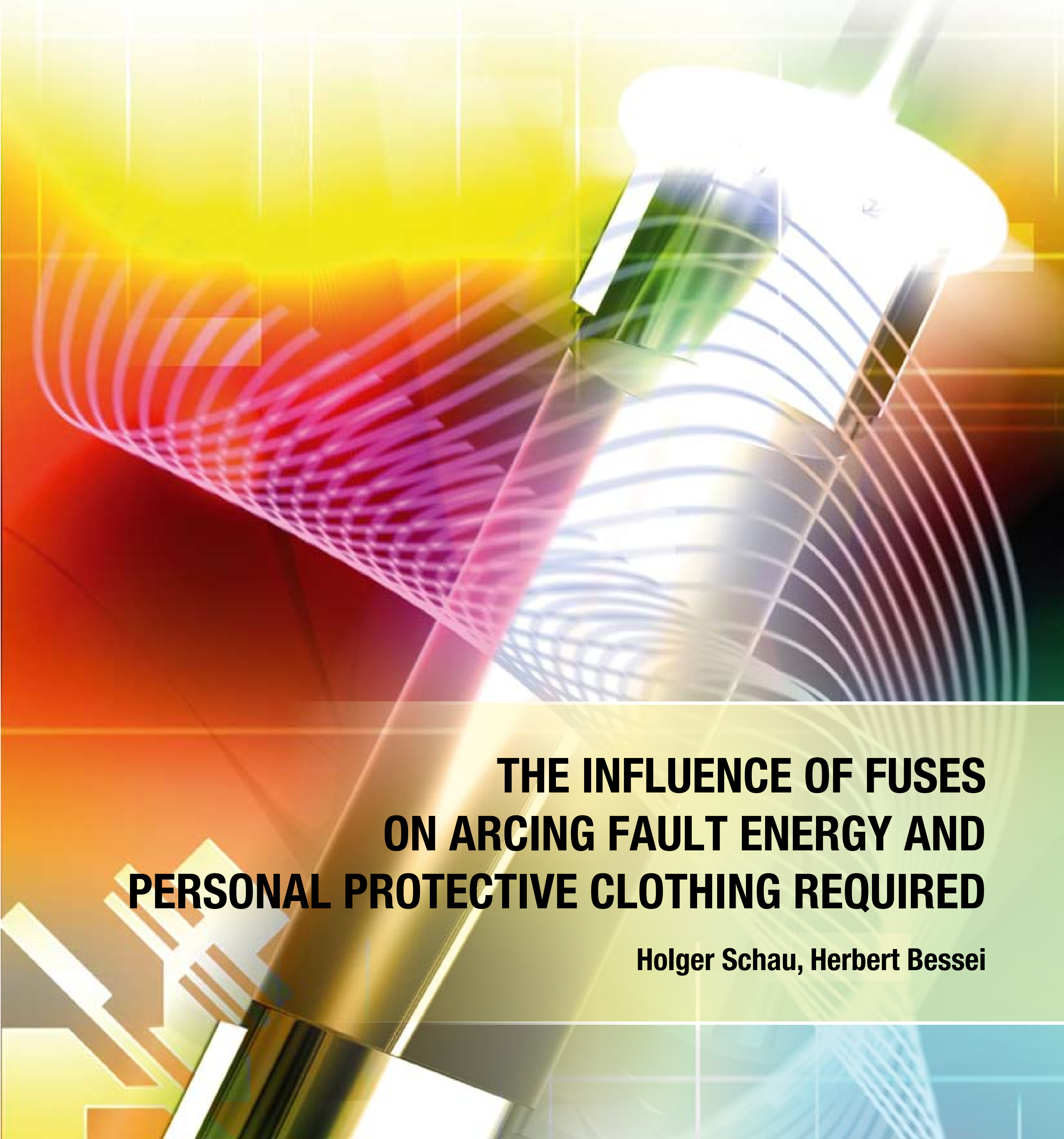

THE INFLUENCE OF FUSES ON ARCING FAULT ENERGY AND PERSONAL PROTECTIVE CLOTHING REQUIRED

Holger Schau, Herbert Bessei

The influence of fuses on arcing fault energy and personal protective clothing required

Holger Schau[(1)], Herbert Bessei[(2)]

[(1)] Technische Universität Ilmenau, POB 100565, D-98684 Ilmenau, Germany, holger.schau@tu-ilmenau.de
[(2)] fuseXpert, Geibstr. 27, D-55545 Bad Kreuznach, Germany, hbessei@fuseXpert.de

Abstract

The level of personal protection required against the thermal risks of electric fault arcs is influenced by the characteristics of the electrical protective devices as well as the protection level of the PPE, both aspects shall be co-ordinated. The electrical protective devices determine the utilization range of PPE. Fast-acting protective devices may significantly increase those ranges. Being proportional to the arcing fault energy, the thermal arc hazards are strongly influenced by the short-circuit duration. NH fuse-links, when correctly selected by also taking into account the current attenuation effect of the fault arcs, may reduce short short-circuit durations significantly.

Measurements and test were carried out in the high-power lab to evaluate the breaking characteristics of NH fuse-links in a LV short-circuit current path with fault arcs and the resulting thermal risks of fault arcs when controlled by the fuses. The incident energy resulting from the fault arcs is measured for this purpose. Conclusions are drawn on what protective clothing tested according to the box test (EN 61482-1-2) may provide adequate personal protection in dependency on prospective short-circuit current and fuse rating.

Keywords: LV arcing fault, fuses, fault duration, incident energy, personal protective equipment.

1. Introduction

The electric fault arcs occurring with short-circuit faults in electric power equipment and installations are enormous sources of power. There are particularly thermal effects (radiation and convective heat flux, metal splash) with high risks for persons especially in case of direct exposure, e.g. during live working or working in the vicinity of live parts.

From risk analysis [1] the hazards and effects of fault arcs are known to be mainly dependent on

- electric arc energy W_{arc},
- electric arc active power P_{arc},
- duration of arcing fault t_{arc},
- distance to the arc a.

The physical parameter characterizing the thermal effects at an exposed surface is the incident energy E_i. This is the density of the heat energy resulting from the heat flux in the distance a from the arc. The relationship between the electric arc energy and the incident energy is, however, very complex and sophisticated. The heat transmission function f_T is nonlinear and depends from a large variety of influences [1,2]:

$$E_{i0} = f_T \cdot W_{arc} \qquad (1)$$

The electric arc is a thermodynamic system showing a stochastic behavior with strong changes with time. It is not possible to derive a general transmission function. And it is also impossible to exactly calculate the incident energy on the base of a physical model.

The electric arc energy is determined by the arc active power and the arc duration. The electric arc active power depends on the conditions of the electric power system (short-circuit capacity of the system) and the power equipment construction. The arc duration is equal to the fault duration t_k and is determined by the clearing time of the network short-circuit protection devices (or special electric protective devices installed).

Consequently, personal protection can generally be achieved by limiting the exposure energy as well as the arc duration.

Tested personal protective equipment (PPE), mainly protective clothing, is the necessary preposition to prevent personal injury if there is the risk of direct arc exposure while working. The most important technical measure to protect persons consists, furthermore, in the use of suitable electrical short-circuit protective devices such as electrical fuses (e.g. NH fuse-links). If co-ordinated, PPE and electric protective devises may together essentially contribute to increase personal safety against electric fault arcs.

Measurements in the high-power lab have been carried out. The experimental investigations were made at the set-up and test system of the box test according to IEC or EN 61482-1-2, respectively, with installing fuses of different ratings in the electric test circuit and measuring the electric arc energy and incident energy. These tests enable in principle to draw conclusions on the limitation of the arc hazards by means of fuses.

2. Test set-up

All tests of the lab measurements described in this paper were performed according to EN 61482-1-2 [1]. The test facility includes the following elements:

- electrical test circuit and electrode assembly
- test box surrounding the electrodes,
- test plate with two calorimeters,
- measuring system,
- data acquisition system.

The electric test arc is fired between two vertical electrodes surrounded by a plaster box with a parabolic shape and a volume of $1.6 * 10^{-3}$ m^3. The box is open to one side. In front of this opening a test plate where the incident energy is measured is placed.

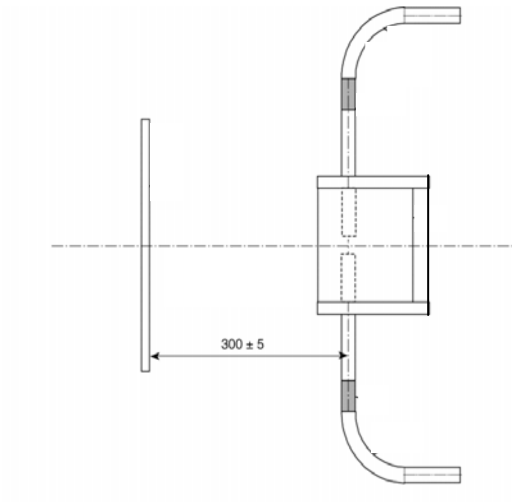

Fig.1: Principle set-up for arc tests

Fig. 1 shows the test box with electrodes and the power supply cables as well as the test plate. The distance between test box and test plate is exactly 300 mm.

The upper electrode consists of aluminum and the bottom electrode is made of copper, both with a diameter of 25 mm. The electrodes are arranged in a distance of 30 mm (electrode gap).

The test plate consists of an insulating and heat-resistant material. The test plate is centered to the arc and parallel to the perpendicular arc axis. Two copper calorimeters are mounted in the plate.

3. Electrical test parameters

The tests were performed in the high-power test laboratory supplied by a test transformer of 800 kVA.

The test voltage was 400 V AC (50 Hz). Tests were carried out in three series of different prospective test currents. The prospective short-circuit current (metallic short-circuit of electrodes) in the 2-phase circuit was set to values of 2.3, 4 and 7 kA. Metallic short-circuit tests as well as arc tests were performed. The test circuit impedance ratio R/X is shown in Tab. 1.

Tab.1: R/X ratio of the test circuit impedance

Test current	R/X
2.3 kA	0.21
4.0 kA	0.44 and 0.55
7.0 kA	0.56

Tests were started by switching-on the test circuit by a contactor. The test arcs were fired by means of a fuse wire. The fuse installed in the test circuit broke the test circuit. In those cases the test duration (current flow) was not interrupted by the fuse after 1 s a test circuit breaker switched-off the circuit.

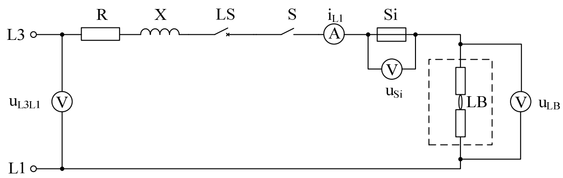

Fig. 2: Electric test circuit

Fig. 2 shows the test circuit. The abbreviations stand for:

L3, L1	phase 3, phase 1,
R	resistance,
X	reactance,
LS	circuit breaker,
S	contactor,
Si	fuse,
LB	arc (simulated fault arc).

The data acquisition system recorded the phase-to-phase voltage (u_{L3L1}) of the test circuit, the actual test current (i_{L1}), the arc voltage (u_{LB}), the fuse voltage (u_{Si}), and the temperature rise curves of the two calorimeters. In the arc tests the test current recorded is the arc current.

The fuses installed in the test circuit were NH fuses 500 V AC (NH00, NH1, NH2, NH3). Fuses with various ratings (100 A to 500 A) and different operational characteristics (utilization ranges: general purpose gG, and ultra-fast characteristic aR) were used. The majority of tests was performed with the general purpose NH fuses for line protection. In a limited number so-called “work protective fuses” with ultra-fast characteristic were investigated.

Fuses of different manufacturers were used.

4. Test program

As mentioned above, the test program was separated in three different test series. Each test series differs from the other one by the prospective short-circuit current of the test circuit. First a short-circuit current of 2.3 kA was set. In this series fuses with rated currents (fuse ratings) of 100 A up to 315 A were tested. The second series included fuses of 100 A up to 400 A with a short-circuit current of 4 kA. In the third series fuses of 200 A up to 500 A were used, the short-circuit current was 7 kA.

At the beginning of each series the short-circuit current, which was available, was measured by shorting the electrical circuit. Then fuses of the each rating selected were tested three times: first the test was carried out for bolted fault (without any fault arc), and then twice with fault arc.

In the following, the test current is always indicated as r.m.s. value of the bolted prospective current. The actual current flowing in the fault arc tests is named as arc current.

5. Measurement evaluation

As a first step the measured values were evaluated to identify electrical arc energy. A quantification of arc energy was achieved by measuring arc current and arc voltage. With the knowledge of operating time (t_{op}) the arc power is to be calculated:

$$W_{arc} = \int_0^{t_{op}} p_{arc}\, dt = P_{arc} \cdot t_{op} \,. \qquad (1)$$

The incident energy can be calculated from the temperature rise curves of the calorimeters using the following equation:

$$E_{i0} = K \cdot dT_{\max} \,. \qquad (2)$$

Because the calorimeters are directly exposed to the arc this is the direct exposure incident energy E_{i0}. K is the calorimeter constant. It is the product of the mass and specific heat of the calorimeter copper plate divided by its cross-sectional area. It has to be multiplied by the maximum temperature rise measured (delta peak temperature) dT_{max} during the arc test observation time of 30 s.

The evaluation of the incident energy is based, according to the box test procedure, on the Stoll limits for the onset of second degree skin burns [4]. The corresponding Stoll value is found by means of the Stoll constant S = 50.204 kW/m^2 and the time t_{max} when the delta peak temperature is reached (time to delta peak temperature) with the equation:

$$E_{i\ Stoll} = S \cdot t_{\max}^{0,2901} \qquad (3)$$

The time to delta peak temperature is in a range of about 4…10 s under the energy conditions studied.

The comparison of the incident energy measured and the Stoll value gives the conclusion about second-degree burns. If the measured value is above the Stoll value, second-degree skin burns may occur. For this estimation always the larger incident energy value measured by the two calorimeters was used.

According to IEC 61482-1-2 in PPE testing there are two test or protection classes, class 1 and class 2. The PPE tests are to prove if PPE protect persons under the test exposure conditions by being thermal arc resistant and preventing incident energies causing 2nd degree burns (transmitted incident energies may not exceed Stoll limits). The Stoll curve is not exceeded if PPE of the according class are used. The classes are characterized by the energy levels according to Tab. 2.

Tab. 2: Box test protection levels

class	E_{i0} in kJ/m^2	W_{arc} in kJ
1	135	158
2	423	318

The class energy values characterize the energy levels up to which PPE provide protection against the thermal hazards of fault arcs. These levels are used for assessing if the arc energies resulting in case of fault interruption by a fuse exceed the protection level of PPE.

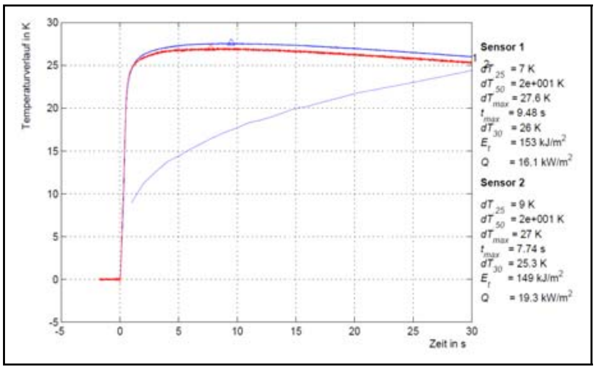

Fig. 3: Temperature rise curves of the two calorimeters measured for an example

Fig. 3 shows the temperature rise curves of the two calorimeters measured for the example of an arcing fault with a prospective short-circuit current of 4 kA interrupted by a 315 A gG fuse. The delta peak temperatures are marked in the curves. In addition the Stoll limit curve is also presented in this figure in form of a transformed temperature-time curve illustrating that the Stoll limit is exceeded significantly in this case. The incident energy (highest value) is 153 kJ/m², meaning that personal protection is not given for PPE class 1 but would be provided by using class 2 PPE.

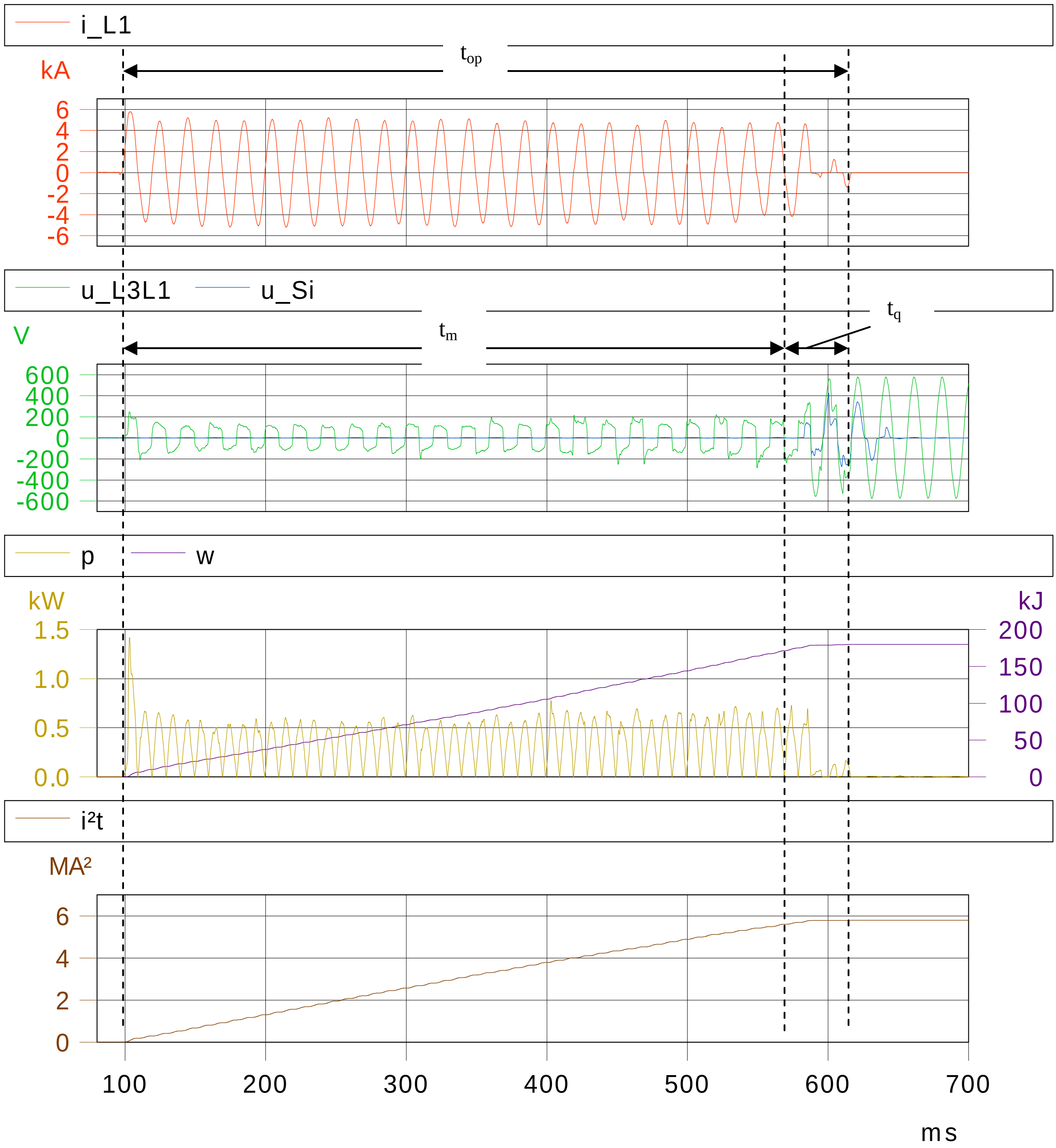

Fig. 4: Oscillograms of the electrical parameters of a test example (test current 4 kA, fuse NH2 gG rating 315 A)

The oscillograms of arc current, arc voltage and fuse voltage for this example are shown in Fig. 4. Furthermore the arc power (instantaneous values p), the electric arc energy and the operational integral of the fuse (MA^2s) are presented. This fuse integral i^2*t is calculated for all tests, too.

The arc energy over the interval of test arc existence is about 180 kJ. The same conclusion (as found before on the base of the incident energy consideration) results from this value: class 1 PPE does not provide personal protection but class 2 PPE will do it.

The energy values are connected with the operation time (t_{op}) of the fuse (fusing time). The operating or fusing time t_{op} consists of the melting (or pre-arcing) time (t_m) and fuse arcing time (t_q). The fuse arcing time is that time which is necessary to extinguish the switching arc within the fuse cartridge. The time periods are marked in Fig. 4. In the example there is a fusing time of 575.1 ms. The melting time is 487.1 s and the fuse arcing time is 88 ms. The fusing time is equal to the arc duration t_{arc} and presents also the short-circuit duration t_k.

The ratio of the prospective fault current to the fuse rated current is 12.7. The arc current in the test being 3.34 kA, a ratio arc current to fuse rating of 10.6 results.

6. Measurement results

6.1. General breaking behavior

The breaking behavior is generally characterized by scattering. In the arc test the fault arc current determines the breaking process. The arc tests are repeated twice for each test setting, always the longer fusing time and greater energy values were selected as the according test result. So results are on the safe side.

Depending on the ratio between the test current and the fuse rating, the fuses show current-limiting breaking or non-current-limiting breaking. In the example in Fig. 4 the latter one is given.

Current-limiting breaking is characterized by a very fast fuse operation in case of large current. The fusing time (operating time) is shorter than a current half-cycle, the current does, as a rule, not reach its prospective peak value. The fuse switching arc limits the let-through current. The operational time is not only dependent on the current but also on a variety of other parameters such as switching angle, impedance ratio R/X etc. Regarding the fusing time, the fuse behavior is in a "chaotic range" [5], meaning that there is no clear defined function or tendency. The fuse behavior is characterized by its melting integral (pre-arcing), the time values given in the fuse characteristic are so-called "virtual" operating times that are not equal to the real operating times.

In those cases the fault arc energy as well as the thermal incident energy resulting is in general very small because of the short fusing times being below about 10 ms. The current-limiting range has no practical importance what will be shown by the following estimations, too.

Work at opened switchgear or live working is usually practiced up to a range of the prospective 3-phase short-circuit current of about 25 kA. The short-circuit current in the L.V. main distribution of a 630 kVA transformer is about 22.5 kA maximum. In a 400 V system the normalized arc power k_P is about 0.38 (for the R/X of 0.2) according to [2]. For the maximum power system short-circuit capacity

$$S_k'' = \sqrt{3} \cdot 0.4 \text{ kV} \cdot 22.5 \text{ kA} = 15.588 \text{ MVA}$$

resulting from the current range up to 22.5 kA and the short-circuit duration t_k (according to the fusing time) of 10 ms, the electric arc energy is only

$$W_{arc} = k_P \cdot S_k'' \cdot t_k = 0.38 \cdot 15.588 \text{ MVA} \cdot 10 \text{ ms}$$
$$W_{arc} = 59.2 \text{ kJ}$$

to be expected in case of a 3-phase arcing fault. The incident energy will not be larger than 78.7 kJ/m² (using the maximum box test ratio between incident energy and electric arc energy of 1.33 according to Tab. 2 as worst case estimation). The real arc energy and incident energy values will be (under circumstances significantly) smaller in most practical fault scenarios.

The Stoll limit resulting for a time to delta peak temperature of 4 s is 75.1 kJ/m², for 5 s it is 80.1 kJ/m². In most practical cases time to delta peak temperature is longer, leading to higher Stoll limits. That means that the Stoll limit will not be exceeded and there is no risk of second degree skin burns if there is a current-limiting fuse breaking behavior. In addition the energy values are far below the energy limits of class 1 PPE.

In the arc test carried out with current-limiting fuse interruptions the arc energy was in a range of only about 2…14 kJ. The incident energies ranged between 2.5 and 11.7 kJ/m^2.

For these reasons mentioned before the current-limiting fuse operation can stay and will be out of consideration in the following.

The test series have shown that a current-limiting fuse behavior was given under arcing fault conditions if the ratios of the prospective (bolted) fault current to the fuse rating current $I_P/I_{nSi} = I''_k/I_{nSi}$ was higher than 20…25 for general purpose fuses (utilization category gG). In case of very fast-acting characteristic fuses (aR) a ratio I''_k/I_{nSi} > 8…10 is necessary to obtain a current-limiting fuse behavior.

In practical applications as so-called "working protective fuses" which are temporarily installed during live working activities take place in power equipment, often NH aR fuses with ratings of 160 A to 250 A are used. Consequently the current-limiting behavior may be expected in case of arcing faults if the prospective short-circuit currents at the working places are higher than 1.3 to 2 kA what is given in most practical scenarios.

NH fuse links operating current-limiting provide personal protection by preventing arc durations causing thermal risks. Higher arc energy and incident energy levels result from longer arc durations which are resulting from a non-current-limiting behavior. These conditions have to be considered mainly in the following.

6.2. Operating times

In the Fig. 5 to 10 essential analysis results of the measurements are summarized. These figures show the fusing times, arc energies and incident energies measured in the arc tests for non-current-limiting fuse behavior. All results refer to NH fuses of the utilization category gG (general purpose fuses).

The measurement results are supplemented by extrapolations, made on the base of tendencies obtained in connection with fuse t-I characteristics, to draw conclusions on protection ranges.

Fig. 5 shows the fuse operating times t_{OP} measured in the 3 series of different prospective short-circuit currents in the arcing fault tests. The parameter is the fuse rating I_{nSi}.

Regarding fusing times also bolted faults are considered.

The fusing time depends mainly on the actual fault current flowing in the electric circuit. This current is strongly influenced by fault arc conditions. There is a current attenuation resulting from the nonlinear fault arc resistance. In the test series the current attenuation factor was between 0.78 and 0.87 (average 0.85) according to the test set-up (particularly the electrode gap of 30 mm). In general the current attenuation is dependent on different factors [2].

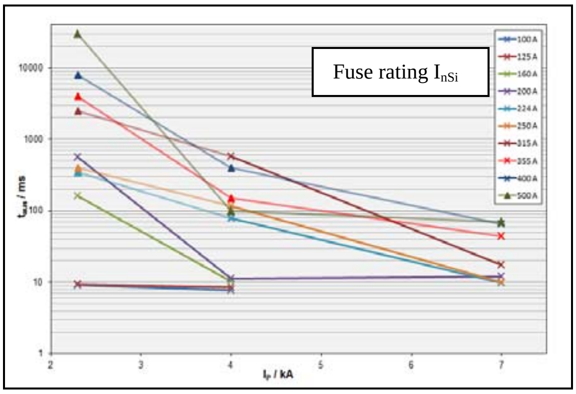

Fig. 5: Fuse operating times versus prospective short-circuit current for arcing faults (x –measured, Δ – extrapolated), gG fuses

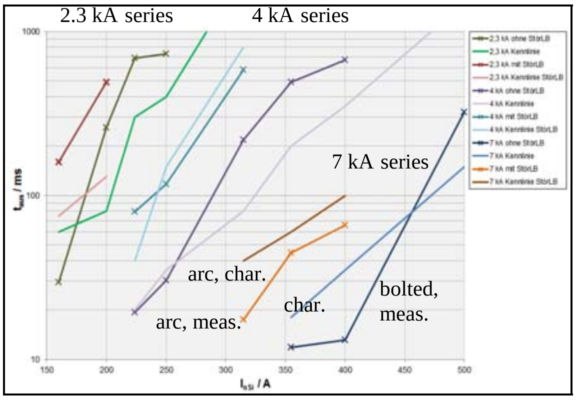

Fig. 6: Comparison of the fuse operation times for bolted faults and arcing faults measured in the 3 test series with the values obtained from the characteristics, gG fuses

Consequently the fuse operating times are longer in case of arcing fault tests than those of bolted short-circuit tests. The determination of the fuse operating time for arcing faults has to be based on the actual fault arc current. Because the arc resistance varies stochastically the actual current attenuation or arcing fault current cannot be predicted exactly. Fusing time determination based on bolted short-circuit currents generally result in a considerable inaccuracy.

Measurement results show also deviations to the theoretical operating times according to fuse current-time characteristics. In Fig. 6 the fuse operating times measured in the 3 test series for bolted as well as arcing faults are shown in separate curves as well as the values obtained from the fuse characteristics by means of the bolted fault current and the actual arc current measured (theoretical values). The curves connect the values for the different fuse rating currents. The first 4 curves belong to the 2.3 kA series, the second 4 curves to the 4 kA series, and the last 4 curves to the 7 kA test series with different fuse ratings. The curves of the values measured are marked by crosses, the curves without marking result from the characteristics. The curves for bolted faults show the shorter operating times and are, consequently, left of those of the arcing faults.

6.3 Arc energy

In Fig. 7 the electrical arc energy is shown as a function of the prospective short-circuit current. A curve is plotted for each fuse rating.

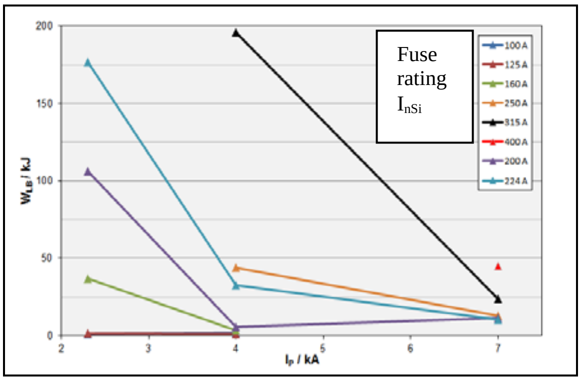

Fig. 7: Electric arc power measured in the test series in dependency on the prospective short-circuit current, gG fuses

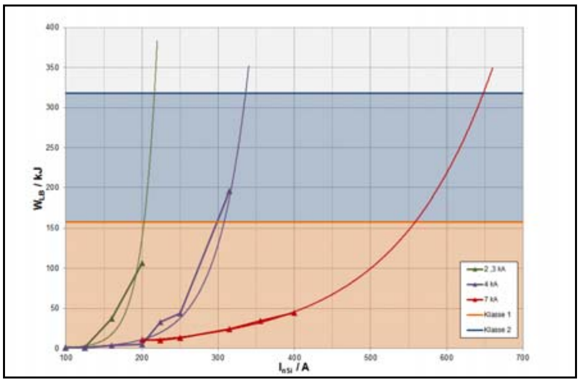

Fig. 8: Electric arc energy to be expected in dependency on NH fuse rating (measured values and extrapolation functions for the different short-circuit currents), gG fuses

The arc energy is the higher the larger the fuse rating is, and the smaller the prospective short-circuit current is. The arc energy increases when the ratio between prospective short-circuit current and fuse rating current becomes smaller. The critical cases from the protection point of view are small ratios I''_k/I_{nSi}. Main reason is the increase of the arc duration (fuse operating time) with decreasing fault current for a given fuse rating.

In Fig. 8 the arc energy is shown in dependency on the fuse rated current. For each individual short-circuit current a curve is plotted. The electrical arc energy increases with rated current as found before.

The measurements were supplemented by extrapolation curves derived from regression functions and estimations based on fuse characteristics and fusing times expected for attenuated fault currents. In the figure, furthermore, the protection ranges of PPE are marked. The red range indicates the protection by PPE class 1, the blue one the range of PPE class 2. It can be concluded up to which fuse rating personal protection is given by the fuse in combination with class 1 or class 2 PPE for the according prospective short circuit current. For instance, with a prospective short-circuit current of 4 kA and a fuse rating of 315 A there is protection with class 2 PPE (see example in Par. 5), with a 355 A fuse the protection does not more exist. As another example, for prospective short-circuit currents higher than 7 kA personal protection against the thermal hazards of electric fault arcs can be assumed as long as the fuse rating is 500 A or lower when using PPE of class 1, and not higher than 630 A when using PPE class 2.

6.4 Incident energy

Fig. 9 shows the incident energy measured for the 3 prospective short-circuit currents with the different fuse ratings. There are generally the same relationships as found before in case of the arc energy.

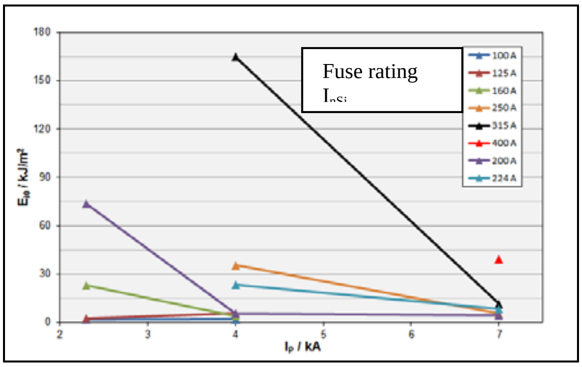

Fig. 9: Incident energy in the test series in dependency on the prospective short-circuit current, gG fuses

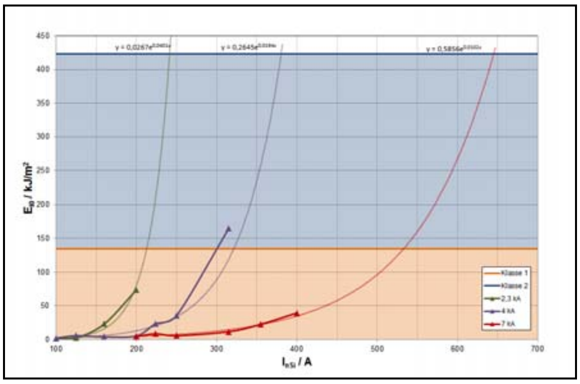

Fig. 10: Incident energy to be expected in dependency on NH fuse rating (measured values and extrapolation functions for the different short-circuit currents), gG fuses

In Fig. 10 the incident energy is shown as a function of the fuse rated current. Each of the individual short-circuit currents analyzed are represented by a curve. The curves are similar to the curves of Fig. 8 for the arc energy, too.

Regarding the conclusions for the protection ranges resulting from the application of the fuse ratings, the limits found on the base of the arc energy are also confirmed by the consideration of the incident energy.

7. Summary of test results

Table 3 presents a summary of the results achieved. It shows the fuse ratings up to which personal protection against the thermal hazards of an electric fault arc will be provided in combination with PPE of class 1 or class 2. The green colored range (marked by “+”) characterizes the combinations where protection is given. In those cases where the measurement results are close to the limits a categorization on the “safe side” was chosen. The results are valid for general purpose fuses (gG).

According to the tests in which 3 levels of the short-circuit current are adjusted, the application of the results has to made so that each line of the table is valid for a prospective short-circuit current equal or larger than the value indicated (minimum short-circuit current. It is useful to supplement the investigations by measurements for other levels of prospective short-circuit currents, too. For a given short-circuit current the protection situation may be improved by using a smaller fuse rating. The protection range limit is described by the maximum fuse rating.

The results of Tab. 3 are valid for 2-phase short-circuits. The energy levels measured result from a 2-phase fault arc. In case of 3-phase arcing the electric arc energy and the incident energy are higher. Consequently the protection limits are displaced.

Tab. 3: Protection ranges resulting from the use of NH gG fuses and PPE (2-phase arcing faults)

Prospective short-circuit current	PPE box test class	NH fuses gG AC: fuse rating I_{nSi} in A									
		NH 00			NH 1			NH 2			NH3
		100	125	160	200	224	250	315	355	400	500
2.3 kA	Class 1	+	+	+	+	-	-	-	-	-	-
	Class 2	+	+	+	+	+	-	-	-	-	-
4 kA	Class 1	+	+	+	+	+	+	-	-	-	-
	Class 2	+	+	+	+	+	+	+	+	-	-
7 kA	Class 1	+	+	+	+	+	+	+	+	+	+
	Class 2	+	+	+	+	+	+	+	+	+	+

8. Conclusions

The paper considers the use of NH fuses for reducing thermal hazards of LV fault arcs. For measurements the test set-up and a corresponding test program are introduced. The evaluation of measurement data covers the main parameters determining the protection needs, such as arc duration, electrical arc energy and incident energy. The protection aim is the prevention of 2nd degree skin burns (Stoll limits) without a thermal destruction of the necessary PPE.

The results show that NH fuses are able to limit the thermal arc hazards. If the fuses operate current-limiting, the arc duration is normally reduced to a degree where the resulting arc energy and incident energy does not inadmissibly harm the workers. The current-limiting behavior is given if the ratio between prospective short-circuit current and fuse rating current will be higher than 20…25 for general purpose fuses (utilization category gG). It is also generally provided by very fast-acting or ultra-fast acting NH fuses with ratings of 100…250 A that are used as “work protective fuses”.

Fuses are also able to protect persons when there is a non-current-limiting operation. In case of working activities connected with the possibility for the worker to become directly exposed to fault arcs generally PPE shall be used. PPE tested according to the box test is classified in one of two possible protection levels. Class 1 is the lower protection level and has to be seen as basic protection. For this, the combination of NH fuses and PPE was investigated.

The measurements were particularly concentrated to the current ratios where a current-limiting fuse behavior is not to be expected.

Both arc energy values measured and incident energy ones measured lead to the same protection conclusions (hazards as well as PPE necessary). It is sufficient to consider one of these parameters. From the practical point of view this is the electric arc energy. This parameter is also used for risk analyses and assessment.

The measurement results confirm the theoretical knowledge that the arc energy and incident energy show a falling tendency with growing prospective fault current. The assumption that the arc hazards are proportional to I^2t is not correct in case of fuses. Besides of the prospective short-circuit current at the fault place the rating of the upstream fuse is of first importance for the selection of PPE suitable.

Large arc durations as the result of long fusing times, particularly of more than 1 s, are generally critical. In most of these cases the protection levels of PPE can be exceeded.

Some of the conclusions of the protection by NH fuses were based on extrapolations. It is necessary to confirm these results by measurements, too. The aim for further work to do is to find out the exact limits where a protection by means of class 2 PPE is exceeded. It is necessary to extend test durations.

With the same regard other levels of the prospective short-circuit currents shall be investigated in order to both, reducing the steps between levels measured and extending the short-circuit current range. Regarding the latter aspect, NH fuses of higher ratings (including also transformer fuses gTr) should be used.

Main points for further investigations are measurements of 3-phase faults and the experimental confirmation of transformation considerations. These first analyses were focussed mainly on the test circuit conditions used in the standardized box test of PPE. The measurements are to be extended to 3-phase short-circuits (3-phase test circuits and arcing faults).

If there is a three-phase arcing fault the fuse operating time measured will be connected with arc energies that are, depending on the arc fault characteristics, 1.5 to 3 times as much as those determined under the 2-phase arcing conditions. Thus the protection limits will differ accordingly. This has to be proved experimentally by test series.

Acknowledgements

This paper results from a research project supported by the NH/HH-Recycling e.V. based in Stamsried, Germany. The authors like to thank this association for enabling this project and the permission to publish the paper.

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ICEFA 2011

9th INTERNATIONAL CONFERENCE ON ELECTRICAL FUSES AND THEIR APPLICATIONS

DISSOLUTION OF FUSE ELEMENT NOTCHES BY SnCu SOLDER AND THE TEMPERATURE RISE OF FUSE ELEMENT

Martin Bizjak, Mitja Koprivšek, Matija Strehar, Viktor Martinčič

Dissolution of fuse element notches by SnCu solder and the temperature rise of fuse element

Martin Bizjak(1), Mitja Koprivšek(2), Matija Strehar(2), Viktor Martinčič(2)

(1) Iskra MIS, d.d., Ljubljanska cesta 24a, 4000 Kranj, Slovenia, martin.bizjak@iskra-mis.si
(2) Eti Elektroelement, d.d. Obrezija 5, 1411 Izlake, Slovenia, mitja.koprivsek@eti.si

Abstract

The dissolution of fuse element material in SnCu1 melt was investigated experimentally at the conditions as close to those of fuse link as possible. Test strips of E-Cu were dipped into large volume of molten SnCu1 kept at various specified temperatures in order to measure the reduction of their thickness due to the dissolution of Cu strip into SnCu1 melt. Thickness was measured by metallographic methods. Then the dissolution parameters were evaluated with the approximation of semi-infinite one-dimensional problem, where mass flux density of Cu into the SnCu1 melt determines the diffusion of Cu due to concentration difference through the solid inter-metallic layer of constant thickness. For this solute-solvent system a dissolution coefficient K is evaluated concerning the Arrhenius law for its temperature dependence. The actual temperature, at which M-effect takes place in fuse element, was assessed by computer simulation of its thermal steady state at the over-current of fuse blow. The dissolution process is considered to evolve over the consecutive steps of stationary conditions till the final rupture of the notch, so the initial thermal state is calculated when solder just melts and the final pre-rupture state where the notch is just dissolved. The relative magnitude of coefficient K was assessed along the segments adjacent to the rupturing site for the purpose to give us an insight into the phenomenon of abnormal M-effect.

Keywords: dissolution of Cu strip in SnCu solder, dipping experiment, diffusion in solid, dissolution parameters, dissolution rate K, temperature of fuse element, calculation of temperature rise.

1 Introduction

Operation of fuse link under over-current load shall follow time-current characteristic, which is confined between the limiting values according to the relevant product standard [1]. The actual characteristic for the given type of fuse correlates to the phenomena leading to the rupture of fuse element by melting as well as to those at blow by high-current arc. At moderate over-currents the melting of fuse element (wire, strip) takes place provided by M-effect alloy, which is often a special type of solder deposited at the preferential rupturing sites. The melted M-effect alloy steadily dissolves the notches on the perforation of fuse element strip and the time at which the entire thickness of the notch is dissolved under the specified over-current determines the tripping characteristic of the fuse at the pre-arcing conditions. Therefore the evaluation of parameters of the dissolution process enables the prediction of time-current curve. The investigation of dissolution results in better understanding of the M-effect as well as the reasons for an eventual deviations from the regular operation of fuse link, which can lead to excessively high surface temperatures of its cartridge and consequently to the thermal degradation of adjacent parts [2].

2 Physical backgrounds to the evaluation of dissolution parameters

The dissolution of solid component into the liquid solvent is considered to take place by the diffusion through a thin solid interface layer of thickness δ. The mass loss (dm) of material occupying a volume V, which is closed by a surface S, due to the penetration into a liquid solution through the area of surface S in the time interval (dt) is given by general relations for mass flux Φ_m (1)

$$\Phi_{\mathrm{m}} = -\frac{\mathrm{d}m}{\mathrm{d}t}$$

$$\oint_S j_{\mathrm{m}}\,\mathrm{d}S = -\frac{\partial}{\partial t}\int_V \rho_{\mathrm{m}}\,\mathrm{d}V \qquad (1)$$

where the mass flux density j_m on the surface S of solid material in the volume V having mass density ρ_m flows into a liquid solution. Mass flux is driven by the diffusion, which is determined by the diffusion coefficient D appropriate for a given solute/solvent pair, under the gradient of solute concentration (grad c). Gradient stated in equation (2) is considered nonzero only inside the border layer of thickness δ:

$$j_{\mathrm{m}} = -D\,\mathrm{grad}\,c$$

$$j_{\mathrm{m}} = -D\frac{\left(c_{\mathrm{solution}} - c_{\mathrm{solid}}\right)}{\delta} \qquad (2)$$

The concentration of solute material in the solution $c_{solution}$ is considered constant over its volume, while c_{solid} is the concentration of solute contained in the solid volume V. The reformulation of (1) for the plain parallel geometry in semi-infinite space results in (3),

$$j_{\mathrm{m}}\,\Delta S = \frac{\partial}{\partial t}\left(\rho_{\mathrm{m}}\,\Delta S\,\mathrm{d}x\right)$$

$$j_{\mathrm{m}} = \rho_{\mathrm{m}}\frac{\partial x}{\partial t} \qquad (3)$$

where the layer of uniform thickness dx is dissolved from an element of area ΔS on surface S in time interval dt. By combining equations (2) and (3) the expression (4) is derived for the evaluation of the thickness x of the dissolved solid surface layer:

$$\frac{\partial x}{\partial t} = K\frac{\left(c_{\mathrm{solution}} - c_{\mathrm{solid}}\right)}{\rho_{\mathrm{solid}}},\ K = \frac{D}{\delta} \qquad (4)$$

The coefficient K is a dissolution coefficient determined experimentally. On the other hand the analog mathematical derivation of equations (1) and (2) leads to the well known Nernst-Brunner equation (5):

$$\frac{\partial c_{\mathrm{solution}}}{\partial t} = -K\frac{S}{V}\left(c_{\mathrm{solid}} - c_{\mathrm{solution}}\right) \qquad (5)$$

frequently used as the theoretical background for the evaluation of dissolution parameters of solid copper into Sn-based solder in printed circuit boards [3, 4]. The temperature dependence of the diffusion coefficient D is generally given by Arrhenius law [5] formulated by (6)

$$D = D_0\,\exp\left(-\frac{\Theta}{T}\right) \qquad (6)$$

where T is absolute temperature, Θ is a characteristic temperature derived from the activation energy W_a and D_0 is a pre-exponential factor. Due to the analogy between coefficients *D* and *K* the equation (6) is applicable also in equation (5).

3 Experimental determination of dissolution parameters

3.1 Experimental procedure

The experimental procedure was analogous to those reported in [6]. A soldering bath with thermostatic regulation was filled with few kilograms of SnCu 1 for a dipping experiment. Test samples of E-Cu strip (thickness 0,20 mm, width 20 mm, length approx. 5 cm,) were dipped into solder at the predetermined temperature for the specified time. After that a metallographic cross section of test samples were made in order to measure the thickness of the rest of intact Cu-material in strip. The difference between the original thickness of copper strip and the thickness of Cu remained unchanged after dipping is considered equivalent to the thickness dissolved into SnCu1 in time *t* and equal to *x* in eq. (4).

3.2 Analysis of test samples

The metallographic cross-sections of test samples were investigated in the metallographic microscope. A typical structure of interface between solid Cu strip and re-solidified solder is shown in Fig. 1:

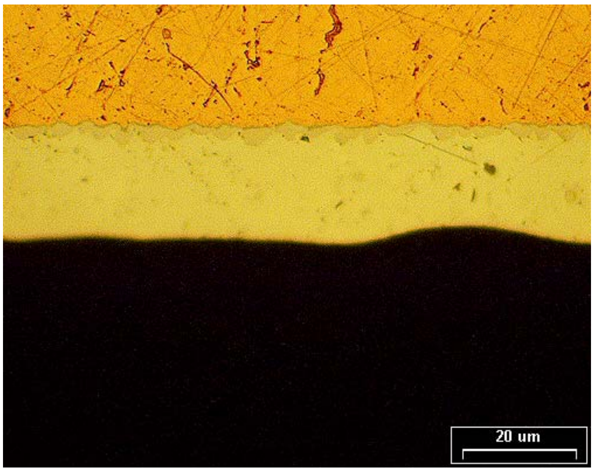

Fig. 1: Cross-section of test Cu strip – re-solidified solder layer on copper base with inter-metallic layer in-between.

A border layer consists of two inter-metallic alloys of variable thickness. Near the unalloyed Cu the inter-metallic phase ε of relatively uniform thickness composed of Cu_3Sn [3,6,7] was formed while near the solder melt the inter-metallic phase η of Cu_2Sn_3 [3,6,7], which exhibits a scallop structure. The re-solidified solder coating shows uniform metallographic structure over the whole volume. However, the test conditions should reflect the conditions of M-effect taking place in a fuse element as possible. Therefore the melting process in fuses was investigated in parallel as well: the alloy structure and the border layers observed on the on test samples are analog to those appeared at M-effect in melting fuses, shown in Fig. 2:

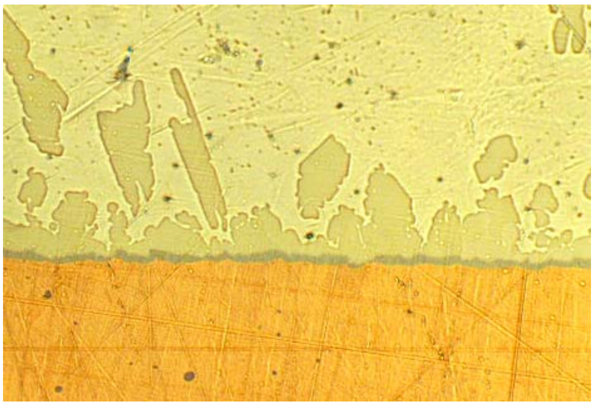

Fig. 2: Inter-metallic layer on the soldered segment of fuse element after blow.

Concerning the structure of re-solidified melt, which is mixed with more or less uniformly distributed crystals of phase η, the applied approximation for the equations (4) and (5) is confirmed as essentially realistic: mean concentration gradient is close to zero outside the interface layer δ comprising phases ε and η. Moreover, the thickness *δ* of layer δ is irrelevant in the calculation of dissolution parameters as the dissolution coefficient *K* calculated from measured results does not depend explicitly on it. Regarding Fig.2 the value of $c_{solution}$ in (4) and (5) represents the uniform concentration of Cu in the melt irrespective to shown metallurgic structure of re-solidified solder. The concentration $c_{solution}$ of Cu in the melt is given as the mass of Cu per volume of melt (kg/m^3) and by analogy the concentration of Cu in solid strip (c_{solid}) is identical to mass density of solid Cu strip (ρ_{solid}).

3.3 The method of evaluation

The thickness of the intact material of Cu-strip after dipping test was measured microscopically on the cross-section of test samples. The difference between original thickness and the measured value determines double thickness (2 x) of the dissolved layer. The attained accuracy of measured x illustrates the situation shown by the outlook of a resulting test sample in Fig. 3 as an extreme case of sample used for thickness measurements.

Fig. 3: Test sample strip after dipping illustrates the non uniform dissolution of test strip over its surface.

For the evaluation of dissolution parameters the equation (4) was used. According to the approximation by infinitely large solder volume the right side of (4) is considered independent of time t. After the integration over the dipping time t and concerning the analog expressions for D and K by equation (6) the relation between the dissolved thickness of Cu strip x/µm in the molten solder versus time t/s regarding the temperature of SnCu-melt T/K is given by equation (7):

$$x = K_0 \exp\left(-\frac{\Theta}{T}\right)\left(1-\frac{c_{\text{solution}}}{\rho_{\text{solid}}}\right)\cdot t$$

$$x = K^* \cdot t \cdot \exp\left(-\frac{\Theta}{T}\right) \qquad (7)$$

where K_0 is a pre-exponential constant independent of t and T. The pre-exponential constant K^* for the specified initial mass concentration of Cu in solvent SnCu1 (nominally 1 wt% of Cu) can be in principle evaluated from measurements by (7), but in the elapse of dipping tests the Cu content in SnCu1 test has increased to almost 3 wt%, which has also contributed to the inaccuracy of evaluation.

3.4 The evaluation of K^* and Θ

The dissolution parameters were evaluated from the equation (8), which is derived from (7),

$$\ln x - \ln t = \ln K^* - \frac{\Theta}{T} \qquad (8)$$

where pairs of values x_i (t_i; T_j) obtained by particular i-th measurement at corresponding set temperature T_j are arranged into an X Y plot. Variables X and Y and the relevant coefficients **a** and **b** are determined by (9):

$$Y \equiv \ln x - \ln t,\ X \equiv \frac{1}{T},$$

$$\mathrm{a} \equiv \ln K^*,\ \mathrm{b} \equiv \Theta, \qquad (9)$$

Fig. 4 shows XY plot with X_i,Y_i pairs regarding the definitions in (9), on which the best-fit linear function Y = a + bX has been obtained by linear regression.

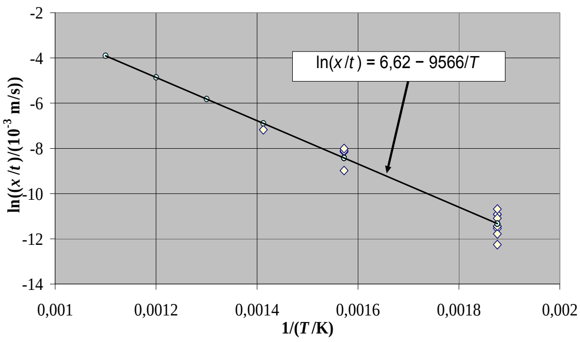

Fig. 4: Plot of measured x obtained at corresponding temperature T and time t fitted by linear regression function.

As the result coefficients Θ and K^* for the dissolution of solid E-Cu into SnCu1 solder were obtained as follows:

$$\Theta = 9566\,\mathrm{K}, \quad K^* = 0{,}752\ \mathrm{m/s}$$

In the literature describing the growth of inter-metallic layer on Cu-conductors of PCBs covered by Sn-base solder [6]. The reported values of Θ are substantially lower than those calculated from the present measurements. Values of the order of melting point magnitude would also be expected.

4 Temperature range at which M-effect takes place in a fuse link

The actual conditions at which the dissolution of fuse element takes place are substantially temperature dependent. Measurements of the temperature along the fuse element are not easy to perform with the appropriate accuracy even in the pre-arcing phase. The temperature rise has been frequently calculated by various simulation methods [8, 9, 10, 11]. The aim of the present study was to indicate phenomena leading to the abnormal M-effect during fuse operation as well. For this purpose the temperature distribution over the most critical segments of the fuse element has been assessed.

4.1 Simulation approach for the calculation of temperature rise

The fuse element under discussion, having a rated current 160 A, is loaded by current of 252 A. It is made of E-Cu strip of thickness 0,20 mm, perforated by 6 rows of round openings distributed over its length which form 6 columns of current contractions across its width. For the purpose of simulation the current path of length 43 mm was considered divided of 9 identical parallel sections of width 2,5 mm, each loaded by 28 A (250 A/9 sections). A series of 6 contractions spread along its length in the position of notches, each modeled by narrow rectangles of width 0,872 mm and length 2,00 mm. The simulation task was therefore reduced to a section of width 2,50 mm loaded by 28 A as a part of infinitely wide fuse element in order to reduce the problem on the one-dimensional, where the conditions varies in the direction of current flow along the fuse element.

The applied calculation method follows the physics of thermal equilibrium in the above mentioned section of fuse element strip with specific electrical conductivity σ, thermal coefficient of electrical resistance α and thermal conductivity λ concerning also thermal conduction through the sand filler to the ceramic cartridge. The connecting terminals and the ceramic cartridge of fuse link are considered to belong to the ambient, which temperature T_a is constant and equal everywhere in this “ambient”. The value of thermal conductivity of sand filler λ_s was found in the literature [9]. The thermal equilibrium is described by a type differential equation (10), which is valid for each particular segment and notch of the modeled section.

$$\lambda \frac{\mathrm{d}^2 \theta}{\mathrm{d}x^2} + \mathrm{k}\theta + \mathrm{a} = 0 \qquad (10)$$

In equation (10) coefficient λ determines thermal conductivity of Cu-strip, coefficient **k** relates to the difference between the dissipated power and thermal flux to the cartridge, while the coefficient **a** relates to the generated heat wherever at x. In general k > 0, k = 0 and k < 0 is possible regarding conditions for the particular segment or notch. The calculation of temperature rise ϑ along the fuse element (x) was performed following solutions of equation (10). They are formulated in (11) except for k = 0:

$$\mathrm{k} < 0:$$
$$\theta = \mathrm{C}_1 \cosh\left(\sqrt{\frac{|\mathrm{k}|}{\lambda}}x\right) + \mathrm{C}_2 \sinh\left(\sqrt{\frac{|\mathrm{k}|}{\lambda}}x\right) + \frac{\mathrm{a}}{|\mathrm{k}|}$$
$$\mathrm{k} > 0:$$
$$\theta = \mathrm{C}_1 \cos\left(\sqrt{\frac{|\mathrm{k}|}{\lambda}}x\right) + \mathrm{C}_1 \sin\left(\sqrt{\frac{|\mathrm{k}|}{\lambda}}x\right) - \frac{\mathrm{a}}{|\mathrm{k}|} \qquad (11)$$

Arbitrary constants C_1 and C_2 are determined by the edge conditions for each particular segment or notch, which were derived from the coupling conditions between successive parts of modeled section.

Functions (11) were applied not only in the case of solid Cu-strip of uniform thickness but also for a double layer of solder of arbitrary thickness on Cu-strip. Moreover, they were applied also for the double layer of SnCu-melt/Cu-strip. In the case of dual layer an equivalent electrical and thermal conductivity was calculated for such material combination. Due to the lack of material data for SnCu1 the data for Sn is used for approximation. As the data for melted Sn and SnCu alloys are also not available the approximations stated for melted metals were taken from the literature [12].

4.2 Results of temperature-rise simulation

The calculation of temperature T along the fuse element is, regarding expressions in (11), based on the temperature rise Θ, which is superposed on the constant ambient temperature T_a of ceramic cartridge and terminals. T_a depends on the cooling effect of the actual ambient around the fuse link. For the simulation purpose the T_a value is chosen such that at least the melting point of SnCu1 is achieved at the value of load current taken for simulation which is equal to those used in actual operation tests of fuse links. To achieve the melting of solder on the soldered segment of fuse element was considered prerequisite for the initiation of M-effect process. Following steps of M-effect proceeds over the consecutive states of thermal equilibrium at which the dissolution of Cu steadily reduces the thickness of solid Cu-strip of the notch at the unchanged T_a value till its rupture.

In the result $T(x)$ plot of temperature distributions T /°C along the fuse element are shown in Fig.5 for the initial and final phases of M-effect: first, at the moment the solder is just melted, and second, when the notch completely dissolves throughout its thickness. In both cases the external conditions remains unchanged.

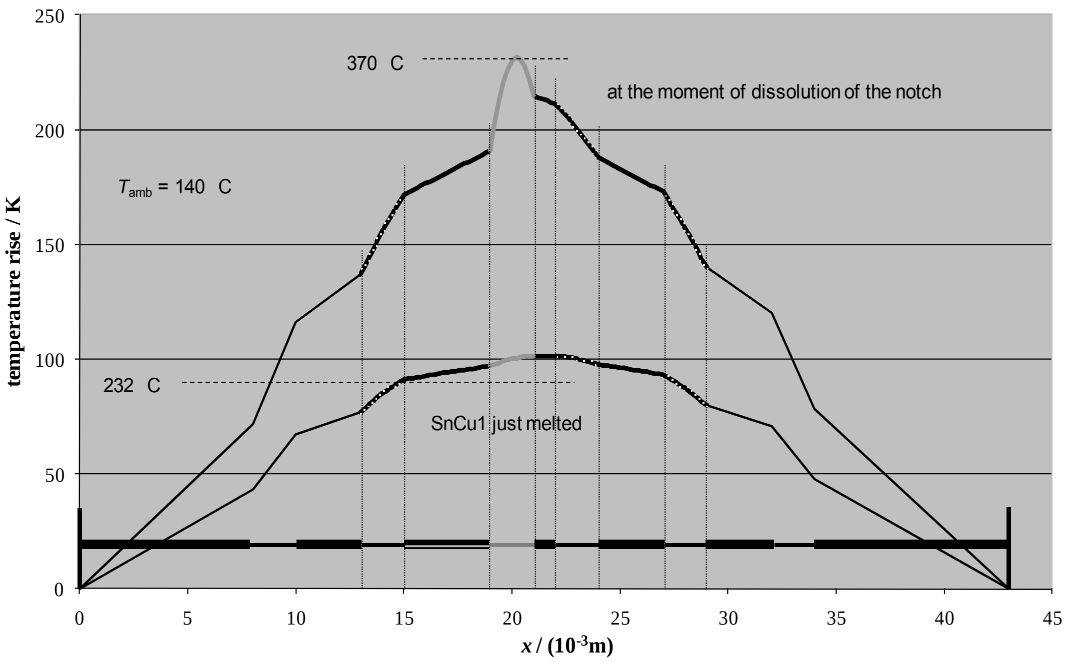

Fig.5: Distribution of temperature rise along fuse element 0,2 mm in the beginning and at the end of M-process. Bars above the horizontal axis represent the distribution of segments and nodes along the fuse element

4.3 The dissolution rate for segments near to the soldered notch

The tendency of molten solder to spread beyond its area of deposition could significantly influence the operating characteristic of fuse. In fact the temperatures of segments nearby to those deposited by solder is far above the melting point of SnCu1, the dissolution process can occupy much broader area than expected, when solder melt reaches these places. The potential intensity of dissolution in the hottest areas of fuse element was assessed for such cases by the ratio of dissolution coefficient $K^*(x)$ relative to K^*_{232} at the melting point of Sn. The results are shown graphically in Fig.6.

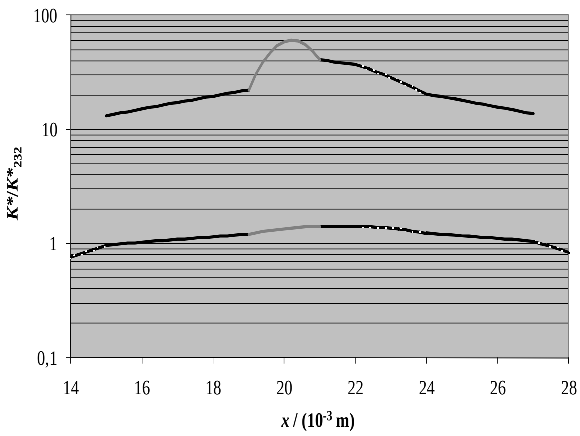

Fig.6: Relative value of dissolution coefficient K^* regarding K^* at the melting point of Sn along fuse element strip 0,2 mm.

From the graph of Fig. 6 it is evident that the dissolution rate for segments near the rupturing site by M-effect would be of the same order of magnitude and they represents potential sites where alloying of Cu strip by melted solder can take place in the case they would be wetted by the solder.

4.4 Formation of high resistive high-temperature solid SnCu-alloy

The operation of melting fuse at pre-arcing conditions is based on the formation of low-temperature melt due to the dissolution of fuse element strip by M-effect alloy providing that heating by the over-current attains the melting point of this alloy, which enables the dissolution of fuse element. The over-current should maintain the resulting alloy melted till break. It is possible due to low melting point of the alloy resulting from the dissolution process. In the case of Cu strip deposited by Sn-base solder the melting temperature depends on the chemical composition of SnCu alloy as it is evident from the binary diagram of SnCu state [7]. The lowest melting temperature corresponds to the eutectic SnCu0,7 and it increases by the amount of Cu. Therefore the insufficient amount of solder deposit can lead to the formation of alloy with too high melting temperature, which cannot be attained by the specified over-current. The fuse element is likely to turn into heating element causing excessive heating of fuse cartridge and the operation of fuse link does not comply with the stated time-current characteristics. The various possible ways of evolution of M-effect are illustrated graphically in Fig. 7, shown by arrows. The rupture of fuse element is represented by two left-side arrows, leading to the formation of SnCu melt in the area of temperatures obtained by simulation. The right-side arrow represents the formation of solid SnCu alloy which does not result in breaking.

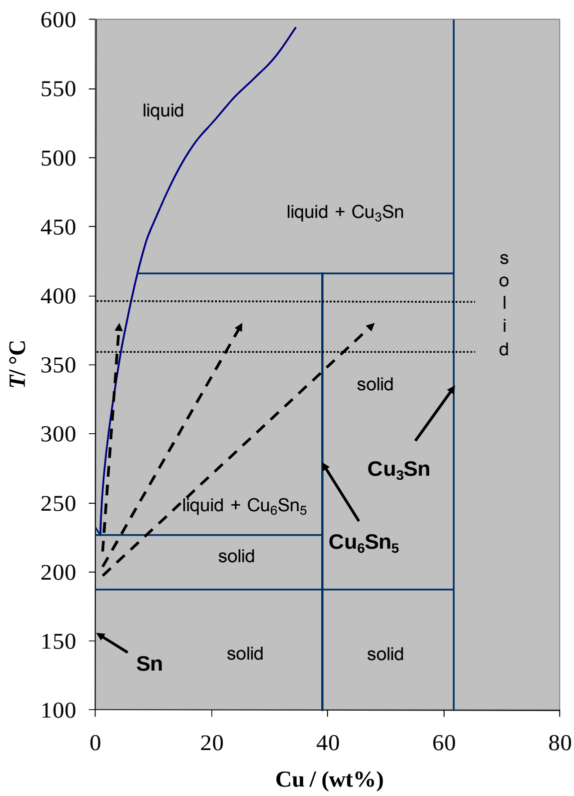

Fig.7: Various possible development of M-effect in the case of fuse element strip 0,2 mm shown in binary SnCu diagram.

5 Discussion

The dissolution parameters of solid Cu into molten SnCu1 were evaluated from measurements in order to investigate the dissolution of fuse element made of Cu strip by SnCu1 solder. As the result values of dissolution coefficient *K* and exponential parameter *Θ* were obtained. The performed measurements and applied evaluation procedure were similar to those described in the literature. Some results obtained by measurements differ significantly from those referred elsewhere probably due to the dissimilar subject of investigation: the referred literature mainly deals with the growth of the inter-metallic layer on the soldered Cu conductive paths of printed circuit boards.

The data concerning the temperature distribution over the fuse element is prerequisite for the study of M-effect. A temperature measurement of fuse elements inside the fuse link is a complex procedure and the obtained results of limited accuracy. Therefore in parallel to the dissolution experiments the simulation of temperature distribution over the segments and notches of perforated fuse element strip due to heating by over-current was performed by semi-analytical calculation methods. Regardless of the lack of required material data and applied approximations the results obtained by the described simulation correlates to the available measured data. They are considered to be qualitatively applicable for further studies of M-effect.

6 Conclusions

The obtained values of the dissolution parameters along with the estimated temperature distribution over the fuse element evaluated for a given moment of dissolution time by semi-stationary approximation enable the complete time-relating simulation of dissolution process by involving the dissolution rate, which was evaluated as well. The purpose of such simulation is presumable explanation of the abnormal M-effect. In this paper the initial and the final state of dissolution are presented. It is pointed out that not only the specially designed rupture site of fuse element but also neighboring segments are sites of high temperature where the formation of SnCu alloy can take place in the case of excessive solder migration. But due to the limited amount of solder deposit on Cu strip the process can results in the formation of SnCu alloy with higher content of Cu and consequently with considerably higher melting temperature. In this case a **solid** SnCu alloy presumably appears instead of low-temperature SnCu **melt** (see Fig. 7). High electric resistance of solid SnCu alloy turns fuse element into heating element.

There is no clear evidence whether the wetting of surface of fuse element by solder due to diffusion substantially contributes to the spreading of the dissolution area. An unwanted surface migration of melted solder over the of fuse element leading to the formation of solid SnCu alloy during M-process can presumably be driven also by surface tension of liquid solder meniscus which covers the perforated sites of fuse element strip. This effect has not been investigated yet.

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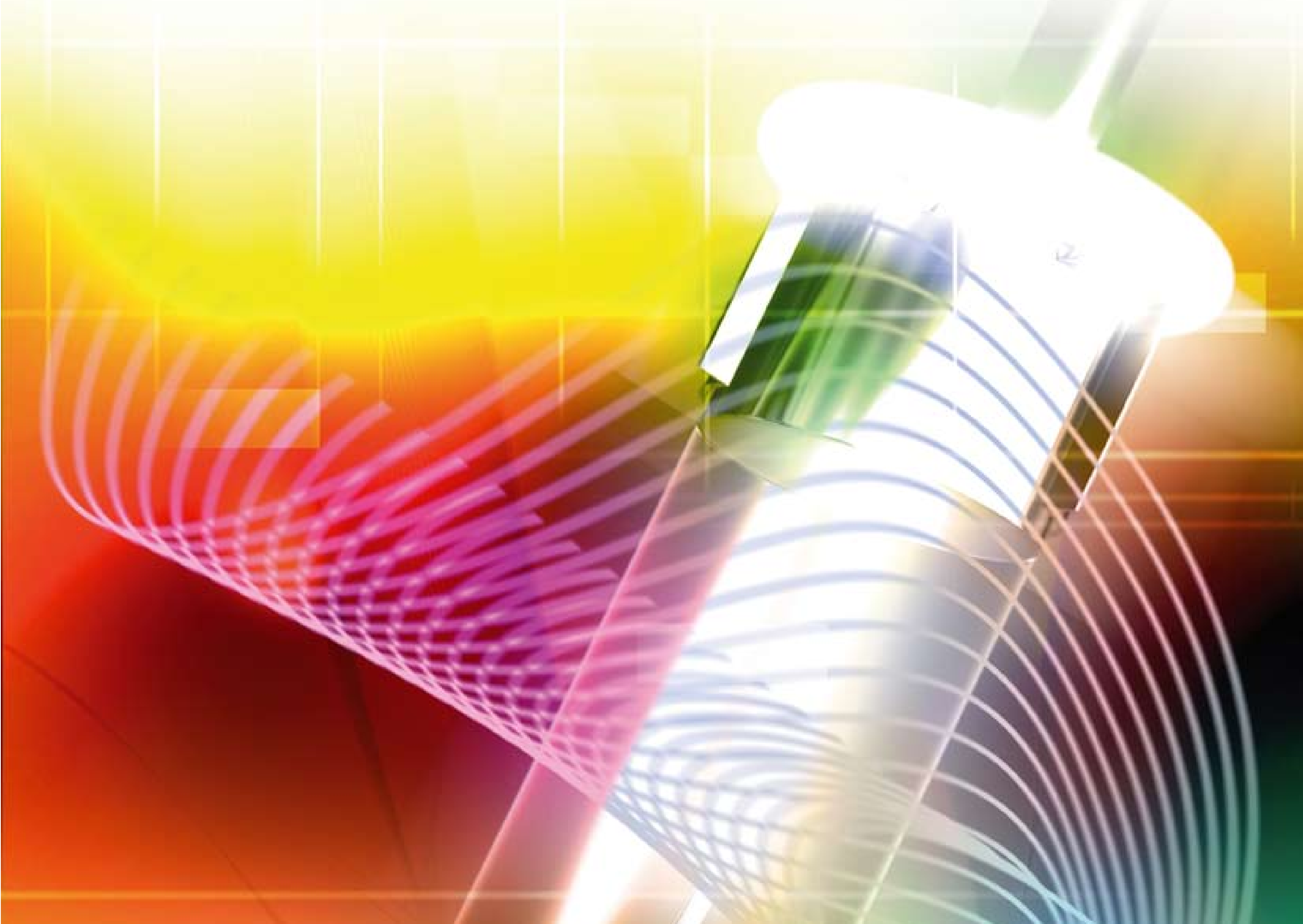

THERMAL ANALYSIS AND TEMPERATURE CALCULATION FOR THE NV MELTING FUSE

Anton Hamler, Sašo Grill, Jelena Popović Cukovic

Thermal analysis and temperature calculation for the nv melting fuse

Anton Hamler, Sašo Grill, Jelena Popovic Cukovic

University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17,
2000 Maribor, Slovenia, jelena.popovic@uni-mb.si

Abstract

This research discusses the NV melting fuse, which is used to protect various types of circuits because of its good properties. The calculation is based on the 3D finite element (FE) analysis that is conducted with the software Vector Fields Opera. Current field analysis has been conducted from which Joule losses are determined along with static and transient analysis of thermal field of NV melting fuse. Analyses have been carried out for a different melting fuse current and for different shape of perforation of melting fuse. The obtained results provide necessary information on distribution of Joule losses and temperatures for cases of different currents.

Keywords: NV melting fuse, finite element method, current field calculation, thermal field calculation.

1. Introduction

There are many different ways to protect electrical devices and users against overload and short circuits. One of the first examples of protection of electrical power grid has already been used in the pioneer years of electrical engineering. In 1890, Thomas Edison, as part of his electric energy distribution system presented and patented a melting fuse. Its concept of functioning is fairly simple. The functioning is reliable and that is the reason why it is still utilized nowadays. The operation is based on Joule losses, which occur in melting element of the melting fuse. When the current throughout the melting element is higher than the nominal current, the Joule losses increase to a value, which heats up the melting element up to the melting point. Turn-off characteristic of a melting fuse is directly dependant on the Joule losses in a melting element and its heating. Heating is than dependent from heat transfer to other parts of a melting fuse. With intention to know the exact process in a melting fuse, the measures of current field has been conducted, on the basis of which the Joule losses have been evaluated. Those measurements have been used later on for the calculation of a thermal field as a thermal source. Analyses have been conducted on a NV type of a melting fuse with a nominal current of 160 A and for two types of perforation of melting elements.

2 Construction of the NV melting fuse

NV melting fuses [1] are used for short circuit protection of low voltage power grids. Despite various types of currents and fault voltages, NV fuses guarantee a short circuit protection, when a fuse is choen correctly based on the turn-off characteristics as well as maximum reliable and cost rewarding prices.

During its operation, a NV melting fuse terminates the current in less than 5 ms [2]. This means an extremely quick turn-off efficiency of a breakdown, which is for a 50 Hz grid, less than a quarter of a time period.

NV melting fuse is made of a number of electrical conductive and non-conductive parts (Fig.1). Melting element (1) is the most important part of the fuse. It is made out of a thin copper strip that is used for a more precise positioning of Joule losses and therefore it contains a number of perforated parts (2). Perforated spots cause the narrowing of conductive areas for electrical current. Because of such, ohm resistance increases in these areas. Many consecutive areas of perforation, in relation to a current direction, assures at the same time that during the melting of a melting element, the arc distributes into many shorter parts. Hence, a quicker and more reliable extinguishing of an arc is assured as well as a consecutive termination of circuit.

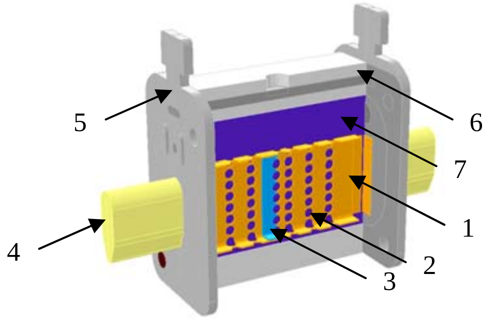

Fig. 1: NV melting fuse.

With the perforation of a melting element and additionally with a layer of low temperature melting alloy in the area of one perforation segment (3), it is possible to influence on the turn-off characteristic. Melting element is welded at the ends onto contact knives (4), which are impressed into the lids (5). The lids are fastened onto a fuse housing (6), which is made out of steatite. Steatite respectively soapstone is very good as an electrical insulator and it is basically magnesium silica in its structure. Area between the housing and the melting element is filled with pure silica sand (7), which has exactly defined chemical and granular structure. The sand with its thermal conductivity in considerable amount influences on the turn-off characteristic of the fuse. At the same time it influences on the time of extinguishing the arc. The fuse also has a built in indicator that interrupts the melting elements, which makes it easier to identify destroyed fuses as well as their replacement.

3. Mathematical description of the current and thermal field

3.1 Current field

Current field is a special example of a static electric field, which is observed only in electrical conductive areas. It is defined with an electric static potential [3]. Electric field strength **E** is given with (1).

$$\mathbf{E} = -\nabla \varphi \tag{1}$$

Current density **J**, in conductive areas is described with an equation (2), in which σ is specific electrical conductance:

$$\mathbf{J} = \sigma \mathbf{E} \ . \tag{2}$$

Since the current field is without a source, than the divergence of current density **J** equals to zero (3):

$$\nabla \cdot \mathbf{J} = 0 \ . \tag{3}$$

By taking into consideration (1) and (2) in (3), the Laplace equation of current field is easily obtained (4):

$$\nabla \cdot \left(\sigma \nabla \varphi \right) = 0 \ . \tag{4}$$

Upon the known distribution of electric field strenght and current density in electrical conductive region the Joule losses *p* can be calculated as (5):

$$p = J \cdot E \ . \tag{5}$$

and overall Joule losses for volume *V* are equal (6):

$$P = \int_V J \cdot E \, \mathrm{d}V \ . \tag{6}$$

3.1 Static thermal field analysis

Static thermal field occurs when the input thermal energy is equal to the dissipated one. At that time, in the observed area, there are not any changes in thermal energy. Thermal field can be presented with the use of temperature *T* as a scalar potential [4], [5]. Density of thermal current *q* is given with (7)

$$\mathbf{q} = -\lambda \cdot \nabla T \ , \tag{7}$$

where λ is thermal conductivity. Divergence of thermal current density offers density of thermal sources *Q* (8).

$$\nabla \cdot \mathbf{q} = Q \tag{8}$$

By combining equations (7) and (8), Poisson's equation is obtained for temperature distribution:

$$\nabla \cdot \lambda \nabla T = Q \ . \tag{9}$$

The corresponding boundary conditions determine whether thermal current flow is based on convection or radiation.

3.2 Transient analysis of thermal field

Transient analysis of thermal field is necessary when accumulated thermal energy varies with time. The change of thermal energy is equal to the difference between generated heat and dissipated heat, which is transferred over the areas of analysed region. It is described with (10), where ρ stands for mass density and *C* is heat capacity [4], [5].

$$\rho C \frac{\partial}{\partial t} T = Q - \nabla \cdot \mathbf{q} \tag{10}$$

By joining the equations (7) and (10), the temperature distribution is obtained (11).

$$\rho C \frac{\partial}{\partial t} T - \nabla \cdot \lambda \nabla T = Q \tag{11}$$

The boundary conditions of the analysed region need to be taken into consideration for the transient analysis.

4 Analysis of current and thermal field for the NV melting fuse

4.1 Geometric model of the NV melting fuse

Numerical analysis is based on 3D FE model of the melting fuse. The cross section of the model is shown in figure 1. FE analysis is conducted with programme tool Opera - Vector Fields [6]. The model contains all elements that are crucial for the description of current and thermal field. Very thin layers and perforations cause difficulties during the discretization of the model. Analysis is carried out for two different fuse models. The difference between them is in the shape of perforations whereas one contains round and the other square perforations. The most narrow portion between perforations of the melting element is equal in both cases. However, higher ohmic resistance occurs in the case of round perforations.

The material (thermal and electric) properties are given in table I [7]-[9]. The melting element is made out of copper, contact knives are made out of brass, the lids are from cold rolled alloy of aluminium and magnesium and solder is alloy of tin and copper. The melting point of solder is much lower than the melting point of a copper strip. The non-conductive areas also impact on the turn-off characteristic of the fuse. Silica is extremely important, because it is located between the melting element and housing. It prevents the arc from spreading and absorbs the heat. The housing is made out of steatite, which is characterized by high thermal resistance and very high dielectric constant as well as mechanical hardness.

Boundary conditions are scalar electric potentials that are set up on the surface (4) of the contact knife (Fig. 1). The potential difference between contact knives is chosen to ensure the expected current. Temperature values set up at the boundary of the domain specify the values a solution needs to take on the infinite surfaces.

Table I: Electric and thermal properties of used materials

Material	Specific conductivity □ (S/m)	Thermal conductivity λ (W/m/K)	Specific heat *C* (J/kg/K)	Density ρ (kg/m^3)
Brass CuZn37	16·10^6	120	376	8550
Steatite	10^{-12}	2.9	920	2710
AlMg3	20·10^6	140	960	2650
Cu	59·10^6	388	385	8920
SnCu1	9.1·10^6	67	217	7310
Silica	10^{-15}	1	1201	830
Air	0	0.0257	1005	1.205

4.2 Current field calculation for the NV melting fuse

Heat source of the NV melting fuse is Joule loss. The current density is not equally distributed along the melting element. Therefore, the current field needs to be calculated in order to determine power loss. Current density along the melting elements is shown in Fig. 2. Figure 3 shows the coordinate dependence, which is perpendicular to the narrowing of the melting element area.

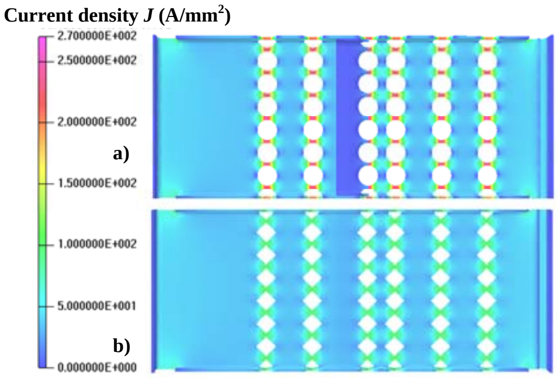

Fig. 2: Current density distribution in the melting element for current of 200 A: a) round perforation, b) square perforation.

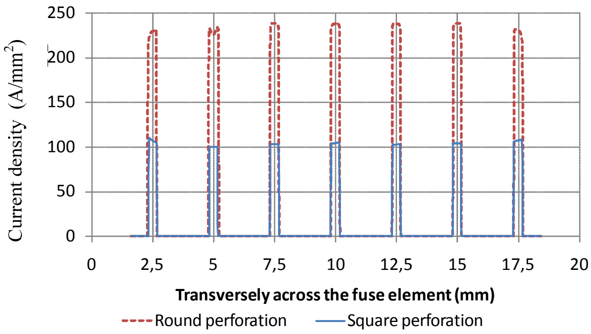

Fig. 3: Current density distribution in the melting element along the perforation line at the current of 200 A.

Distribution of Joule loss is calculated on the basis of the current field calculation (Fig. 4). Each FE contains an amount of current density that is further implemented as a heat source for thermal field calculation. Total power dissipation at the current of 200 A is 11.78 W for round perforation and 8.36 W for square perforation.

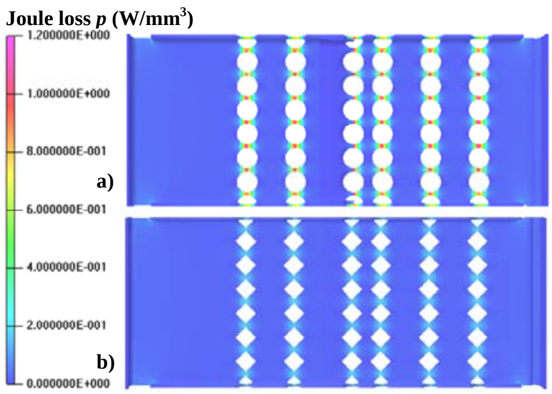

Fig. 4: Distribution of Joule loss for the melting element at the current of 200 A: a) round perforation, b) square perforation.

Figure 5 shows the distribution of electric potential along the melting element for both perforation shapes.

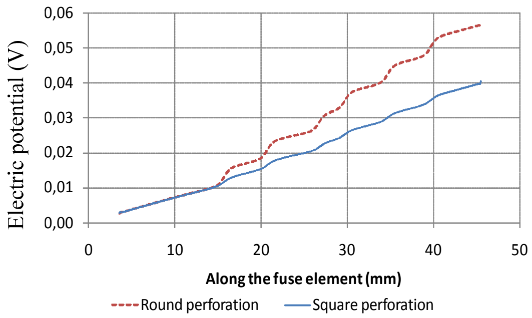

Fig. 5: Electric potential along the melting element at the current of 200 A.

4.3 Calculation of static thermal field at the current of 200 A

During the calculation of static thermal field, the same discretization is used as in current field calculation.

Therefore, the calculated Joule loss of each FE can be used directly as an individual source of heat that is further applied in thermal field calculation. The room temperature is 25 °C. The current of 200 A represents the upper limit for both the solder and the melting element.

The temperature distribution for the fuse cross-section along the melting element is shown in Fig. 6 and includes a round and a square perforation.

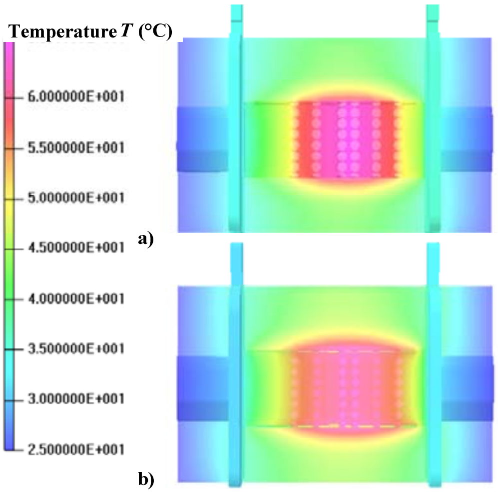

Fig. 6: Temperature distribution throughout the NV melting fuse at the current of 200 A for the static analysis; a) round perforation, b) square perforation.

4.4 Calculation of transient thermal field at the current of 800 A and 2000 A

Transient analysis of thermal field shows how the fuse behaves when exposed to the short circuit current. Because of such, the simulations have been carried out for 800 A and 2000 A. For both current values, the heat sources are calculated from the current field, which, of course, does not depend on the temperature. Temperature distribution along the thickness of the melting element is shown in Fig. 7, as well as for the solder and round perforation. The previously mentioned temperature distribution is for a particular moment in time when the temperature of the solder reaches the melting point, which is 240 °C. That critical point is reached in 4.6 s at the current of 800 A (Fig. 8). In the case of 2000 A, it is reached only in 0.17s. Figure 7 also confirms that the heating at 2000 A is mostly adiabatic. The short time needed for heating indicates that the heat does not transfer onto other parts of the melting fuse.

Figure 8 shows how fast the melting element area located beside the solder heats up with respect to time when the current equals 800 A.

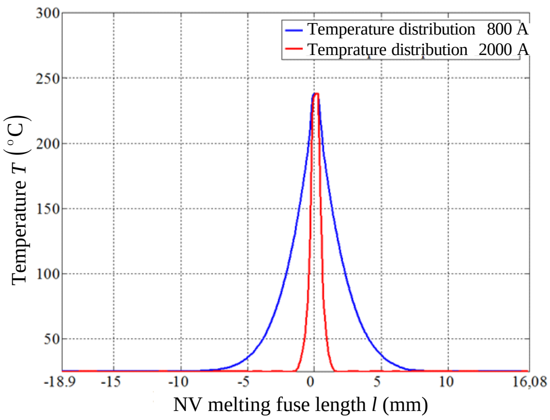

Fig. 7: Temperature distribution along the perpendicular direction of the melting element at the current of 800 A and 2000 A for round perforation; note that it is given for a particular moment in time when temperature reaches 240 °C.

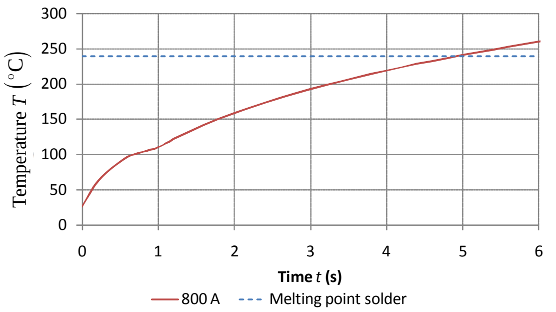

Fig. 8: Transient thermal behaviour of the fuse with the round perforations of the melting element, at the current of 800 A.

5. Conclusion

The experimental way to conduct the fuse analysis is not always suitable and most welcome. The problems occur when the turn-off characteristic varies among different fuse samples. The other more significant difficulty is the following: when testing the melting element once, the solder melts and it is impossible to repeat the experiment with the same sample. Therefore, it is very useful to apply accurate simulations and obtain the corresponding results.

The accurate simulation for current and thermal field requires a 3D numerical model as well as to posses the exact electric and thermal properties of the used materials. Thermal properties of the silica are varying with the purity and granulation and therefore, can cause problems in simulations.

Calculations and simulations confirm that the actual working conditions of the fuse can be presented and even under the different current supply and different surroundings. All results have not been experimentally verified except the case of current 256 A. The temperature of all crucial construction parts of the fuse has been measured with corresponding thermo couples. The time needed for the solder to melt has been measured as well. The transient analysis confirms that short-circuit currents that are few times larger than the nominal current, cause the heat to accumulate in the melting element, before the solder melts. In such case, the heat transfer to the remaining construction parts of the fuse is negligible. On the other hand, its role is important when the operating current of the fuse is just a little bit above the nominal value. The analysis shows as well that the perforation shape has an impact to the released heat inside the melting element. Joule loss is higher in the case of round perforations, because the conductive areas are smaller and therefore, the electric conductivity is lower.

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PRESENT AND FUTURE REQUIREMENTS FOR THE PROTECTION OF PHOTOVOLTAIC SYSTEMS

Nigel P.M. Nurse

Present and future requirements for the protection of Photovoltaic systems

Nigel P.M. Nurse

Cooper Bussmann, Burton on the Wolds, Leicestershire, UK, nigel.nurse@cooperindustries.com

Abstract

Although the production of electricity using Photovoltaic (PV) cells has been possible for many decades, it is only recently, with increased costs of carbon based electricity production and CO2 reduction initiatives, together with improvements in inverter technologies, that large scale systems have become commercially viable. The paper describes how the protection requirements of both small and large PV systems have developed and the challenges that have been faced by fuse-link manufacturers to provide the end user with over-current protection. The paper will also cover the background to the introduction of international standards for fuse-links to protect PV systems and some of the developments in system components that will influence the next generation of protection.

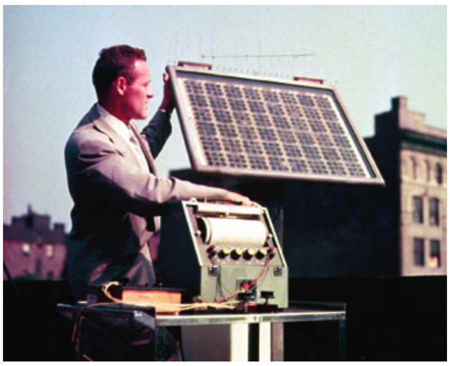
Keywords: electric fuse, PV photovoltaic cells, current limitation, overvoltage.

1. Background

The effects of sunlight on chemicals has been observed for many millennia. The most important effect for our planet is, of course, photosynthesis where sunlight converts carbon dioxide into organic compounds, often sugars. Another notable effect is that observed in photographic and photolithographic processes where light can trigger changes in colour or durability of chemicals.

A photovoltaic (PV) effect (voltage created by light) was observed by the French physicist A.E Becquerel in 1839 and the effect was first demonstrated practically by Charles Fritt in 1883. The effect was explained by Einstein, for which he received the Nobel Prize in 1921. In modern semiconductors the effect was patented[1] in 1946 during work that preceded the invention of the transistor.

Whilst the concept became well known – if light is shined onto a p-n junction a voltage will be created and current will be available to flow through attached components - the assembly techniques were difficult and expensive, with the available power per unit area being very limited. The first PV cells made from silicon were produced during the mid 1950's and limited to just a few milli-watts per cell, with a cost 100 times greater than other methods of generating electric power.



Illus. 1: First solar panel

As each PV cell generates small power levels, to produce a useful amount of energy it is usually necessary to combine the cells in series and parallel combinations.

Most development was in cells made from crystalline silicon, with the area of these cells being limited to the diameter of the silicon ingot it was cut from. The diameter of ingots gradually increased but until the processes to allow larger diameter crystals of silicon to be produced were developed, the current levels were very small for each individual cell. Even now the most popular cells (150mm square) provide less than 9 amperes at only 0.5 volts.

Photovoltaic energy is only usable in direct current (dc) systems and without cost effective and efficient conversion equipment to convert the dc to alternating current, PV systems could only used for standalone situations where limited and predictable energy consumption of direct current was required, and cost was not a major factor. The highest profile example of such an application was to power satellites.

Although the most popular and established method of PV cell manufacture was based on the silicon crystals, there was always research into other possible technologies such as thin films of amorphous silicon or cadmium-telluride. Such methods are not as common place as crystalline silicon but are gaining popularity.

More recently panels (or modules) of serial, and sometimes, parallel silicon crystalline PV cells have begun to be developed in standard sizes which has reduced the cost of a system. Individual cells are made from standard silicon ingot sizes, and doped to be p-n junctions. They are assembled in series within a frame and protected by glass, the whole being placed in an aluminium frame. Typical modules (crystalline cells) are made with 72 cells in series, giving an output capability of up to 9A at 30V and are typically 1.4m x 1m in size.

For modules using thin film technology, where the PV materials and connections are deposited on a glass substrate the outputs would typically be 1.5A at 90V, with the module being typically 1.4m x 1.1m.

The benefits and drawbacks of the various systems are not within the scope of this paper.

Key Characteristics of PV modules

The following are the key characteristics of PV cells that influence the selection of circuit protection devices (and other components):-

- Insolation / Irradiance: The amount of light energy arriving at the PV modules determines their output current. Module data is shown at Standard Test Conditions (STC), but in practice higher values than this are available in many locations.

- STC: operating value of in-plane irradiance (1000 Wm^{-2}), PV device junction temperature equals the nominal operating PV cell junction temperature (NOCT), and air mass (AM =1,5)
- I_{sc}: electric current at the output terminals of a PV device at a particular temperature and irradiance when the device output voltage is equal to or close to zero
- V_{oc}: open-circuit voltage as measured under standard test conditions, STC
- Temperature Coefficients: Both the voltage and current performance of PV modules are influenced by temperature.
- I_{rev} or $I_{MOD\_MAX\_OCPR}$: The maximum reverse current permitted to flow through the module for one hour without damage to the module, according to IEC61730-2, often termed “maximum series fuse rating”.

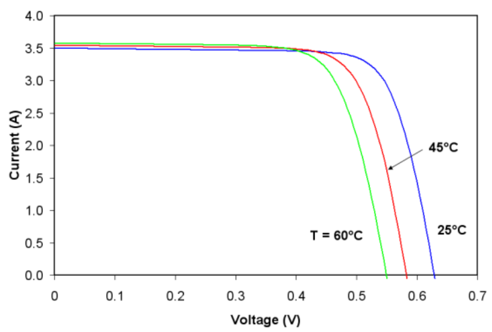


Fig. 1: I-V Characteristic for PV cell

At the same time as larger modules became common place, a new power semiconductor became established; the Insulated Gate Bi-polar Transistor (IGBT). With low drive power requirements and fast switching capabilities, this device allowed high frequency pulse width modulation circuits to be employed to economically and efficiently convert dc to ac. After immediate success in the variable speed drive and uninterruptable power supply (UPS) industries, this device was employed in dc to ac converters for the PV market. Prior to the advent of IGBTs, dc to ac converters employed bi-polar transistors or thyristors. The former suffered from the need for high-power drive circuits and associated poor efficiencies, the latter employed large inductors and capacitors to commutate the thyristors: both these systems were relatively inefficient. However after rapid development during the 1990s, IGBT circuitry became common place and high conversion efficiencies could be achieved. With an efficient inverter system and more cost effective modules, it became possible to create PV systems that could link to ac distribution grids and produce ac power at a cost closer to that from fossil fuels.

Alongside developments in the size of cells, module assembly techniques and inverters, it was observed that the cost of fossil fuels was rising and that burning fossil fuels was potentially the cause of climate change. However, whilst a number of systems were installed by those keen to show that we need not be reliant on fossil fuels for electricity, the cost of installing PV-based generating systems was still not economical. The payback period of PV systems was estimated to be 30 years and as the number of systems would be small, cost reductions from volume manufacture. and would not be achieved. There needed to be one other input to create a situation that would stimulate the market for electricity from PV systems and ensure investors received payback well before the system needed replacement. However with traditional Grid operators being monopolistic and / or bureaucratic, connecting PV systems to the grid was difficult, if not impossible to arrange. This lose – lose situation was only reversed by government interventions that used taxpayers’ money to subsidize the electricity from PV (and often other non fossil fuel) systems. This was to ensure investor returns and there was also government intervention to introduce open markets allowing easier grid connections for smaller suppliers.

In most countries the effect of government intervention has firstly been to remove barriers to grid connections and secondly, and more importantly, to introduce feed in tariffs (FIT) that pay producers an inflated value for the energy produced. The direct effect of these activities is that the production of electricity from PV has risen at around 30% annually since 2000. From a small number of relatively small (<20kW) systems that were perhaps powering isolated users with modules on a house or farm roof, systems have now grown to multi MW systems occupying many hectares, with a prediction of more than 18GW to be installed during 2011.

2. System developments

In a short time, the small PV systems of only a few watts have progressed to a few kW and now, to as large as, 10MW. During this time a number of key changes have happened to the topography and dimensions of the basic components and indeed the types of components themselves.

In this section a number of systems will be detailed and it will be seen that the rapid development of systems has brought a number of unforeseen difficulties and problems. Whilst a small system on a boat or recreational vehicle (RV) may use a single module and a charge controller to charge a battery, the system to produce many MW is somewhat more complex.

As suggested earlier, the current and voltages are limited in PV systems; it is this aspect that influences many of the components and their use. As the power is limited it is important to also limit losses in the system. For example, large systems would not have been developed if the efficiencies of the inverters had not been as high as present IGBT-based inverters.

2.1 Protection requirements

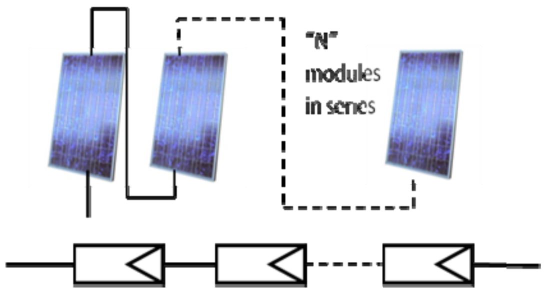
The authors are unaware of any cost effective circuit breakers that might provide protection to circuit elements in PV systems and so this paper will concentrate on over-current protection by fuse-links.

It is clear that cables should not be overloaded and should be selected to be capable of carrying more current than the PV systems can provide, remembering, of course, that in fault conditions current may be available from system elements other than the PV modules.

Until the introduction of FITs, most PV systems were relatively small and the special requirements for protection were unlikely to have been considered in depth. Most of these earlier systems would use only a few modules in series or parallel. If offered at all, any protection would have most likely been provided by general-purpose circuit breakers or fuse-links as the designers felt appropriate. By their nature, PV cells create no voltage when short-circuited, so they can be considered to self protect under these conditions.

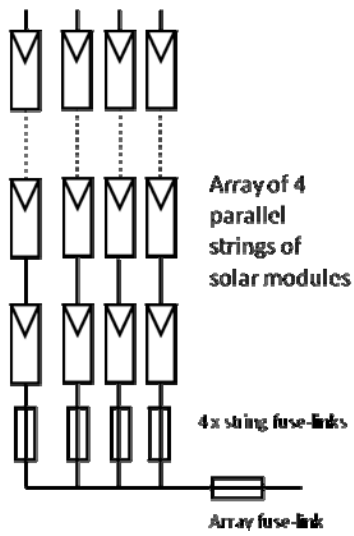
In the event of a reverse current situation the current may be stopped by a 'blocking diode' or the reverse current may not be harmful, as the reverse capability of the cells is often around 3 times the forward capability and the cells should withstand this value for over an hour. In these systems it may be simply that all the components concerned are sufficiently robust and if one item fails, the remainder will not be damaged, or that in these cases, in practice rather than by design, a general purpose fuse-link included as cable protection would provide sufficient protection to the other components.

Only when systems began to be developed with many modules in series, referred to as strings, did the voltages become high enough to expose the limitations of traditional protection. Notably, the requirement for protective devices to open very low overload currents was highlighted, especially at high dc voltages.



Illus. 2: String arrangement

As systems developed further by adding strings in parallel, the arrangement shown in Illustration 3. (showing four strings in parallel) is achieved.



Illus. 3: Basic array

The addition of many strings in parallel to form large arrays of modules and then the further paralleling of a number of arrays gives rise to a number of new faults and failure modes within the PV system which are not seen in smaller systems. As this paper will describe, these systems require circuit protection devices that operate at low levels of over current which have not generally been available, especially at the higher voltages being used in larger systems.

2.3 Requirements for fuse-links

The key requirements for fuse-links in PV systems are :-

- The ability to open safely in dc circuits.
- Be capable of operating at 1.35 times their rated current within one hour.
- Be capable of carrying 1.13 times their rated.
- Ability to operate in ambient temperatures up to 80°C (with allowable current re-rating).
- Have the ability to not deteriorate when subjected to cyclic loading and cyclic temperatures.
- Have the ability to interrupt high fault currents
- Have small physical sizes
- Have low power losses

These requirements are embedded in the international standards (section 3).

Fuse-links are renowned for their ability to interrupt high fault currents especially in ac circuits. However, they are known to have difficulties in operating at low over-currents especially in dc circuits and where they are exposed to high ambient temperatures and where the currents are cyclic in nature.

For fuse manufacturers, these requirements represent a challenge. The design techniques required to satisfy some of the above criteria can adversely affect other criteria.

In general, to achieve a higher voltage capability (especially in dc circuits) additional series weak spots and additional length are added to fuse elements. Whilst additional length and weak spots will ensure the higher voltage is safely interrupted, both these items both add resistance to the fuse-link, which increases power losses during normal conditions.

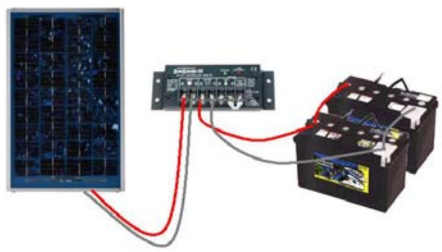
According to standards, fuse-links must carry a current above their rating for a set time without operating (the non-fusing current). Fuse-links will also be required to operate within a set time at a value above their rated current (the fusing current). For fuse-links to protect strings in PV systems, the difference between these two defined currents is smaller than in any other fuse system previously developed, and means the tolerance window for designers is tighter than previous systems.

These challenges have been overcome and fuse-links that meet, or exceed, the requirements of the standards (section 3) are now available. This ensures that installers can have the high quality protection and reliability they expect from fuse-links.

2.3 Battery systems

For systems involving batteries, care must be taken to ensure that, in the event of a failure of the series diode (if fitted), the current from the battery cannot damage the PV module. Whilst in daylight the module will supply small currents to the battery, at night the battery can discharge through the module unless it is limited by some other means. The module has a reverse current withstand rating established during its approval process. This rating should not be exceeded by more than 1.35 times for more than one hour. Therefore, any module or series of modules supplying battery systems should include series fuse-links that will open within one hour when carrying the reverse current rating for the module. Fuse-links to class gPV (see section 3.) provide this protection.

To protect the cables and other circuit components it is also necessary to use fuse-links in any cables supplying loads (inverters for instance). The fuse-links should be selected to provide protection to cables and/or downstream devices and should be rated to be capable of opening in dc circuits at a voltage greater than the battery voltage. Fuse-links in these two positions will also protect the battery from damage in the event of short circuits in cables from the modules or to the output equipment.



Illus. 4: Layout of battery-based system

2.4 Multi-string, single array systems

The largest numbers of PV installations are those that would be termed 'small systems'. They would typically be under 10kW, and are either isolated or connected to the grid. They would use a number of strings of modules and a single inverter. Such systems are not only the highest number of installed systems but they also represent 80% of the generated capacity presently installed. It is expected that the installation capacity in the near future will also be at this rate, with only 20% being in the large solar farms (see later).

As indicated previously, when three or fewer strings are in parallel, it is not necessary to use fuse-links to protect modules against reverse currents from strings in parallel that are feeding current into a string that has a faulted module, as the healthy modules in that string will usually survive twice the forward current in the reverse direction for many hours. However, fuse-links should still be included in the strings to ensure protection of modules and cables in the event of fault current originating from failed inverter components. These fault currents may be of a high value if capacitors can discharge into the modules. Of course, if the string cables were insufficient in size to carry the maximum current from two strings then string fuses rated to protect the cable would be required. (see Illustration. 3.)

2.4.1 Selection of string fuse-links.

The string fuse current rating must be selected to allow for the maximum output currents from the modules (correcting the datasheet values for irradiance and operating temperatures) and allowing for fuse-link re-rating due to local ambient temperature and altitude. The string fuse-link voltage rating must be selected to be higher than the maximum voltage from the string (number of modules in the string multiplied by the datasheet maximum output voltage for the module), corrected to include any variation due to ambient temperature of the modules.

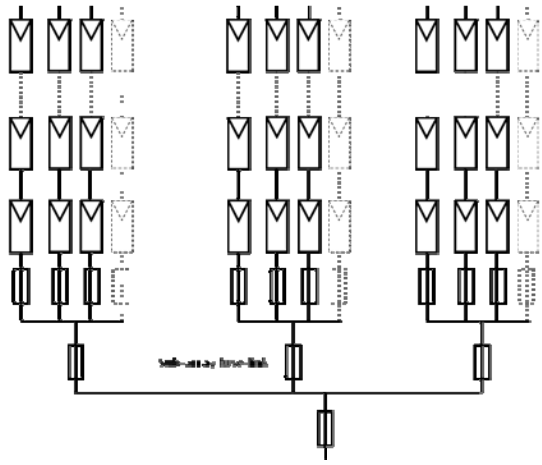
The selection of string fuse-links is detailed in fuse-link manufactures' data sheets and many other sources. However, it has been suggested that to simplify the selection of the fuse-link a current rating of 1.56 x I_{sc} of the module can be chosen.

Under low over-current conditions it is not likely that any two fuse-links in series would operate at the same time so even in systems where there is a fuse-link in both the positive and negative cables they should each be capable of operating alone at the maximum positive system voltage.

2.5 Multi- array systems

For solar farms the typical arrangement is to combine the current from the strings in a combiner box together with string fuse-links and then connect larger cables to the inverter.

In the largest systems this process may combine the arrays in a similar manner before the current reaches the inverter, as shown in Illustration. 5.



Illus. 5. Large multi-array system

As with string fuse-links in an array, any fuse-links in the larger cables should be rated to protect the cables and consideration should be given to the possible fault currents available from parallel faults.

The fuse-links not directly in the strings are referred to as sub-array fuse-links and array fuse-links, if there is a second layer of combinations as shown in Illustration 5.

Guidance on design of arrays will be detailed in the forthcoming IEC 62548 "Design requirements for photovoltaic (PV) arrays". Guidelines are also being prepared within the IEC committees for the specific installations requirements for large solar farms and also for installation on buildings.

Installation practice is also now being regulated with many countries having certification for installers to ensure competence of the installation and safe practice for those installers connecting the electrical elements of the system and the grid connections. The installation practices on solar farms where system voltages of 1500v dc are being proposed will bring new requirements for installations and safe practices, including fencing.

3. Standardisation

Even before the rapid growth of large PV farms was established, the need for codes and regulations had been anticipated by the bodies concerned with Standardization: the need was noted in the 2002 edition of IEC 60364 section 7-712 [2] where the DC part of PV installations is noted as "under consideration". By 2005 the AS/NZS standard 5003[3] was published which gives extremely comprehensive guidance for PV installations and their protection, and the later recent editions of IEC 60364 section 7-712 detail the installation of PV systems and the protection elements required. This section specifies circuit protective devices in strings and for array protection; as well as showing reverse diodes on modules and blocking diodes for strings.

For fuse-links, standardisation of specific devices had been discussed in the USA and Europe during 2008. A first draft of UL 2579[4] was published that year and proposals for the IEC standard being discussed during the early part of 2009. After one of the most rapid introductions of a standard, IEC60269 part 6[5], "Supplementary requirements for fuse-links for the protection of solar photovoltaic energy systems" was published in September 2010. This standard recognises a number of physical sizes for fuse-links, standardises testing and establishes the utilisation category of gPV fuse-links that specifically protect PV systems.

The key feature of this standard is that fuse-links should operate within their conventional time at 1.45 times their current rating under test conditions, which in practice means the fuse-links will operate within one hour at 1.35 times. This ensures that the modules are protected because the standards for modules require that they should withstand 1.35 times their rating for two hours.

The standard also includes temperature cycle and current cycling tests that are designed to reflect real-world situations and which mirror the tests required of the modules.

The full voltage testing is also intended to represent practical situations, recognising the low inductance of PV supply circuits but including faults current of at least 10kA which may occur in the PV circuit in the event of failures within the inverter system.

Whilst PV systems and their key protection requirements were addressed by the standard, it was recognised that installers needed a recognised standard in place immediately, rather than delay publication while a more comprehensive document was developed; hence the standard did not include requirements for holders for gPV fuse-links. To ensure that holders were not excluded from the standard for too long and to ensure suitable protection for any new developments in PV systems could be included, the standard was immediately put in to a maintenance cycle.

4. Where are we going from here?

The components for PV systems are under constant change. Whilst there seems to be little expectation of higher current ratings from crystalline cells in the near future, there is progress in organic films which will need protection and developments in cells with PV concentrators where lenses or mirrors increase the insolation. The protection requirements for these developments are still unclear, so fuse-link manufacturers await the challenges ahead.

Inverter topologies and the arrangements of modules with respect to earth are continually changing and adequate protection of alternate arrangements will always need to be considered as each is developed.

In large inverters the use of high speed fuse-links to protect the semiconductor devices is still commonplace and any changes to topologies or devices used will influence the specific requirements of these fuse-links. The more common use of transformerless inverters certainly means that dc and ac fault current may be present and the relative magnitudes may require novel testing systems to be developed.

Only with time, will we see if PV farms will develop with large central inverters using only one or two inverters connected to the grid or if systems will develop with many smaller inverters connected to the grid. Problems can be envisaged with grid stability for either of these systems. For large systems, the effect on the grid in the event of disconnection may be considerable. For smaller systems the reliability of the control systems which must maintain grid frequency at nodes with a large number of inverters may be a problem. In both systems the development of the protection regime will be important and should include fuse-links whether the grid connection is to a low or high voltage network.

In order to improve system efficiencies there are a number of inverter and system installers that are preparing to increase the open circuit voltage of larger PV installation to 1500V. This will be a challenge for fuse-link manufacturers as well as all the other system component manufacturers. Once suitable components become available, then the installation standards and working practices will, in turn, have to be adapted to suit higher system voltages.

The debate as to whether to use fuse-links for protection if reverse diodes are included will surely go on for some time. The higher power loss of diodes relative to fuse-links and the possibility that the diodes fail short-circuit, does suggest that string fuse-links will be included in systems for many years. The use of fuse-links to protect strings is enshrined in installation codes and manufacturers' installation manuals so this doctrine should continue for many years to come; the author has estimated that there are many millions now installed.

In some installation guides there are references to "earth" fuse-links, although the exact purposes and required operational performance is not clear. With the various topologies of inverters and options for grounding modules, there will be discussions for some time to come on the inclusion of fuse-links in the earth connections of installations or not.

The IEC standard will be required to be specific about the 1.35 times condition for the fusing current to align fully with standards for modules. The standards will need to further review the requirements for array fuse-links as to whether a true gPV fuse-link is required or whether only a gG fuse-link is required. Alternatively, it may be necessary to adjust the "conventional times" for fuse-links to be 1 hour for gPV fuse-links so as to prevent damage to modules in arrays.

Selectivity of array fuse-links and string fuse-links will be a further discussion point. From the protection point of view it is important to protect the modules from damage from over currents but operationally it may be undesirable to have both array fuse-links and also string fuse-links operate, a situation that can potentially occur, albeit a remote possibility.

Module and inverter manufactures may be using solar modules for their test programs whilst many approvals test facilities use rectified ac for the dc test source or a static dc source (e.g. a battery). Although a PV module will follow the V-I curve (no voltage when shorted varying to maximum voltage when no current is flowing), a rectified or static dc source will have a voltage – current relationship that is based on the performance of the fuse-link and any series inductance and resistors. It would be useful if independent test houses could use test sources that better simulate the output of PV cells when performing tests on fuse-links.

For the fuse-link designers there are a number of challenges. The ever-present need to reduce package sizes and power loss whilst ensuring a high dc voltage capability at very low over currents will be with them for the foreseeable future.

One thing to be sure of is that the use of PV systems will continue to be a large part of the overall mix of renewable electric power generation and, if cost-effective power storage can developed successfully, it will form an even larger part when we can start to utilise PV generated electricity during the night as well as the day.

References

[1] "Light sensitive device" U.S. Patent 2,402,662 Issue date: June 1946
[2] IEC 60364, IEC publication 2002, and later revisions
[3] AS/NZ 5003, Australia Standards publication, 2005
[4] UL 2579, Underwriters Laboratories draft standard, versions since first draft, 2008
[5] IEC 60269-6 IEC publication 2010

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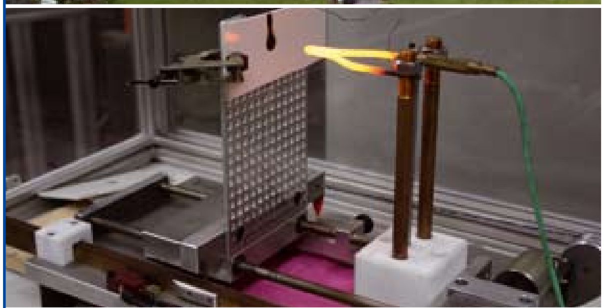

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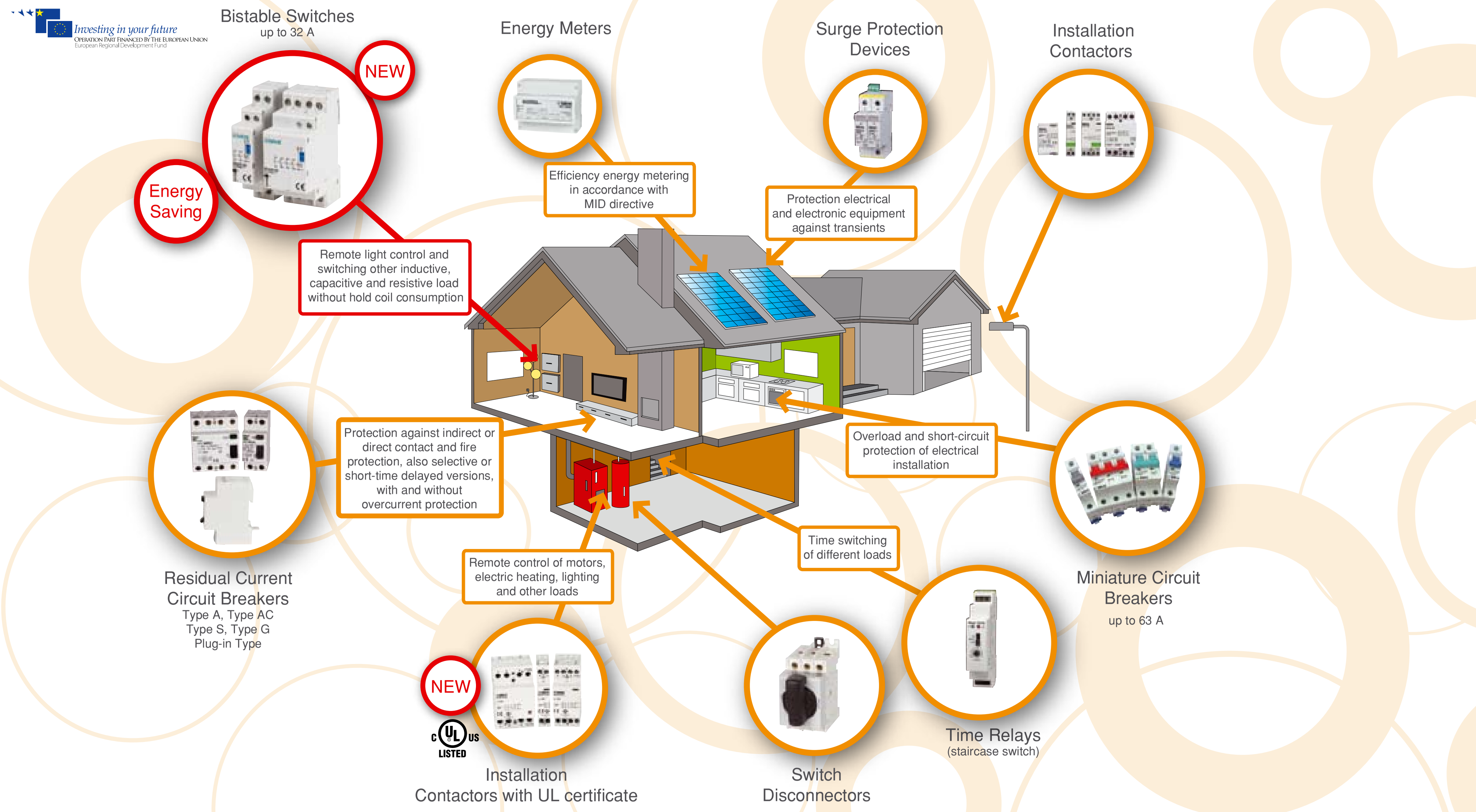

Iskra®
Iskra MIS
Ljubljanska c. 24a, SI - 4000 Kranj, Slovenia
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CONTACTS

University of Maribor
Faculty of Electrical Engineering
and Computer Science
Smetanova ulica 17
SI-2000 Maribor

prof. dr. Jože Pihler
Tel:+386 2 220 70 61
Fax: +386 2 252 54 81
icefa@uni-mb.si
joze.pihler@uni-mb.si

ICEM-TC
Gosposvetska cesta 84
SI-2000 Maribor

Lidija Korpar Koritnik
Tel: +386 2 234 23 80
Fax: +386 2 234 23 82
icefa@uni-mb.si
lidija.koritnik@icem-tc.si

ISBN 978-961-248-297-8