ADVANCES IN THE PROTECTION OF SEMI-CONDUCTORS BY FUSES

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1. INTRODUCTION The use of semi-conductor rectifiers for power control has become well established and techniques for their protection have developed alongside the devices. The equipment designer has many methods at his disposal which can be combined to give an appropriate level of protection. These include fast acting (semi-conductor) fuses, fast or medium speed circuit breakers, contactors, firing control of thyristors and surge current suppression whereby firing pulses are quickly removed from a thyristor gate. Current limiting by-pass switches (electronic "crow-bar") are also used. In some cases (e.g. rail traction) the use of high impedance supply transformers (10% impedance), mechanically strong busbar systems and "over size" thyristors and diodes can enable equipment to withstand the thermal and magnetic forces long enough for a conventional breaker to operate.

In most protection schemes, fast acting fuses are included as being the most economical solution to device protection in the short times associated with short circuit conditions. This is because a fuse forms an analogue model of the semi-conductor junction. It is capable of responding thermally faster than a junction and also absorbing circuit energy at a very high rate. The fuse also has the advantage of not requiring maintenance, since after operation on a fault, it is replaced by a new fuse.

2. FUSE PROTECTION The information needed for correct fuse application can be divided under three headings.

1) Information to ensure the fuse will protect the semi-conductor under fault conditions.

2) Information to ensure the fuse will satisfactorily carry the current, including any overload, required.

3) Information to ensure that the fuse will not operate when other parts of the protective system are intended to operate.

Advances in the protection of semi-conductors by fuses have taken place in all three areas, partly as a result of actual improvement in fuse performance but also, most significantly, as a result of a greater understanding of fuse behaviour. In the past much of the theoretical work associated with the fuse was done by research bodies unconnected with industry rather than fuse manufacturers, and most practical fuse development was by "trial and error". It is only in

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recent years that manufacturers have realised that a fundamental understanding of the fuse is necessary for its correct application and development, and with the advent of large digital computers, have been able to actually understand the associated phenomena.[1.2.]

2.1. PROTECTION OF THE SEMI-CONDUCTOR DEVICE   Methods used for determining whether a device is protected for high fault levels usually depend on the use of I^2t (more strictly $\int i^2 dt$) and/or peak current. A difficulty exists when neither of these is sufficient on its own. This is because the I^2t and peak current withstand of a device depends on the actual current shape and duration, and fuse I^2t and peak let-through varies with fault circuit conditions. Other criteria, for example $I^2\sqrt{t}$, have been proposed,[3] but in general I^2t still remains the most widely used parameter. Some methods of resolving the difficulty are as follows.

2.1.1. Device Withstand   Information is usually presented in the following forms:

a) Maximum non-repetitive surge current (peak value of a half sinewave current 50 or 60 Hz) versus number of equal amplitude pulses. The equivalent rms value is then half of the peak.

b) The value of just one pulse is quoted in published information as I_{TSM}. The 10 ms withstand for 50 Hz current is then $\frac{I_{TSM}}{2}^2 \times 0.01$ Amp^2 seconds.

c) For shorter times, the I^2t is normally less than the 10 ms value and may be presented as I^2t versus time. It may also be presented as peak half sine-wave versus time, or the I^2t quoted for one or more fault durations (e.g. 5 ms and 1.5 ms). In all cases the withstand is for a half sinusoidal pulse of the appropriate duration (i.e. a higher frequency is used for testing).

Although the I^2t withstand decreases with time the peak current withstand increases. For example, a particular device may have a non-repetitive single cycle surge withstand of 9000A at 5 ms, gives a I^2t withstand of 200,000 A^2sec., while at 1.5 ms its surge withstand would be 12,700A giving a I^2t withstand of 120,000 A^2sec. I^2t figures are usually quoted for the device junction hot (max. temperature) before fault. Figures may also be given for junction cold (I^2t generally 20% higher) and with zero re-applied voltage (may be 60% higher than with 100% re-applied voltage).

2.1.2. Fuse let-through I^2t There are many circuit parameters which affect I^2t let-through. They have been extensively discussed[4.5.] but will be briefly mentioned here.

i. Supply voltage - this affects only the arcing I^2t and an increase from say 250V to 500V with a 500V rms fuse can give an increase in arcing I^2t of about 150% to 200%.

ii. Fault level - this affects both pre-arcing I^2t and arcing I^2t and in general an increase in fault level decreases pre-arcing I^2t, by reducing time, and increases arcing I^2t. Overall I^2t can thus be increased or decreased depending upon the design of fuse and the supply voltage.

iii. Power factor – the lower the power factor (or higher the $\frac{X}{R}$ of the fault circuit the harder it is for the fuse to clear due to the larger circuit inductance, and hence stored energy. I^2t let-through at 0.1 power factor $(\frac{X}{R} = 10)$ can be as much as 1.8 times that with a power factor of 0.7($\frac{X}{R} = 1$). With a dc fault, the comparable parameter is circuit L/R (time constant). An increase in L/R will increase arcing. Also, due to the lower rate of rise of current, a greater heat loss will occur during the pre-arcing time. This will increase the pre-arcing I^2t.

iv. Point on wave – the point on the voltage waveform at which the fault occurs, and hence the voltage the fuse sees during arcing, can have a large effect on I^2t let-through. A ratio as high as 5 to 1 worst to best case conditions can result.

v. Frequency – increase of frequency increases rate of rise of fault current and leads to lower pre-arcing times. Inductance will also be less for the same power factor and fault level and a decrease in I^2t results. Decrease in frequency causes a more onerous duty for the fuse, ultimately approaching a dc condition. This is known to require, often considerable, voltage derating for an ac fuse.

vi. Pre-loading – if the fuse elements are already hot, having been carrying current prior to a fault, a considerable reduction in pre-arcing and consequently arcing I^2t can occur (typically greater than 25%).

With such a wide variation in I^2t it is normal for a fuse manufacturer to specify I^2t not in simple tabular form, as with many industrial fuses, but to provide sets of curves, normally one for each fuse rating to give accuracy, of I^2t versus fault level. These are drawn at various supply voltages for the most onerous conditions of power factor (< 0.2) and point on wave, with the fuses cold prior to test. This means that in practice I^2t will never be higher, and will usually be lower, than the published data thus giving a suitable safety factor.

2.1.3. <u>Co-ordination of fuse and thyristor</u> One method of fuse and device co-ordination, based on I^2t, which has successfully been used for several years, is shown in fig. 1. Lines are drawn on I^2t/fault level curves to represent the total operating time of the fuses. As the fault level increases, so the operating time is reduced. Device withstand information can then be plotted directly on the fuse let-through curves and any fuse curve lying below the withstand curve will provide protection. In fig. 1., a thyristor having a withstand of 45,000 A^2s at 5 ms and 36,000 at 1.5 ms is shown plotted on fuse curves for the appropriate supply voltage. The 200A fuse will protect the thyristor up to 100,000A, the maximum breaking capacity, while the 235A fuse will protect with faults of up to 60,000A. If the maximum fault level were below 6000A (about 20 times rated current) the 275A fuse would be suitable. This method therefore gives a suitable fuse, if the fault level is known, or the level to which a fault must be limited (using line inductance for example) in order to use a given fuse.

When this method of co-ordination is used, it is seldom necessary to consider peak current let-through and withstand. If a fuse lets through a near sinusoidal pulse with an I^2t let-through less than the device withstand, it must inherently contain a peak value less than the withstand of the device. At higher values of fault current, the fuse let-through waveform becomes more triangular. Device manufacturers normally allow an increase in peak withstand if the waveform is triangular rather than sinusoidal such that the two waveforms have the same I^2t. For all currents then, if the decrease in device I^2t with reduction of fault duration is taken into account, peak current withstand will also be taken care of.

2.1.4. Arc voltage The maximum voltage produced across a semi-conductor fuse during arcing is normally greater than the maximum peak value of the supply voltage. If semi-conductor devices which are blocking see this voltage, care must be taken that they are of a high enough voltage capability. A fuse will produce a minimum arc voltage on fault, related to the number of its restrictions. This will occur even with a very low supply voltage since di/dt in the circuit inductance will supply the remaining emf. For example, a 700V fuse on 120 volts may produce an arc voltage of 300 volts, while on 65 volts will still produce about 300 volts. Care must be taken to check manufacturers data if a fuse is used at a low voltage relative to its rating. A similar effect occurs if two fuses in series in a three phase bridge both operate. Both cannot be relied upon to operate in all cases, since two arms may feed into one or one fuse may be pre-loaded and operate first. Consequently, an arm fuse is normally rated to cope with full line to line voltage. If only one 600V fuse operates at 480V the arc voltage may be 850V. If two fuses in series operate each fuse at 240V would produce 470V giving a combined arc voltage of 940V.

2.2. CURRENT RATING OF A FUSE Industrial type fuses have a fairly well defined rated current based on a temperature rise limit in a standard test rig and an associated watts loss. There is also a conventional fusing and non-fusing current with, in the U.K., a fusing factor (approximately the ratio between "rated" current and that just required to cause operation of the fuse). The current rating of a semi-conductor fuse is usually much less well defined. Fusing factor can be used - but providing this is not below about 1.2 so preventing "nuisance blowing" on non-harmful overloads, this is not very helpful, since a semi-conductor fuse is basically for short circuit operation rather than overload operation (this will be discussed in more depth in section 2.3.).

Watts loss is also of less importance than with industrial fuses since the heat generated in a thyristor can be 5 or more times that generated in its associated fuse. For the same reason the temperature rise of fuse terminals is of less importance, except where they are limited by associated equipment (for example insulation). Also there may be a necessity for restricting fuse temperature because of the use of low melting point materials (such as solder).

If the basic conditions of minimum fusing factor and maximum cap temperature (if applicable) have been satisfied, the ultimate criterion of rating must surely be that of deterioration. Almost any non-ferrous metal when subjected to cyclic stress will eventually fatigue, and fuse elements are no exception. An element receives two forms of stress; firstly every time the equipment is switched on the element temperature will rise from ambient, this will also occur with long period cyclic loading (e.g. 1 minute on, one minute off). Secondly, semi-conductor fuse elements are of necessity so sensitive that the restriction temperatures follow the square of the current waveform and apply, in the case of 50Hz current, stress one hundred times per second! Experience has shown that providing such temperature excursions are limited, by restricting overall element temperature to certain values, a very long fuse life can result (e.g. 10^5 hours). An obvious criterion is therefore element temperature which, with measuring and computing techniques, can be related to hot to cold resistance ratios. The manufacturers of some ranges of fuses therefore specify this ratio (which requires voltage and current measurement) or use it to set a more easily measurable quantity (e.g. cap temperature).

Because a semiconductor fuse runs relatively hot - a consequence of being such a high speed device - it is very much influenced by its surroundings and attachments. The following sections detail some of these variations, all based on maintaining an upper limit to element temperature to ensure long fuse life.

2.2.1. Ambient Temperature Fig. 2 shows a reduction in current rating necessary if the local air conditions vary. It is important to realise that it is this local micro-climate rather than the ambient temperature (normally defined as that outside the cabinet in which the fuses may be placed) which is of importance. It is advisable to find a fuse's actual current rating by looking at such a curve rather than to place too much emphasis on the "rating" marked on the fuse. This marked rating should often be regarded as little more than a list number for replacement purposes which, sometimes, gives an idea of typical current carrying capability.

2.2.2. Busbar Size The above statements are particularly true now that a standard test rig exists with specified sizes of busbars (IEC 269-4 and BS 88: Part 4 1976). Up to 75% of a fuse's heat loss is from the attached busbars and so these have an effect on fuse rating. Fig. 3 shows this variation. For example, a fuse previously rated on busbars of 1 in. x 0.25 in. (25.4 mm x 6.35 mm.) at 275A has, on the new size bars 1.25 in. x 0.25 in. (31.75 mm. x 6.35 mm.), a rating of 283A (cross sectional ratio 1.24, surface area ratio 1.2 giving an increase to approximately 103%). In practice the fuse may be used on much smaller bars, e.g. 20 mm. x 5 mm. This gives a cross sectional ratio of 0.5 and a surface area ratio of 0.65. From fig. 3 this will reduce the rating to about 93% giving I = .93 x 283 = 263A.

2.2.3. Forced Cooling Cooling air is often used to improve the utilisation of thyristors. The associated fuses can also be cooled and fig. 4 shows an uprating curve for various air flows. The element temperature is maintained constant, and the extra heat loss requires a steeper temperature gradient from element to body and cap. For this reason the fuses appear to be running very cool, but the current must not be further increased if reliability is not to be lost. The current rating of the fuse, to which the uprating is applied, is found from the current rating versus ambient temperature curve using the appropriate temperature of the cooling air. A more recent method of uprating fuses is to attach them to water cooled busbars. One such arrangement is shown in fig. 5. This arrangement enabled an uprating of 40% to be obtained, keeping the element temperature approximately constant. This arrangement protects a 2500A rms thyristor at 480V rms having a 5 ms I^2t withstand of 5.1×10^6 A^2sec. The fuse can carry 2200A rms continuously when supplied with 1 gallon/minute of 25°C cooling water. Water cooling is so efficient that it can provide considerable cooling to the busbars also.

2.2.4. Length of Busbars The testing specified in IEC 269-4 and BS 88-4 calls for fuses to be mounted vertically and to be attached to busbars of 500 mm. length carrying a current density of between $1A/mm^2$ and $1.6A/mm^2$. To the ends of these busbars, as a part of the circuit, are attached further lengths of busbar of at least 1 metre long and of similar cross sectional area. This arrangement is seldom duplicated in practice, and it is of interest to examine the effect of shorter lengths of busbar. The results of one such investigation, carried out using numerical analysis of the fuse and busbar, is shown in fig. 6. In this case a length of busbar 1, attached to the fuse and to the heat sink was used. Such a "heat sink" is formed by any part of the equipment with a temperature substantially independant of the heat supplied by the fuse. The 100% curve represents 1 metre of busbar attached to a heat sink at ambient temperature and in effect shows the temperature distribution along it. If a heat sink of a given temperature were attached to the busbar at a point of equal temperature the fuse would be unaffected. If the heat sink were attached to a point of high temperature, the fuse could be uprated, as shown by the other curves. If the heat sink were attached to a part of lower temperature some reduction in rating will be necessary, but this tends to be small. For a busbar length of at least 400 mm., unless the heat sink is very hot, the derating required is negligible. This is because the busbar dissipates most of the fuse heat loss by convection and radiation and a slight temperature rise will dissipate more heat, including heat from the heat sink.

2.2.5. Overload A fuse must also be capable of withstanding acceptable equipment overloads. If this overload persists for a time sufficient for the fuse to reach a substantially steady temperature, the fuse current rating must at least equal the overload current. "Rules of thumb" have been used to determine acceptable cold start and hot start non-repetitive overloads and also regular cyclic overloads. These rules usually relate to the fuse's time/current curve and typical acceptable overload values for the above three conditions are 77%, 67% and 50% of the current which, according to the time/current curve, would give operation at a time equal to the overload duration. Cyclic loading of fuses is very complex and a complete paper on this subject is included in the conference.

2.3. CO-ORDINATION WITH OTHER PARTS OF THE PROTECTION SCHEME A semi-conductor fuse is normally required to operate only with very high fault currents since it is in this region a fuse is so effective. It is normal to use circuit breakers, etc., where the breaking duty is less severe and device protection not so critical. Also on overload the fuse may not be fast enough to protect a thyristor, since it is designed to have a very steep time/current curve to give a high current rating with fast short circuit operation. Unlike most industrial fuses it usually does not include 'm' effect low melting point alloy. This time/current curve provides the information necessary to ensure discrimination with circuit breaker overload trips.

Figure 7 shows a typical time/current curve. It may be shown as a single curve with a tolerance on the current. This is normally $\pm$ 10% to allow for manufacturing tolerances, although many manufacturers hold $\pm$5% for most ratings. Alternatively two curves representing the upper and lower limit may be drawn. A possible way of presenting industrial fuse time/current curves, uses the IEC 269 bands whereby the upper limit includes arcing. The two limits then become minimum pre-arcing time and maximum operating time. In both cases virtual time is used (I^2t divided by the square of the rms fault current). Thus any fuse whose upper curve lies below the pre-arcing curve of another will discriminate with it; i.e. it will clear before the larger fuse melts. This is useful for fuse discrimination, but for breaker discrimination only the minimum pre-arcing curve is actually needed. In addition with semi-conductor protection the use of virtual time tends to be confusing since I^2t withstand is always in terms of actual time.

Variation in fault waveform has a most significant effect on time/current curves which is why they are standardised by using symmetrical sinusoidal current. This variation will now be examined.

2.3.1. Asymmetrical Current Fig. 7 also shows the effect of fault current asymmetry on the time current curve, which can be quite significant for times below one second.

2.3.2. Half Wave Rectified Current Fig. 8 shows the effect of half wave rectified current on the time/current curve. Obviously operation cannot occur in even half cycles since no current is present. Any time-varying current in which the current repeatedly approaches zero will have such discontinuities around the current zeros. This is explained in greater depth in ref.1. As the fault current increases, operating time with the half wave rectified current is progressively less than with sinusoidal current. This is due to two factors. Firstly, the larger restriction temperature excursions produce more heat due to resistance change in the restriction. This increases the general temperature rise of the element. Secondly, the increased temperature fluctuation itself causes earlier operation, since the element as a whole does not have to get as hot in order for the restrictions to melt. This situation applies to all rapidly time varying currents and currents with a large form factor will result in shorter operating times for most of the time/current curve.

2.3.3. DC Current Direct currents tend to produce longer pre-arcing times than the equivalent rms sine waves. Figure 9 shows a step increase in current (dc of very short time constant) compared with an ac current of the same rms value. Despite the greater rate of rise of dc current initially, the ac current rapidly produces a greater heat generation (as explained above) and this coupled with notch temperature fluctuation gives much faster operation. Figure 8 shows the effect on a time/current curve of dc currents of various time constants.

If fuse co-ordination with a circuit breaker is required the time/current curve can be used to ensure that the fuse does not operate with the appropriate overload current. It must be remembered that since a circuit breaker may be feeding parallel paths or fuses may be in the arms of a bridge, an appropriate correction factor is needed to compare the fuse and breaker characteristics directly. If the fuse overload current is non-sinusoidal, then, particularly for times of less than 1 second, an appropriate time/current curve is necessary. This is especially the case with dc of long time constant.

An alternative approach, and often the only one which can be used if the fault is very irregular, e.g. 1000A rms for 20 ms followed by 1300A rms, is to use a characteristic of pre-arcing I^2t against pre-arcing time. There is for a given fuse a value of pre-arcing I^2t which is approximately constant and corresponds to the condition in which no heat is lost from the restriction (adiabatic heating). For semi-conductor fuses the time for which this is valid can be very small, e.g. less than 0.3 ms. Heat is lost from the element restrictions to the rest of the element and then to the filler and so the pre-arcing I^2t increases with time (becoming infinite when the fuse carries any current which does not cause eventual melting). The heat loss can be so great that at as little as 5 ms the pre-arcing I^2t can be over twice the minimum. This curve is approximately valid for any fault waveform.

2.3.4. <u>Use of Pre-arcing I^2t/Time Curves for Co-ordination</u> We will first examine the validity of such a curve.

i. Element Thickness. Heat loss from a fuse element to the surrounding filler becomes significant for pre-arcing times over about 15 ms. This causes a variation in characteristic and if a generalised curve for a whole range of fuses is being used the curve opens out into a band. This can be seen in fig. 10 where I^2t is expressed in multiples of minimum (adiabatic) pre-arcing I^2t and an element thickness variation of 4:1 exists.

ii. Current Waveform. Fig. 11 shows three curves (for a single element thickness) produced for sinusoidal current, a half wave rectified current and a dc current of 40 ms time constant. The half wave rectified current gives a lower pre-arcing I^2t at a given pre-arcing time. This is because increase in pre-arcing I^2t is a function of heat loss from the restrictions. The half wave current produces more heat for the same I^2t let-through and so reduces I^2t let-through for the same pre-arcing time. In addition the periods of no current in the waveform result in rapid restriction temperature drop and little heat loss during these off periods. The pre-arcing time is thus lengthened without a corresponding increase in heat loss. The half wave curve lies below the sinusoidal curve for all pre-arcing times over one half cycle.

DC current of over a few milliseconds time constant also results in a lower pre-arcing I^2t than a sine wave. This is because restriction temperatures are less than with a sine wave for most of the time. Fig. 12 shows the notch and element temperature variation for two currents which give operation in approximately the same time. One is a sine wave of 1800A rms, the other a dc current with a final value of 2200A and a time constant of 10 ms. The slow build up of dc current effectively increases the pre-arcing time without a corresponding increase in heat loss.

For co-ordination with a circuit breaker the lower limit of these curves, taking into account manufacturing tolerances is required to ensure discrimination. A tolerance of ±5% on the current of published time/current curves represents approximately ±10% on I^2t of these curves. I^2t against time of a fault can be plotted directly onto fig. 11. One example is shown for a dc inverting bridge fault. The dc breaker clears at 20 ms at which point the I^2t is 45% of the dc curve. The circuit breaker will clear without causing fuse operation, but obviously some margin is necessary if fuse deterioration is not to occur. This margin will now be examined.

Pre-arcing I^2t includes I^2t for the notch to reach melting point, I^2t for state change to occur and then I^2t for vaporisation or break up of the restrictions. Irreversible change will occur to a restriction as soon as any state change occurs. The period up to melting represents approximately 73% of the quoted minimum (adiabatic) pre-arcing I^2t. For pre-arcing times of between about 1 and 10 ms the figure is at least 80% and for times in excess of 20 ms it is over 90%. This is because a greater increase occurs in pre-melting I^2t than in either the melting or pre-vaporising I^2t, due to the times involved. For any waveform then, a curve can be produced which gives the minimum pre-melting I^2t against time for a range of fuses (including manufacturing tolerance). To what percentage of this minimum pre-melting curve a fault may approach depends on the fault waveform, whether the fuse is pre-loaded and the frequency of such faults.

a) DC Faults. If the fault will occur rarely (e.g. less than 10 times in the anticipated life of the fuse) it is reasonable for the fault to approach to within about 80% of this pre-melting I^2t if the fuse is unloaded, 60% if the fuse carries current before the fault. If the overload is at all regular, e.g. 1000 times per year, figures of 60% and 45% respectively are probably more realistic, to ensure fatigue will not cause premature operation.

b) Half-wave Rectified Currents. In this case a considerably greater margin should be left due to the very large restriction temperature excursions, particularly for short pre-arcing times. For occasional faults figures of 65% cold and 45% pre-loaded would seem reasonable and for repeated faults 40% and 30% would be necessary.

c) Sinusoidal Currents. This will lie between the other two conditions. If the time is greater than about 0.5 seconds, notch temperature fluctuations are small, and below around 7 ms the notch temperature rise is steady. Under these circumstances (and this will apply to half wave rectified currents also) occasional faults up to about 75% cold, 50% pre-loaded are acceptable or frequent faults at 60% cold, 45% pre-loaded. For ac faults from one half cycle up to around 0.5 seconds the large notch temperature fluctuations result in figures of 65% cold and 45% pre-loaded for occasional faults. Frequent faults demand a reduction to about 50% cold and 40% pre-loaded.

All the above figures have been obtained from a minimal amount of practical testing and the use of restriction temperature/time curves obtained from numerical analysis of the fuse heat flow. Further work and more operating experience using these figures are necessary, but they are presented as a basis for consideration. Life testing is most time consuming and the use of analytical techniques can be very helpful. For times over a few seconds the normal time/current curve can often be used for co-ordination since transient effects are then small.

Returning to the example, and allowing 10% for manufacturing tolerance and 90% as the ratio of pre-melting to total pre-arcing I^2t, the fault at 20 ms is 56% of the minimum pre-melting I^2t. This would be acceptable for occasional pre-loaded faults or a repeated fault from cold (e.g. switch on failure).

2.3.5. Transient effects at rated current   Figure 13 shows the fluctuation of restriction temperature at rated current for a fuse carrying full wave, 180° and 120° conduction currents of the same rms value. It can be seen that the rectified currents give larger notch fluctuations and hence more heat production. Compared with dc current, the three waveforms produced 0.3%, 0.9% and 1.6% more heat respectively. At minimum fusing current, a sinusoidal current produced 0.5% more heat than dc of the same rms value, and the notch temperature was about 40°C hotter with ac, just prior to notch melting.

From this, it can be concluded that although variation in current waveform has a large effect on the short time operation of a fuse, it is very much a secondary effect between rated current and minimum fusing current. It is not until conduction periods become much less than 180° that heat production will increase sufficient to affect the rating of a fuse. Effects such as ambient temperature and busbar size swamp these small differences due to waveform.

3. CONCLUSIONS

This paper has attempted to show that the protection of semi-conductors by fuses has developed and that it is now less of an art and more of a science. It is to be hoped that the days of a user putting bigger and bigger fuses into his circuit until his device is destroyed, are over. Today, with better information being produced by both fuse and semi-conductor manufacturers, the situation is much better. There is no room for complacency, however, and the two sides of the industry must continue to co-operate to ensure future developments take place in both products.

4. REFERENCES

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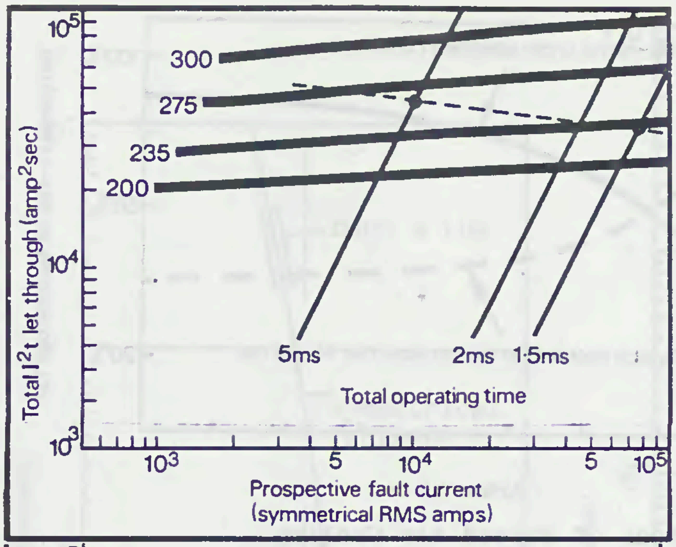

Fig. 1. Fuse Let-through I^2t versus Fault Level.

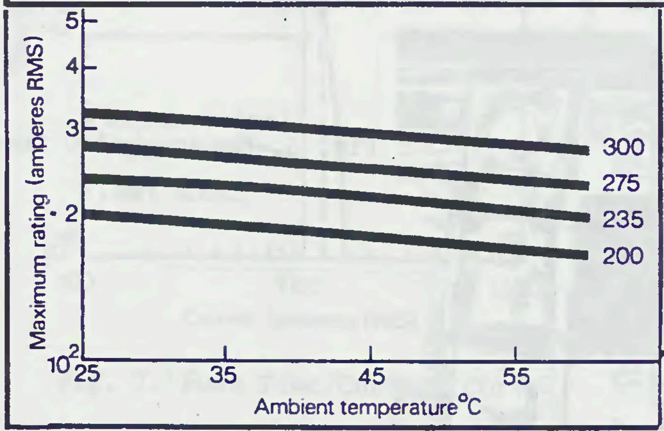

Fig. 2. Maximum Current Rating versus local Ambient Temperature.

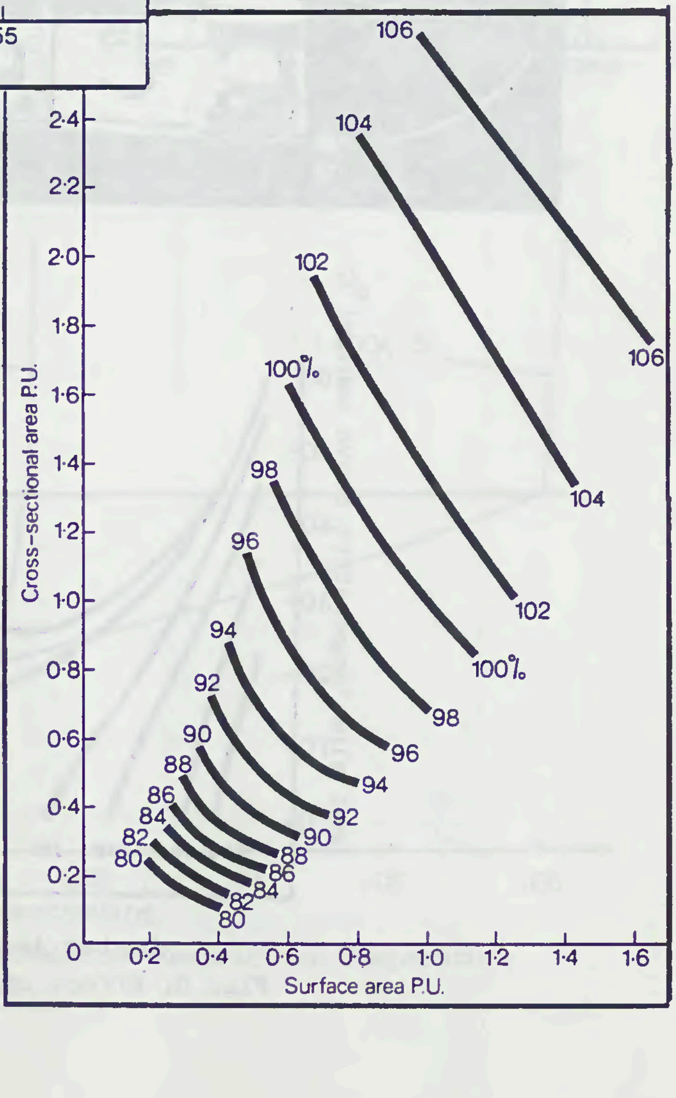

Fig. 3. Variation of Maximum Current Rating with Busbar Size.

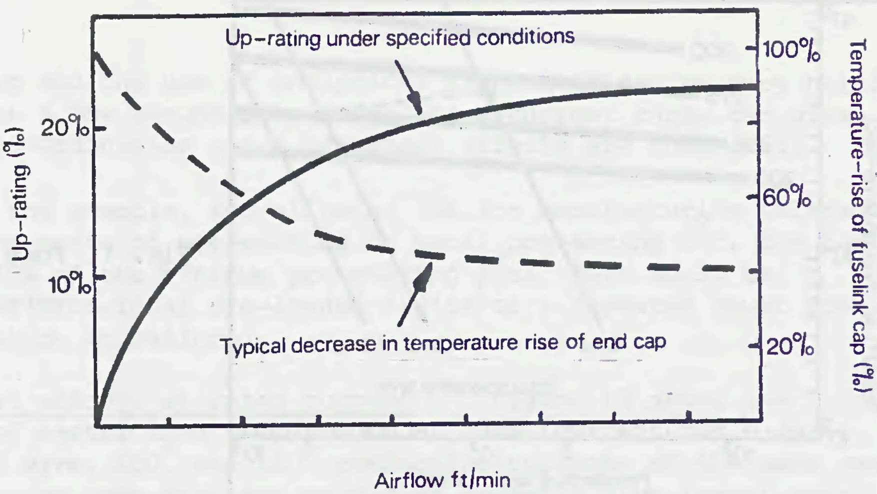

Fig. 4. Effect of Forced Air Cooling.

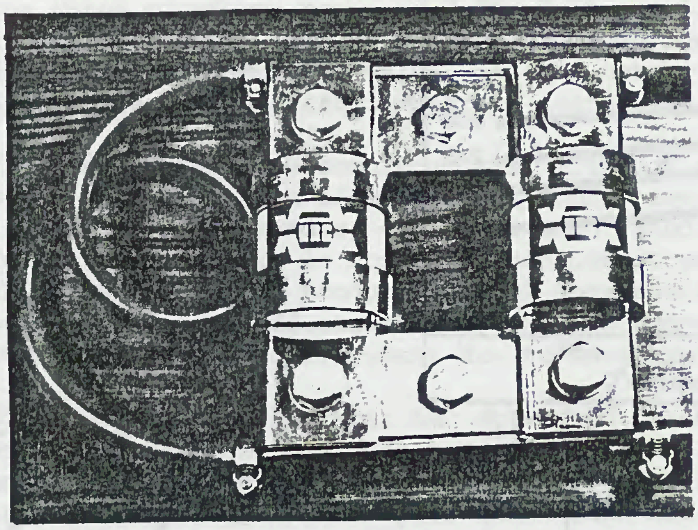

Fig. 5. Water-cooled fuse 2200A rms.

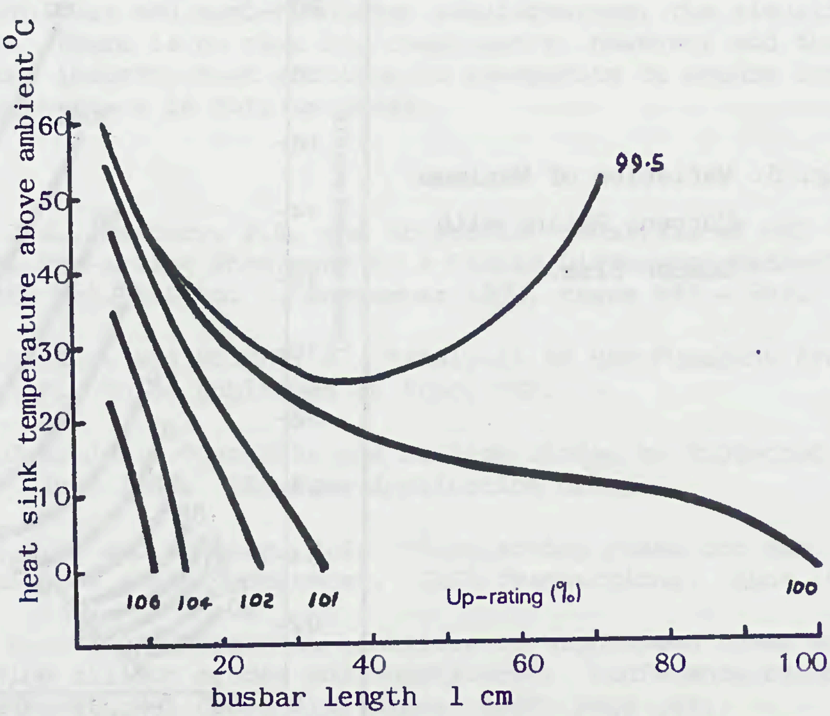

Fig. 6. Effect of Busbar Length on Current Rating.

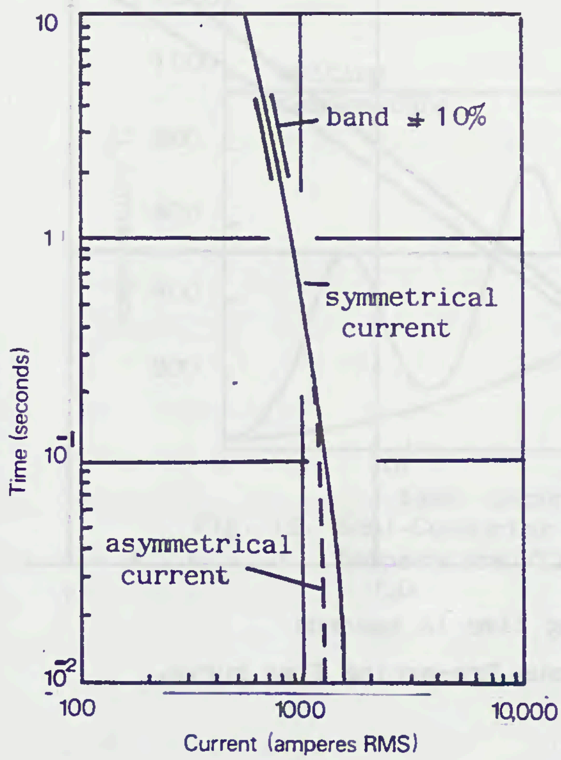

Fig. 7. Fuse Time/Current Curve

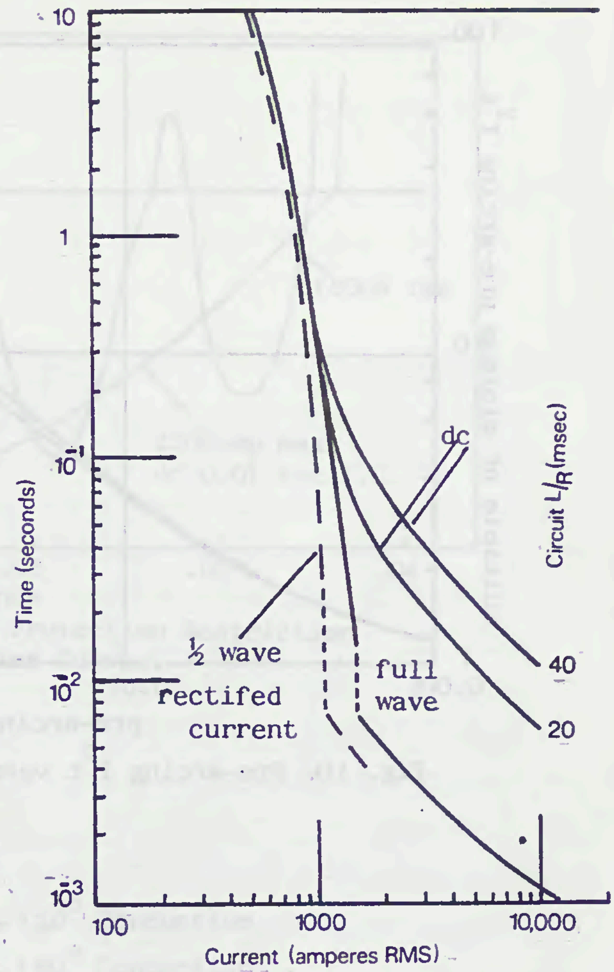

Fig. 8. Effect of Waveform on Fuse Time/Current Curve.

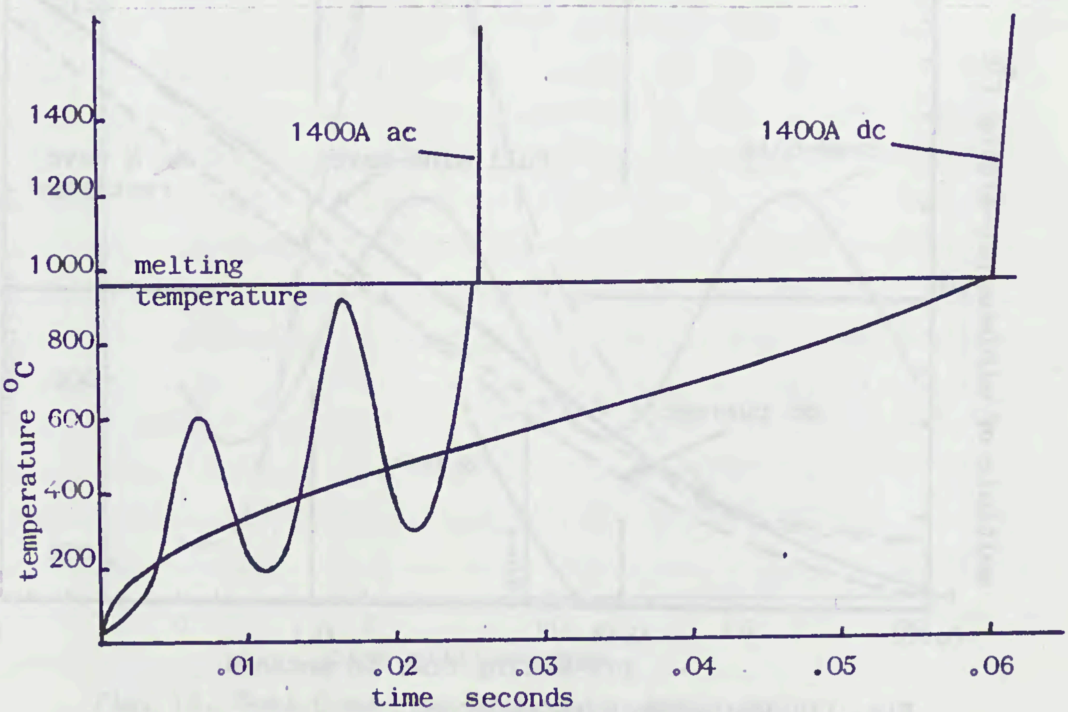

Fig. 9. Semi-Conductor protection Restriction Temperature versus Time Curves.

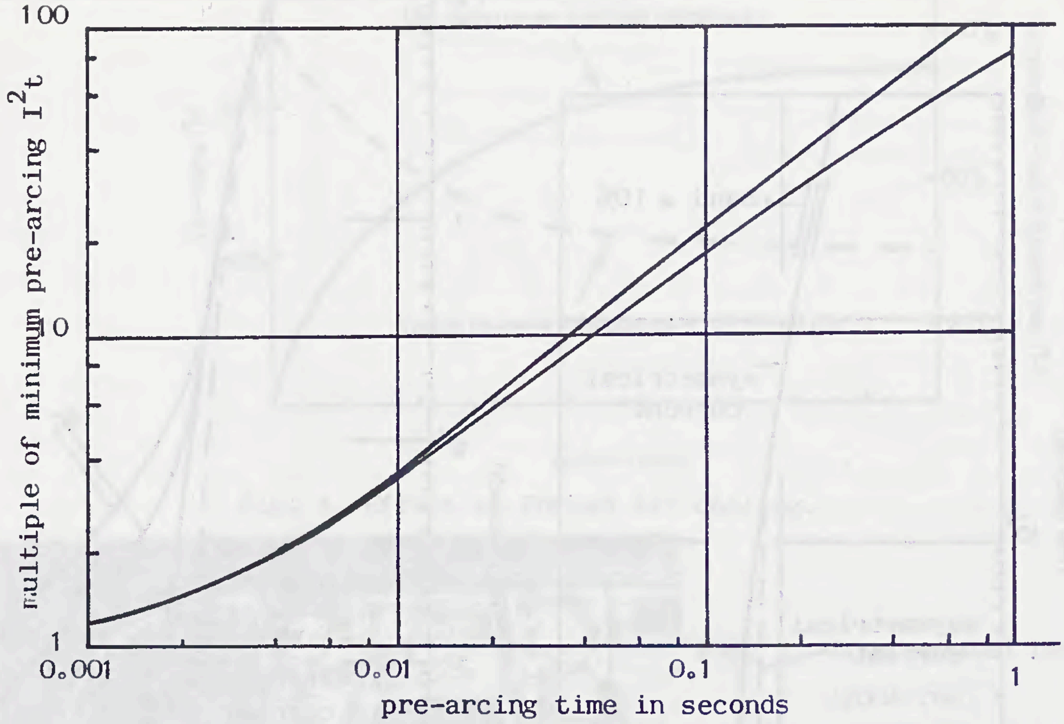

Fig. 10. Pre-arcing I^2t versus Pre-arcing Time curve.

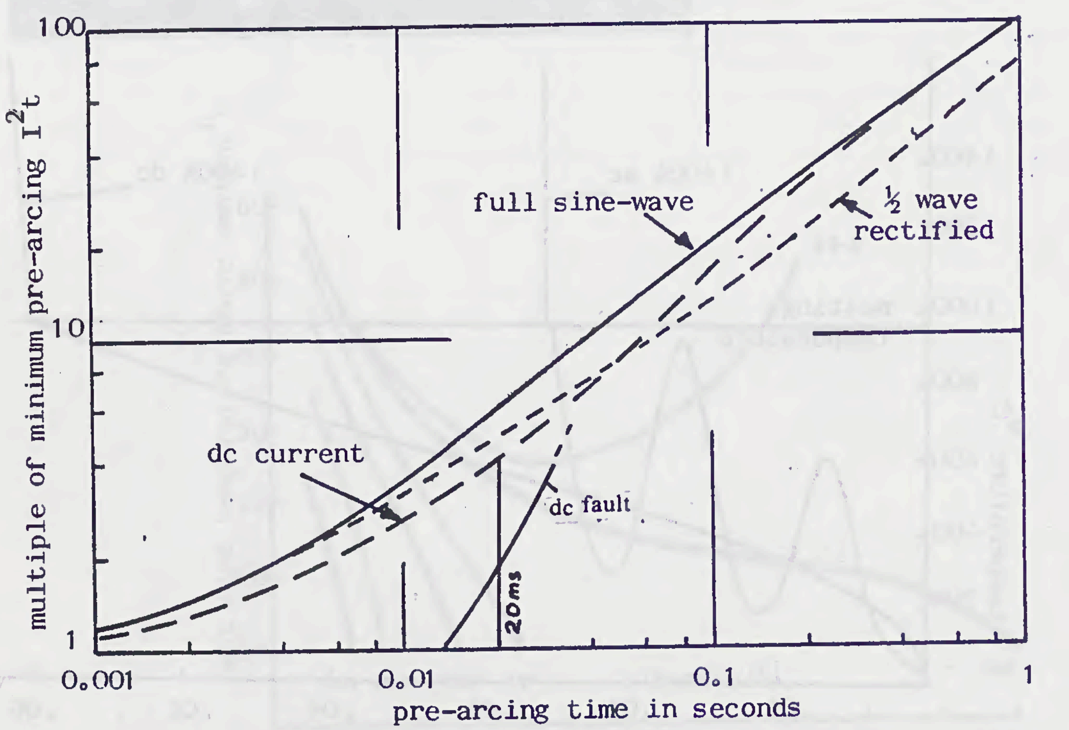

Fig. 11. Variation with waveform.

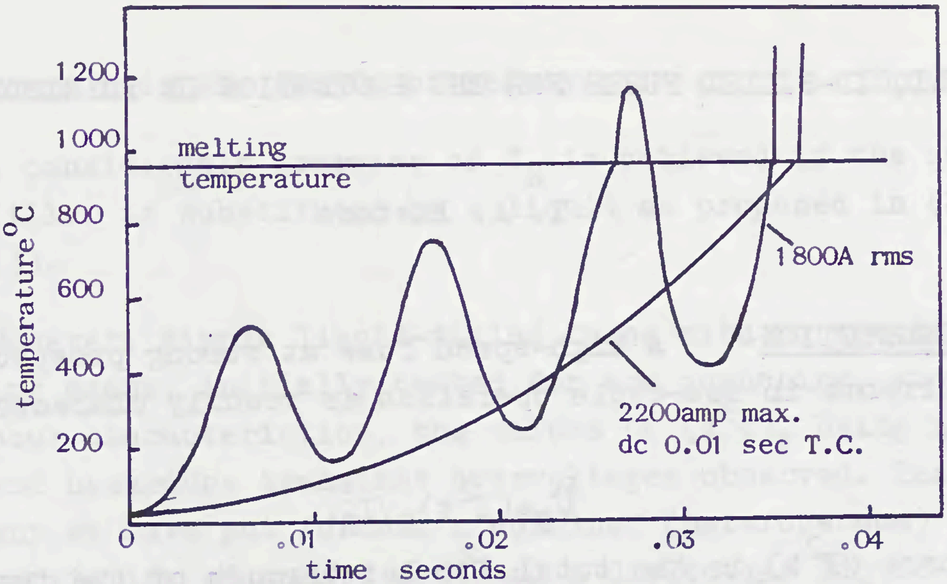

Fig. 12. Semi-Conductor Protection Restriction Temperature /Time Curves.

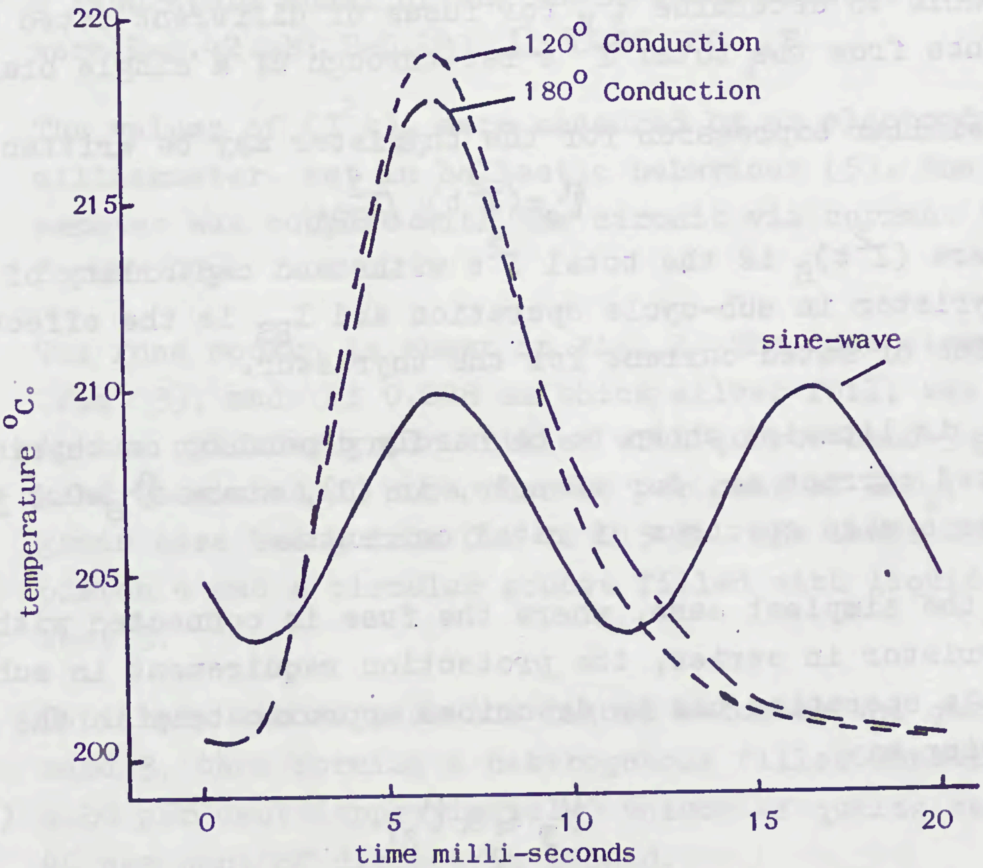

Fig. 13. Semi-Conductor Protection Restriction Temperature Fluctuations at Rated Current.