THE DIMENSIONING OF FUSES FOR DIODES OR THYRISTORS

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INTRODUCTION Fuses for the protection of diodes or thyristors are not just fuses. They have to satisfy special requirements, that often are mutually contradictory. Therefore a compromise is necessary. The art of selecting the right fuse for a particular job is to reach the right compromise, the best balance between the desirable and the possible.

BREAKING CAPACITY It would be wrong to neglect such an important property as the breaking capacity, but nevertheless, in this paper it shall not be mentioned any more.

If all the other important requirements are satisfied, the breaking capacity will not present any problem. It comes along as a matter of fact, but of course, one has to make sure that it is there.

PRE-ARCING PROPERTIES The rectifier designers require in principle that the pre-arcing Joule-integral shall be below a stated value. This is no problem at all, taken as a singular requirement. It is simply satisfied by having a fuse element of a sufficiently small cross-section. The mathematical relation between the prearcing Joule-integral for adiabatic melting and the cross-section is very simple and most reliable.

The problems only arise because the designers also require that the fuse shall be capable of carrying a certain amount of current, and as the cross-section of the fuse element is already given, the current density is also fixed. Some times the rectifier designers ask for more than thousand amperes per square millimeter, and that is very much.

For a given current and current density (and a given metal) the power loss per unit length is established.

It is very important to note, that these power losses do not simply represent money in the form of energy lost. They require costly provisions to ensure cooling to such a degree that the fuse element can be maintained at a temperature well below the melting point. To reach this goal the most desirable approach is to minimize the losses, but rarely sufficient. It is just as important to provide the most effective cooling.

REDUCTION OF LOSSES To keep the losses as low as possible the first and obvious thing to do is to make the fuse element short. Here we meet the first limit that necessitates a compromise, for when the fuse element melts, it must open the circuit, so, with a given surface tension of the molten metal, the minimum length is to a great extent dependent upon the cross-section, magnitude and shape.

This is the first good reason why it is wise to subdivide the fuse element

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into many small parallel fuse elements, for the smaller the individual cross-sections, the shorter the fuse elements can be.

The second, and equally good, reason is, that the losses are not solely concentrated in the fuse element itself. When the fuse element is made as short as possible, the major part of the losses tend to be in the approaches, and these losses can be reduced by dividing the current on a plurality of parallel fuse elements.

In principle, such a division should leave the losses in the very fuse elements constant, but considering the limitation mentioned above, the smaller cross-section paves the road to a still shorter fuseelement, and thereby to a further reduction of the losses.

The practical limitation is a combination of cost and technology.

COOLING OF THE FUSE ELEMENT Even if it is most beneficial to reduce the losses, it is still necessary to cool the fuse elements in order to remove the remaining losses. The most interesting fact in this connection is that the same provisions that reduce the losses also tend to improve the cooling.

Let us consider the most effective form of cooling, which is cooling by conduction through metal. In a simple wire, cooling by conduction is only possible lengthwise through the wire to the terminals, and as this is only effective near the terminals, it is clear that the shorter the wire, the more effective the cooling. Thus a short fuse element is also the most effectively cooled, but only as far as to the terminals, the ends. Here the heat will meet exactly the same obstacles as the current, namely the approaches, and therefore we see that again the division on more parallel approaches will reduce the thermal resistance to the passing of the heat.

Thus the division of the current on many parallel fuse elements is the most important and the most effective means to reduce the temperature rise, for it will both reduce the losses and improve the cooling.

Still, cooling by conduction can only bring the heat into the"terminals", those parts of the conductor that is not intended to melt. To be effective, it is necessary that these "terminals" have a mass of metal to serve as a temporary heat sink and a surface that can convey the heat to the surrounding filling of sand, and from the sand the heat must be capable of escaping into the surrounding world, generally the cooling air or cooling water.

THE ARCING PROPERTIES For the arcing period we also find mutually contradicting requirements, and the need for compromise.

To get a short arcing period, the arc voltage must be high, but a too high arc voltage may be harmful to the diodes or thyristors which the fuses have to protect. For this reason the designers usually place an upper limit on the arc voltage that can be tolerated.

There is, however, a significant difference in the manner this voltage is active. The diodes and thyristors are sensitive to the maximum value of the arc voltage, while it is the average value of the arc voltage that is important in order to keep the arcing time short, and thereby to keep the arcing-time Joule-integral low.

Therefore, the ideal condition is a value of arc voltage which remains as far as possible constant throughout the arcing period, that is, an arc voltage that on the oscillogram shows a rectangular form, and therefore often referred to as a rectangular arc voltage.

THE RECTANGULAR ARC VOLTAGE The arc voltage is composed of the anode drop, the cathode drop and the plasma voltage. Of these the anode and cathode drops are essentially constants, while the plasma is a function of length, pressure, cross-section and cooling.

Under these circumstances, the only way to approach a rectangular arc voltage is to have the constant components as the predominant components, or in other words, to have a minimum of plasma voltage.

This is the same as saying that the arc shall be as short as possible.

THE MULTIPLE ARCS However, the constant value of the short arc leads to a rather low value of arc voltage, and it is rare that this arc voltage of a single arc is sufficient. To get higher values two ways are open. Either several short arcs in series or the acceptance of a longer arc.

Going from one to two short arcs will double the arc voltage, but two fuse elements in series will also double the pre-arcing losses. Such an increase of the losses will be particularly significant for operation under normal load.

If in stead we should create the double arc voltage by means of a longer arc, this would necessitate a much longer fuse element, and very much higher losses. How great the relative increase of the losses will be also depends on how many parallel fuse elements there are, for the more the current is divided, the less will be the influence of the approaches, and the greater the increase because of the lengthening of the fuse element itself. In practice, the same increase of arc voltage will cost a minimum of loss by the use of multiple short arcs.

Still more important, when the number of fuse elements in series is increased, the cooling conditions for the individual fuse elements are not interfered with, but any lengthening of a fuse element will have a detrimental influence on the cooling.

Nevertheless, the most important advantage of the short arc is still the almost rectangular arc voltage. The longer the arc, the greater the difference between the maximum arc voltage and the average arc voltage.

The conclusion of this is, that the best fuse is achieved by producing the necessary arc voltage by means of a sufficient number of arcs i series, but the cheapest fuse to make is the one with the longer fuse elements.

SELECTING THE ARC VOLTAGE It has been mentioned earlier, that the rectifier designer in principle would demand a maximum limit on the pre-arcing Joule-integral. This is a truth with modification, for what is of interest is the total Joule-integral, the pre-arcing plus the arcing Joule-integral.

If for the time being we limit our considerations to the case of an overcurrent of short-circuit magnitude, where the melting of the fuse element is adiabatic, it is true that the higher the arc voltage (average value), the smaller the arcing Joule-integral.

Furthermore, to keep a high value of arc voltage well under control, that is, so that it remains below what the semi-conductors can withstand, it must be done by means of many short arcs, and the many fuse elements in series means losses proportional to the number.

However, as a high value of the average arc voltage results in a low value of the arcing Joule-integral, this will permit an increase of the pre-arcing Joule-integral, for the significant criterion is that the sum remains constant and below the set limit.

An increase of the pre-arcing Joule-integral is the same as a greater cross-section (e.g. more fuse elements in parallel), and that again a lowering of the current density and thereby a reduction of the pre-arcing losses.

THE COMPROMISE Thus we meet another important compromise. A shift to higher arc voltage both increases and decreases the losses, but it does more than that.

The higher arc voltage also permits a shift of the components of the total Joule-integral such that a larger portion falls on the best known part, the prearcing Joule-integral, and consequently the total becomes better known. It is a general rule that with a better known value one can go closer to the limit, and this permits the selection of a still larger cross-section and consequently a further reduction of the losses.

There is also a very important advantage in the fact that the larger cross-section improves the ability to withstand temporary overloads. This ability is further enhanced by the fact that more fuse elements, both in series and in parallel, generally implies a larger fuse body and thereby better cooling.

On the other side of the account it is necessary to admit that all of this leads to a larger fuse which takes up more space in the installation and which will cost more money. Thus the compromise is not limited to the technical problems. It is very much a matter of economics.

THE PROBLEM OF COST The biggest hindrance for the use of the technically best fuse design is simply the cost.

The traditional design has the fuse elements formed by holes and notches in a ribbon of silver, and the effective cooling requires large masses of metal between the fuse elements. When this is combined with the design requirement of many fuse elements in series and many fuse elements in parallel, all of which require extra metal to form heat-sinks and cooling surfaces, then the amount of silver needed becomes considerable.

Silver is expensive, and the price has been rising. It is not unusual that for a good compromise of a semiconductor type fuse, the cost of the silver alone is the greater part of the total cost.

Because of this the search for a substitute for silver has been going on for a long time. Copper has been used with fairly good results for ordinary industrial fuses, but for the fuses for diodes or thyristors copper will fail because of the oxydization of the fuse elements when operated at high temperatures, such as it is generally necessary in this kind of service.

THE ALUMINIUM FUSE ELEMENT No useful substitute for silver was available until it was discovered at the laboratories of LK-NES that there was a way to avoid the well known difficulties associated with the use of aluminium due to its high affinity for oxygen.

When aluminium is used in a fuse of ordinary fuse design a relatively large amount of aluminium will be heated to a temperature where the metal will react chemically with the sand filling to form aluminium oxide and pure silicon, and this chemical reaction is exothermic.

As a result of this exothermic reaction so much extra energy will be released inside the fuse, over and above the energy of the arcing, that the fuse not only will fail to break the current, but it will end up as a red hot molten mass and constitute a danger to the surrounding equipment.

THE ALUMINIUM SEMICONDUCTOR FUSE In order to avoid these difficulties, inherent to the fuse element of aluminium, we have to follow two paths. It is necessary to reduce the amount of aluminium that reaches a high temperature to a minimum and at the same time cool the fuse element in the most effective manner.

It is obvious that these two requirements coincide beautifully with the technical requirements already discussed as advantageous for a fuse for the protection of semiconductor devices.

If we furthermore consider that there is no other type of fuse where the need for the finding of a less expensive metal for the fuse element is more urgent, then it becomes clear that this is the most obvious opportunity to take advantage of this possibility of using the inexpensive aluminium in stead of the expensive silver.

However, theory is of little value if it is not supported by proper technology, and many technological problems were associated with the substitution of aluminium for silver i fuses.

It may be sufficient just to mention that the production of a fuse using aluminium fuse elements requires that thin ribbons of aluminium shall be welded to the heavy sections of metal forming the fuse contacts. Many methods were explored, and several of them led to results that were satisfactory from the point ofview of fuse performance, but exhibiting severe weaknesses from the economic or from practical manufacturing aspects.

To-day fully satisfactory solutions have been found, and the aluminium fuse can be produced in a consistent quality and at a low value of production cost. Because of the low cost of aluminium, the price of these fuses is also lower, and when the large amount of development work has been paid, there will be room for even greater savings for the user.

This method of utilizing aluminium for the fuse elements has been patented in many countries, including the big industrial nations USA and USSR.

CONCLUDING REMARKS It is a most satisfactory result of this development work that it has been possible to produce a fuse using aluminium in stead of silver for the fuse elements, and at the same time replacing copper and brass in the other metal parts of the fuse by aluminium. This represents a significant economic advantage.

It is even more satisfactory to note that this aluminum fuse in many respects will perform as well as the silver fuse, and in some respects even better.

However, in addition to these advantages, it is a case of replacing a rare metal, silver, with an abundant metal, aluminum, and although this to-day may be dismissed as a purely ethical point of view, it may some day be a dire necessity for more than simple economic advantages.