THE BASIC PRINCIPLES TO ENGINEER A HIGH QUALITY'S FUSES FOR PROTECTION OF POWER SEMICONDUCTOR CONVERTORS

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Abstract: The object of the paper is to analyze and cristallize experience accumulated by authors in the course of their long standing activities in the field of research, development and testing (under service conditions including) of the semiconductor fuses and as one outcome of this work – to formulate a key principles of fuse engineering. The imaginative application of suggested generic guidelines can provide the designer with much – needed assistance, helping him to accept the challenge and to manage the complex problem of developing a high quality semiconductor fuses shortening an engineering date and economizing money and resources. The theoretical and practical concepts embodied in author's approach can be also applied to the problem of developing a semiconductor fuses of new generations. These principles are the following as applied to fuse current and voltage rating 25÷3600A, and 380÷1000V~ respectively.

1. INTRODUCTION

In the high power semiconductor equipments in which the high speed fuses can be put in series with the devices, in the lines of feed transformer, at the load side they are subjected to either repetitive or surge working currents of arbitrary waveforms and very wide spectrum of default conditions. That's why the major requirements on these fuses are the high working life, coordination with other fuses, circuit breakers and "electronic protection system" (algorithms of recognizing, revealing and analysis of faults, their location and interruption by means of turn –off and turn-on thyristors), and reability when clearing precisely that fault operation which are needed to with the minimum aftermath regarding converter to be protected, actuating mechanism and processing duties. Quite naturally, the requirement of economy are close associated with the above remains and implies watt loss and overall dimension reduction and optimization of loading rate for devices and fuses with no excess reserve. The fuses satisfying these requirements can be developed by combining three suggested by authors principles, establishment of which presents the goal of the work.

2. OPTIMAL GEOMETRY OF FUSE ELEMENTS

Fuse element zone of small section incorporates three main parameters: shape, length and section of neck. The criterion for choosing the shape we
consider the minimum non-–uniformity of current density distribution at basically steady state conditions. The theoretical study and calculations, using FEM; physical simulation through the conductive paper models in association with the real fuse elements made of Ag, Cu, Al foils and, lastly, analysis of heat and clearing duties performed for the purpose of investigation of pattern of current density distribution in zone of small section had enabled to determine circular perforations as best suited to semiconductor fuses. The neck length

(perforation diameter) is compromise between heat duty which asks the minimal length and interrupting process which may reliably be realized only at neck length of no less than 1,3÷1,9mm. The minimal neck width (at standard metal Ag, Cu, Al – strip thickness of 0,05÷0,25mm) is determined by a feasibility of a technological facility available which in actual practice is about 0,05mm. The maximal neck section governed by Meyer equation $\int i^2 dt = K_m S^2$ in such a way that a permissible let–through integral and peak let–through current would be within a specified limits that results in current density of order 700÷900A/mm^2.

Of special importance is designing full–section part of fuse elements. Here we have three main parameters too: fuse element width, length (step between series necks) and space form. The investigations and many–years experience make it possible to consider the fuse element width of 10÷40mm as optimal for current rating of 25÷3600A. The fuse element width depends mostly upon the current rating. The fuse element length is determined primarily by the voltage rating (and d.c. circuit inductance) and for 380÷1000V is adopted within 10÷16mm.

Yet even at the same element width and length the space form of full section part plays key role in fuse performance. At the heart of the matter is the fact postulated by authors that the fuse cyclic withstandability is controlled [all other factors being the same] by the rigidity of fuse element. On general physical grounds we might expect the different values of rigidity of flat and bent fuse elements but how great are the distinction?

By application of the special approach using in particular the integral evolved by Moore on the basis of Castigliano theorem the relationship was derived for calculation of rigidity of an arbitrary bent full section part of fuse element as compared with the flat full section part. This relationship represents the rigidity as a force-to-displacement ratio [1]:

$$G = EJ / \int y^2(x) \sqrt{1+[y'(x)]^2}\, dx \qquad (1)$$

where:

G – rigidity, E – Young's modulus, J – moment of inertia of the element cross-section, y(x) – arbitrary curve which determines the bending shape of fuse element. For important particular case, namely when full section part is bended in the shape of circle, semicircle, triangle and rectangle the relationships are as follows:

$G_{circle} = E\,J/3\,\pi\,R^3$ (2)

$G_{semicircle} = 2\,E\,J/3\,\pi\,R^3$ (3)

$G_{rectangle} = 3\,E\,J/a^2\,(2a + 6b)$ (4)

$$G_{triangle} = 3EJ / A^2 \sqrt{l^2 + 4A^2} \qquad (5)$$

where respectively:

R – circle radius (1,5÷2,5mm)

a – height of rectangle (2÷4mm)

b – one half of rectangle foundation (2,5÷5,0mm)

A – height of triangle (2÷3mm)

l – one half of triangle foundation (2÷4mm)

In theory accordingly to calculations the rigidity of element bent in the form of circle, semicircle, rectangle and triangle is lower than the rigidity of flat element by 45000, 20000, 15000 and 9000 times respectively (the case of one series bend). In real practice cyclic withstandability of semiconductor fuses having bent elements is higher by 20÷200 times compared with flat elements. The theoretical and experimental investigations of effects of bend shape and amplitude, number of series bends in coupling with packing density of filler and other factors as well as operating experience had shown that all the fuse element full-section parts must be bent the necks being placed at the borders of bends. The bends themselves are to face the inner surface of the fuse body which among others improves heat transfer and excludes damage of necks while inserting quartz filler.

3. MAXIMAL FILLING COMPACTNESS WITH OPTIMAL SET OF GRAIN SIZES. HARD FILLER.

To ensure the reliable fuse performance it is vitally important that the maximal degree of compaction which is of order 1,78÷1,84g/cm^3 would achieved under optimal collection of quartz sand grain sizes instead of grains of one size. In practice it will suffice to have ternary – quinary mixture. Within the boundaries of the mean grain sizes of 0,1÷1,1mm which is optimal the absolute value of grain size has little or no effect on packing density (compactness), taking into consideration large diameter of fuse body which is 20÷100 times as bigger as grain size. The only thing that matters is the ratio of grain sizes in the sand mixture. If use the sand grain of one size be it 0,1mm or 1,0mm the packing density would be the same low of order 60÷70% in both cases. The utilizing the ternary mixture permits to obtain packing density up to 85%, a multicomponent mixture – theoretically up to 100%. Optimal grain mean sizes ratios for quinary mixture are: 1; 1,2÷1,6; 1,6÷2,0; 2÷3; 3÷5 at their % contents 7÷13; 30÷50; 20÷30; 15÷25; 2÷8 respectively. The filling in the fuse cartridge whith quartz sand is carried out by means of special vibration facility.

Application of hard filler in semiconductor fuses is advantageous under almost every operation condition except, perhaps, of interrupting small overload current. The authors had developed the original up-to-date technologies for forming hard filler structure. It incorporates the filling a fuse with quartz sand, composition and method of injection of binding agent, subsequent blowing of air at different pressure 0,25÷2,0atm and temperature 20÷150°C if necessary and lastly process of filler hardening by passing current through fuse. The attempt was made to present an theoretical picture of physical processes during filler hardening by method suggested by authors as well as experimental investigation aimed at elucidation of qualitative and quantitative effects of process factors. Some results of this work were published [2]. The results yielded which portray the influence of hard filler on the fuse functional characteristics can be summarized briefly as follows with respect to mechanical and electrical properties of hard filler. Filler leakage very dangerous by its consequences is fully prevented which is of high priority, for instance, for transport converters operating under constant strong vibrations. Intactness of fuse elements in fuses operating in rotary rectifiers of brushless excitation systems in nuclear power station is totally assured. The fuse have ability to withstand 6000 “g” continuously in addition to the acceleration and deceleration stresses and operate satisfactorily under maximum fault conditions. Increasing of heat condition twice as high as at conventional filler permits up rating of current about 10÷20% or decreasing of power losses in the same degree. Coupled with bent elements the hard filler increases additionally up to several times cyclic service life. The employing of bent elements and hard filler makes it possible to use Al and Cu as an element material through the neutralizing the drawbacks of this material as fuse elements. The main functional characteristics of semiconductor fuses – let-through integral and arcing energy under short-circuit fault – are essentially diminished up to 1,5÷2,0 and 2÷4 times correspondingly. The ratio of fusing integral to let-through integral is substantially improved as well as withstandability to the repetitive small operating overload is increased.

4. TWO-SIDED WATER COOLING

Almost all high power semiconductor converters operate with water cooling of devices which up-rates current rating up to 5÷8 times. The semiconductor device water cooling system can be utilized for cooling fuses as well. As experimental studies and operation experience have shown the water cooling is especially effective for fuses having bent element and hard filler at rated current over 1000A and voltage 220÷660V. The two-sided water-cooling has increased current rating for example from 1600A to 2500A. In this case when water flow rate was varied from 0,2 to 0,033 l/s the temperature changes of water were within a limits 5÷30°C. The heating of water under nominal power take-off of order 200÷300Wt was found to be no more than 1÷2°C. The alterations of water flow rate by 5÷6 times caused nearly no change in power loss. When employing water cooling the thermal constant of fuse is 10÷20 times smaller than at natural air cooling. That is under two-sided water cooling the fuse of 1600A attains the steady state regime within 15min as compared to 3÷4 hours at natural air cooling. Two-sided water cooling complicates the problem of assigning fuse current rating. The conventional procedure based on measuring the fuse terminal temperature doesn't work in this case because both fuse terminal are at water temperature which is practically constant. In such a situation two approach has proven to be sufficiently reliable. The first employs as criteria the fuse body temperature the idea being that its temperature must not exceed the value permissible for fuse terminal (130÷170°C). The second is based on the assumption that at steady state condition the fuse voltage drop is within the limits of 1,3÷1,5 times regarding to initial value. Two-sided water-cooling provides additional (to the above mentioned) resistance against small operating overloads and increases slightly the cyclic ability. However, on the other hand, in the short-circuit duties at interrupting 50÷200 rated current when energy dissipated in the fuse before melting is 1000÷5000 times as much as in steady state and this process is 1÷6ms long, the water cooling doesn't retard fuse melting. The oscillograms of interrupting short-circuit current from 50 rated current with water-cooling and without it are almost identical. Yet because fuse which due to the water cooling is for example of rated current 2500A has in effect a neck cross-section pertinent to 1600A then as a result the let-through integral has proved to be smaller more than twice, arcing energy-by three times and peak let-through current up to 40%.

5. CONCLUSIONS.

Integrated utilization of: optimal geometry of both neck and full section part of fuse element; maximal filling compactness with optimal set of grain sizes and hard filler; two-sided water cooling allows to constitute the principles than can be thought of as a conceptual and in the same time methodological approach to tackling a problem of engineering up-to-date sophisticated fuses for protection of high power semiconductor equipment.

6. REFERENCES

[1] N.A. Ilyina, K.K. Namitokov, I.G. Shklovsky. “Pulse withstandability of the semiconductor protection fuses”, Sixth Int. Conf. On Switching Arc Phenomena, 12-15 Sept.1989, Lodz, Poland.

[2] N.A. Ilyina, G.G. Gemerov, K.K. Namitokov, I.G. Shklovsky. “Principal Manufacture Technologies for Semiconductor Fuses”, Fourth Int. Conf. On Electric Fuses and their Appl., 1991, 74-80, Nottingham, UK.