THE REAL-LIFE SEVERITY AND PECULIARITIES OF INTERRUPTING TEST DUTIES OF SEMICONDUCTOR FUSES

N.A. Ilyina*, G.G. Zhemerov**, E.I. Zaika**, I.G.Shklovsky***

*Kharkov Municipal Akademy, Ukraine
**Kharkov State Politechnical University, Ukraine
***Kharkov Collegium, Ukraine

Abstract: The recommendations and requirements specified by well-known standards IEC and Underwriters Laboratories Inc. in regard to the actual rigorous test conditions are not nearly accurate and unambiguous enough to be in full measure applied in practical designing semiconductor fuses.

The object of the paper is to reveal the truly severe duties under interrupting testing of semiconductor fuses at d.c. and a.c. conditions and to study the peculiarities of fuse behaviour from the view of economic feasibility and completeness of testing as well as proper determination of service conditions.

The basic peculiarities of d.c. and a.c. fault current breaking by semiconductor fuses and the real-life severity of test duties have been investigated as experimental part of an exploration program for development of fuses of 40÷1000A, 380,660V≅ for protection of power semiconductor converters as well as while developing special purpose fuses for large inductance circuit. The results obtained can be represented in the form of three groups.

1. ZONES OF LIGHT DUTY TESTING

1.1. D.C. testing

The interrupting ability is usually the maximum fault current that can be obtained from the test station. According to the exploration program the semiconductor fuses are be developed to qualify under the very strict specifications and codes which were in force for equipment in the former USSR territory. These requirements differ in some respects from the requirements specified by well-known standard IEC and Underwriters laboratories Inc. which does not, in particular, envisage d.c. short-circuit testing for semiconductor fuses. The main problems incorporated the requirements of large time constant, small fuse overall dimensions, coordination with downstream protective apparatus and protected equipment etc. In our maximum breaking capacity tests the ПП40 fuses I_{rated} =400 A, U_{rated} =660V~ interrupted successfully 134,4 kA at 510 V= time constant 20 ms and limited current down to 7 kA in 4,7 ms. These fuses interrupted as well successfully the d.c. short circuit current 93 kA at 510V= and time constant 35 ms. Because of the fact that in these tests ПП40 fuses had demonstrated very reliable operation, small let-through integral and very small arc energy which have been estimated both by calculation from oscillogram and by fusing elements burnback value the decision has been taken to upgrade the d.c. short-circuit testing parameters. In the following experiment this fuse interrupted successfully d.c. short-circuit current 100kA at 850 V= and time constant 35 ms. The similar results in general have been obtained by ПП38 (1000 A, 380 V) fuses.

The analysis of testing results has led us to conclude that the maximum breaking capacity test stipulated by IEC (publ. 269-4) is in fact the most light duty for semiconductor fuses among three prescribed test types. Moreover, if in general the fuse manufacturers lower the voltage rating of a.c. fuses to be used in d.c. circuit (up to 30-40%) then the semiconductor fuses interrupting the high d.c. short-circuit currents could be even upgraded in comparison with the a.c. rating. Taking into account as well that high d.c. short-circuit regimes are rather rarely encountered in practice, the question arises as to whether it makes sense to conduct this test at all. If the semiconductor fuse reliably interrupts obviously more severe duty (such as maximum arc energy current) then what is the meaning of this test. If performing this test we are dealing with the verification of maximum let-through current or clearing time then there is no need for the test because at high d.c. short- circuit current when the adiabatic mode of fuse melting is obeyed the calculation is very simple and reasonably precise. In any event there is good reason to consider this kind test as not indispensable.

1.2. A.C. testing

The interrupting ability testing (the breaking of maximum fault current) can be considered as the one of the most light duty in actual practice (in our case up to 185 kA (rms), 730 V (rms) even at making angle 57-63 degree when maximum let-through current is achieved.

ПП40 fuses I_{rated} = 400 A, U_{rated} =660 V were tested at $I_{s.c.}$ =750 V; power factor 0.09. At making angle 62 degree I_{max} = 19.1 kA; t =3.4 ms; at 33 degree I_{max} =14 kA; t_{int} =4.6 ms. The criteria with respect to which the evaluation of duty lightness have been made were arc energy and fuse elements burnback values. Both these parameters fully conformed with the determination of this regime as light one.

ПП60 fuses I_{rated} =630A, U_{rated} =660 V were tested at $I_{s.c}$ = 142 kA (rms); $U_{s.c.}$ =750 V; power factor 0.085; making angle =60 degree. Three type specimen of fuses were tested: first one was manufactured by standards production technology with hard filler; second one – without hard filler (with usual filler) and third one – with impregnated but not dried-up filler. Deliberate violation of technology was aimed at verification of lightness of this testing duty. All experiments had confirmed this thesis in full measure. All fuses reliably cleared the short-circuit however second and third type fuses showed somewhat poor performance (I_{max} =35.6, 40 and 41 kA respectively).

The testing of ПП38 fuses of I_{rated} =1000 A, U_{rated} =380 v at clearing a short-circuit 185 kA (rms), 450 V, power factor 0.09, making angle 58 degree also had confirmed the relatively lightness of the duty (I_{melt} =29.1 kA, t_{int} = 6.3 ms). Fusing elements of tested fuses had a significant reserve of non-burning out parts.

The interrupting $I_{s.c.}$ =4 I_{rated} =1600 A by ПП40 fuses was the very light regime at 730 V, power factor =0.5. the fusing element remained non-burning-out almost at full length. At the same time problems came into existence when interrupting I_{test} =2500 A at 730V power factor 0.27 by ПП60M with hard filler. Tested fuses were cracked and the end-caps burned up. The fusing element remained non-burning-out almost at full length. The fusing elements asymmetry (series and parallel) of burning-up was arisen due to very intensive heat transfer from elements to fuse body. Owing to doubling the thermal conductivity of the fuse hard fillers the almost all performances had been improved except interrupting $4I_{rated}$. Still according to specifications this duty for ПП60M is not specified. This fuse is designed for power converter of variable drivers (railway transport) and it must interrupt mostly more high current and small currents only at low voltage.

At very small currents (1.5-2.9)I_{rated} a big temperature difference of exterior and internal surface of fuse body arises (40-60 C/mm resulting in cracking of body, but at 3.0-3.3 I_{rated} this phenomenon disappears.

2. MAXIMUM ENERGY TEST.

2.1 D.C. testing

A fairly extensive exploratory testing program which have been undertaken to investigate the basic peculiarities of d.c. short-circuit breaking by developed semiconductor fuses has enabled making an estimates of the testing severity. As the results obtained had clearly demonstrated, the most severe duty for semiconductor fuses is the maximum energy testing which is achieved if the current at the arcing starting moment is approximately equal to fault current instead of 0,5÷0,8 0f fault current as IEC recommended. In addition, as applied to developed fuses, the fault current of the maximum arc energy (that is to say, the most heavy duty test) proved to be in the range between 5 and 12 of fuse rated current and in fact coincided with the minimum breaking current that is widely encountered in our practice. What this means is a possibility to suggest about combining a standard maximum energy test and a overload test that can be a worthy on numerous occasions.

The severity of this test is mostly attributed to the fact that at such current values the arc energy provided from the circuit inductance increases greatly. In our testing of ПП40 fuse I_{rated} = 400 A, U_{rated} = 660 V~ the transition from d.c. short-circuit current 93 kA, time constant 35 ms to d.c. fault current 4 kA, time constant 35 ms has resulted in more than 20 fold increasing in circuit inductance while the melting current changed from 7 kA to 3,9 kA only. It should be emphasized as well that the tangible intensification of series and parallel asymetry of burnback of fusing elements at maximum energy currents of this value had in its turns contributed to onerousness of this duty as well.

The field of greatest interest is experimental investigation of a special purpose high-speed fuses. the fuses of this kind have specifically been developed for protection of wagon electrical equipment of metro railway and should satisfy very stringent requirements. Their rating are: I_{rated} =500 A, U_{rated} =700 V=; time constant 65 ms. In addition to severe conditions of interrupting duty the fuses must meet a high cyclic withstandability that involved an necessity of using a hard filler. The breaking tests have been conducted at traction substation of experimental railway line. Some results of interruption of d.c. short-circuit currents 5 and 18 kA by special purpose fuse are by way of example presented in Table.

Table. – Test results.

Characte-ristics	Short-circuit current (kA)	
	5	18
U_{test} (V)=	950	
τ_{test} (ms)	65	
L_{add} (mH)	13	3
t_{melt} (ms)	1860	50
t_{arc} (ms)	40	14
U_{arc} (V)	2750	2660
E_{prearc} (kWs)	19	2
E_{arc} (kWs)	201	102

It is amply clear that at 5 kA one of the most severe operation duty is formed not only for fuse and a downstream protected equipment under operating conditions but for test facilities during the fuse testing as well.

The duty of overload current by 200÷300% rated current under full voltage conditions which IEC and Underwriters Laboratories Inc. recommended for overload testing is almost not found in actual practice of equipments in the countries of former USSR, much less the semiconductor fuses are intended for breaking these small currents. Furthermore for high-power semiconductor fuses there are no high power testing station which can offer a comprehensive range of d.c. facilities to cover all voltage, current and circuit conditions that are likely to arise in service (the above-mentioned overload currents at full voltage including).

The difficulties emerge during the d.c. testing even at bigger fault currents. For instance, ПП38 fuse of I_{rated} =1000 A, 380 V (having hard filler) at d.c. fault current 6 kA, voltage 240 V=, time constant 20 ms did not melt throughout 300 ms after which the circuit-breaker came into action. The test results obtained while studying the other fuse series proved to be analogous to those reported above. In this connection it should be noted that in case when it is in advance known that a fault currents of order 2÷6 I_{rated}

are to be interrupted for instance by circuit breaker, it seems it's worthwhile the overload test of semiconductor fuses to combine with a maximum energy testing.

In conclusion it may be said that the situation with the determining a heavy and light duties for semiconductor fuses at d.c. mode is substantially more simple than at the a.c. mode. At any case d.c. current increasing may only lighten the interrupting conditions and conversely, d.c. current decreasing makes the interruption more onerous.

2.2 A.C. testing

To reveal the real most severe testing conditions at a.c. short-circuit for semiconductor fuses is very important task from the view of economic feasibility of testing as well as proper determination of service conditions. The most arduous conditions are developing inside of the fuse and they are determined fully by value and rising velocity of arc energy dissipated in fuse which are in its turn governed by many internal and outside factors as well as their combinations.

In this connection it should be noted that a well-known IEC and U.L. recommendations are far from to be unambiguous. Our investigations showed that the arc energy value and the short-circuit-current value at which the arc energy value is maximum are largely dependent on the circuit voltage, fuse rated voltage, arc voltage and making angle. A special role of making angle is dictated by the fact that due to making angle the mean value of circuit voltage during arcing period changes significally depending on the angle and this voltage can increase or decrease in short-circuit current rising.

In our opinion there is no clear-cut maximum arc energy short-circuit current and the value close to maximum energy could be found in the wide range of a.c. short-circuit currents 12-100 I_{rated} with variation of 10-15% depending on the number factors and in many cases at making angle 0. An absolute current maximum has as already noted above been discovered at making angle 57-63 degree (not specified by IEC) and naturally at maximum short-circuit current. It might be well to point out that an important role of making angle manifests itself according to the combination of above-mentioned factors. However a dramatic reduction in circuit voltage (or a dramatic increasing of arc voltage) lowers substantially a effect of all short-circuit parameters. At the same time absolute maximum of arc energy appears when circuit voltage is equal to arc voltage.

The transition from range of 12-100 I_{rated} to high currents zone of 150-250 I_{rated} produces an arc energy diminution by 25-35% while in very small current zone of 2.5-5.0 I_{rated} the arc energy is decreased by 2-3 times.

In the light of the results obtained perhaps it is worthwhile to reappraise some of the IEC recommendations. Specifically, the maximum energy fault current which is as recommended by IEC equal 3-4 I_{10ms} needs to be revised with extending the range at least to 1.75-5.0 I_{10ms}. In this case it is worth noting that information of this sort is not very much helpful for testing experts as well as for fuse designers and users not to mention the fact that the IEC does not specify the value of making angle which determines the mean value of circuit voltage during arcing process and is therefore very important factor.

At interrupting ability testing as IEC suggested the short-circuit current has to be chosen in such a way that the beginning of arcing process conforms to making angle 40-65 degree (1 experiment) or 65-90 degree (2 experiments). Yet our investigations revealed that if arc voltage is fairly high and stable that is the case at intelligently designed semiconductor fuses the making angle 40-65 degree establishes a light duty testing due to that in this period circuit voltage is far from maximum. On the other hand, at relatively small arc voltage and its slow rising the making angle 65-90 degree does not form the maximum energy conditions since arcing process captures the area of small circuit voltage. The U.L. recommendations in the general are close to IEC's.

In the context of the preceding the most onerous conditions of fuse are to be established with due regard for above mentioned investigation results and always after the preliminary tackling a issue about the worthiness of searching a precise value of energy maximum. At the same time it must be emphasized that however much has been learned in the few years, it would be misleading to suggest that testing under worst-case conditions is neatly established. It is interesting to note as well that the key functional performance of semiconductor fuses-let-through integral was kept almost constant throughout the entire current range.

3. PECULIARITIES OF FUSE BEHAVIOUR AT A.C. INTERRUPTING TEST DUTES

Perhaps the one of the most peculiar features of fuse behaviour at a.c. interruption testing is the existence of two so called 'singular points'. In spite of the fact that well-known standards give no recommendations on that score nevertheless these points necessitate a special attention in fuse design, testing and service.

First singular point is in the a.c. short-circuit range of 7-11 I_{rated} currents. It is characterized by two-fold scattering of melting time roughly from 7 to 14 ms due to a discontinuity of time-current curve calculated for the first time by J. Leach et al [1]. This phenomenon lies in the fact that the fuse melting in specific combination of value of sin-current, power factor and making angle (mostly 90 degree) does not occur in some time interval, but an increase or decrease of current by 3-8% causes an operation of fuse.

In the course of testing the ПП40 fuses I_{rated} =400 A, U_{rated} =660V interrupted short-circuit 4 kA at 750 V power factor 0.41 at $t_{melting}$ =5.9 ms. But the diminution of current merely to 3,85 kA produced melting time step up to 15.5 ms. That is to say the singular point for ПП40fuses proved to be about 10 I_{rated} current.

The ПП38 fuses I_{rated} 1000 A, U_{rated} =380 V at I_{test} =8.8 kA, U_{test} =420 V, power factor 0.31 making angle 90 degree melted in 6.1 ms, but at 8.5 kA – 15.2 ms.

The current range in which the singular point is discovered constitutes the zone that is very sensitive to small change of current resulting in time jump. This phenomenon is inherent to semiconductor fuses having a high current density in necks (parts of small section) and high ratio between element full section and restrictions. What is more our experiments showed the existence of discontinuity which recurs at regular intervals and the recurrence interval is generally speaking predictable depending of the current value. As part of the experimental study we discovered the discontinuity from 5-7 to 20-23 ms caused by current decreasing by 4-5%.

Second singular point lies in the range of 5-8 I_{rated} current. Its peculiarity consists that at transition from making angle 0 degree to 90 degree causes the great change of fuse melting time from8-10 ms to 400-600 ms respectively. Such a dramatic alternation of commutation process is attributable to the influence of component of transitional regime. In our experiment in short-circuit of $I_{s.c.}$ =5 I_{rated} = 2000 A, power factor =0.2, making angle = 0 the ПП40 fuse had melted in 10 ms at the moment when current reached its maximum 4500 A. However at making angle = 90 degree, i.e. in case when the interrupting process was free from transitional mode, the fuse melting time rised up to 520 ms and the melting occurred a steady state current of amplitude 2800 A. As distinguished from first singular point here the relatively smooth change of melting time had been observed in passing from angle =0 to 90 degree.

ПП60M fuse had interrupted the short-circuit current ~ 8 I_{rated} = 4.9 kA at power factor 0.27; 730 V, making angle 0 degree melting in 8 ms. That was very light duty for this fuse. But at making angle 75 degree the fuse did not melt in 300 ms and fault current was cleared by circuit-breaker.

ПП38 fuse had successfully cleared the current 6 I_{rated} = 6 kA at 420 V power factor 0.27; making angle 0 degree in 9.8 ms, but at 90 degree did not melt in 160 ms.

4. CONCLUSIONS

As a result of experimantal investigations of semiconductor fuses the most severe and light test duties are refined, the correspondent attention to the singular points has been attracted that makes it possible the financial and energy resources to be economized while developing, testing and servicing the semiconductor fuses.

REFERENCES

[1] J.G. Leach, P.G. Newbery and A. Wright, “Analysis of High Rupturing Capacity Fuse Link Preaching Phenomena by a Finite-Difference Method”, Proc. IEE, vol.120, • 9, sept. 1973, PP.987-993.