WHAT NEXT WITH THE H.B.C. FUSES?

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PREFACE The word "fuse" derives from the Latin "fundo /fundi, fusum/" mining "pour", "cast", "melt" but also "become brittle" or "crumble". A step ahead we have the word "fusio" in English "indundation", "outflow". In more recent times the word "fuse" has been used to denote the production of fluids by means of intense heat and that of producing fusion of materials. Clearly these literal interpretations clarify or convey little about the action of or role of electric fuse as a device for preventing damage to electric circuits under fault conditions.

The simplest description of the role of the electric fuse was probably Edison's who envisaged it as "a weak link in a circuit". Although the description fails to adequately convey the many uses and actions of electric fuses in circuits it nevertheless remains admirably clear, simple and true for the majority of fuse applications and is most people's concept of electric fuse protection.

The I.E.C. definition of an electric fuse is:"A device that, by fusion of one or more of its specially designed and proportioned components, opens a circuit in which it is inserted by breaking the current when this exceeds a given value for a sufficient time. The fuse comprises all the parts that form the complete device". The definition is not intended to include fuses other than those which actually interrupt excessive currents in circuits.

The limitation referred to is important as, in common with most fuse definitions, the previous definition interprets the electric fuse as a plain interruptor of fault currents in electric circuits and, in so doing, conveys a restricted role for the fuse to that of solely a current interruptor. But for some electric fuses would need to interpret the protection role as both current interruptor and initiator of events leading to the safe isolation of faulted circuits from supplies. Hence a global definition should embrace all classes and categories of fault protection afforded by fuses and in addition include its roles as an activating device for tripping contactors and circuit-breakers or energising secondary circuits to initiate alternative or complementary current-interrupting devices.

But simple fusion has take place only if a fuse-element operates in the overload or the moderate short-circuit conditions. Whereas under influence of a heavy short-circuit current the plain fuse-element and constrictions instead that do explode due to rather sophisticated coincidence of the phenomena among which the Joule heating is only one predicting component. After that the fusion is not only operating principle of fuses. For example are in service fuses in which:
- the liquid transfers into electric arc, say in the mercury fuses /U.S.A./ known in principle from abt a century;

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- the solid state fuse-element is mechanically interrupted by an electromagnetically driven special knife /U.S.S.R./, when the overcurrent overruns a specified limit, causing arc-initiation and then circuit current interruption;
- the temporary change of the current-carrying path into the non-conducting state has take place due to reaching the critical state of that metalic path /Japan/

what have not so much common with the simple fusion.

The history of fuse technology reaches as far back as 80-th of previous century and was recently briefly intoduced by the paper [1].

Since the fuse technology already is so mature one could wonder whether the question posed in the title of this paper is felicitous. The answer undoubtedly is: it is the felicitous one because we have to talk about a rather simple and cheap conventional protective element but which development is incessantly constraint by the improvement of overcurrent protective systems and exertion of the new electric devices. More recent examples illustrating this statement are:
- the rapid extension of the short-circuit current-limiting back-up fuses to cooperation with: load-switches, contactors equipped within thermal relay /a very special case are vacuum contactors/, expulsion fuses /U.S.A./ but above all of moulded case l.v. circiut-breakers;
- the implementation of the semiconductor devices was a challange to come into existance of the special fuses for the protection of diodes and thyristors /called in this paper semiconductor fuses/.

A correct answer on the question pushed out in the title largely depends upon the circumstances existing in given country. That what is already solved in one state it is a task for today or future in another one. China for instance [2] already has implemented the aluminium fuse-elements whereas the rest of the world,- as far as I know,- rather did not yet, despite there are known some endeavourings to do that /e.g. Denmark, U.S.S.R./.

Although the fuses manufacturers are restricted by national and international standarts the margin of a freedom existing in course of the designing of new fuses enables to create individual solutions and the designers can still demonstrate their art of the fuse engineering. It is a reason why we do observe on the market a huge number of fuses variations. An opposite example, if I am not wrong, are the conventional electrical machines, in which practically already all is based upon the classical calculations using existing complete programs for digital computations of the whole machine. But of course, the manufacturing processes and the quality control methods of either machines and the fuses are still under intensive improvements.

Normally a paper on the topic like this have to be precede by a review of the present state-of-art, but in here one can omit it as it is adressed to the people working in the fuses. Moreover an apparent witness of the prior art of the fuse technology is a number of books on fuses, specifically issued over the last 15 years [3÷9] and a periodical edition on protective devices [10] in which fuses and their applications are videly represented.

The question being the contents of this paper let's limit to the h.b.c. fuses only, as in the power electric engineering at present and over the nearest future we will have to do practically mainly with the h.b.c. variety. However frankly speaking the gas-expulsion fuses are and will be also widely used but they do'nt have involved so many potential possibilities in creation of the new kinds of features needed for a modern protection as compared with the h.b.c. ones.

To be correct understood all the fuses indicating the short-circuit current-limiting ability are recognized here as the h.b.c. fuses. All of them have the arc-quenching filler, preferably a fine quartz sand. So for example the screw-in household D-type fuses very often used throughout the Continental Europe are also considered as the h.b.c. ones.

Obviously it is impossible to touch all of the aspects even of the h.b.c. fuses only due to a limited space of this paper. But those which are selected in the following have, after my minde, a greater importance. I believe the discussion will enrich the scope and deepness of our clearance on the actual fuse problems.

So limiting the contents of this paper we leave untouched a consistent number of the varieties of fuses /e.g. gas-expulsion, miniature, liquid, vacuum a.s.o./ but it enables to concentrate on the several important features of h.b.c. fuses.

POWER-LOSSES AND TEMPERATURE RISES   Obviously better the fuses smaller the rated power-losses and the steady-state temperature-rises by unchanged technical data.

From the short-circuit current-limiting ability point of view a typical h.b.c. fuse-element shall fulfil two requirements: 1st is to keep its cross-section as small as possible in order to have the smallest pre-arcing time and the 2nd,- to create as high as possible arc-voltage using to that quite reasonable fuse-link length. That's why in comparison with the gas-expulsion fuses, which are not current-limiting ones, striking is that the h.b.c. fuses do indicate several times larger watt-losses. This is the price paid for the current-limiting ability.

For instance, a 15 kV h.b.c. fuse has the element-length of order 100cm, whereas a 15 kV gas-expulsion one,- few cm only. So the h.b.c. fuses are comparatively very much electrical energy consuming devices. Some general purpose h.b.c. fuses of 10 kV rated voltage and 100 A rated current do indicate abt 200 W rated power-losses. Or a h.b.c. fuse for diodes and thyristors of 1000 V a.c. rated voltage and 100 A rated current shows abt 20 W, but of 500 A rated current,- abt 100 W. This is a waste energy, which shall be artificially removed specifically in the case of large power semiconductor invertors within great number of fuses.

So alarming losses giving in cosequence high temperature rises of the h.b.c. fuses do urge us to drastical diminishing of them, what is a beautiful task for fuses designers to cope with.

Some recently suggested new fuses concepts would be in this

respect a challange to the traditional h.b.c. fuses. A promising example could be so-called "two-path" fuses described in a paper for this Conference [11]. However discovering of the all advantages and imperfections of two-path fuses is a question of time only but already it is safe to say this concept really does indicate much better quality at least as concerns the watt-losses and the temperature rises.
Another a very effective direction of action is to cut down the fuse-element length keeping all remaining parameters unchanged. But it needs to enhance the arcing gradient by this same rated voltage using for example a better arc-quenching means or/and improving the geometric proportions of the fuse element. Some examples are: the quartz-sand kept under an overpressure over the whole period of life of fuses [12], use of the sand-liquid filler [13], but also introducing a thinner strip by this same cross-section which should indicate a higher voltage gradient in the power 0.6 which proceed from a relation given in [14] and empirically was shown already several decades earlier in [15] , a.s.o.

A quite different way is to improve the cooling. We obtain as a result the lower temperature rises conservating this same power-losses. But improving the cooling according to the actual practice we rather do the larger rated current keeping invariably these same permissible temperature rises. A good example of this way is the use of a sand-liquid filler [16], but also the use of fuse-elements deposited directly on an insulating substrate and/or glueing the sand-grains in one whole e.g. by a special chemical treatment of sand /TYPOWER fuses of LK-NES Co. Demark/, use of the various cooling sinks a.s.o.

In the context of power-losses and temperature rises there is situated a problem of the thermal cracking of the fuse-link barrel, even in the steady-state conditions, by loads nearly the minimum fusing current. Such sort of cracking surely is known for fuse-designers from several decades, was it also mentioned in the book [3]. But a theoretical approach which does indicate very clear the induced thermal stresses throughout the fuse-link body due to the heat transfer one can study in the rather less known work [17].

CHARACTERISTICS OF OPERATION Among the problems of characteristics of the operation one of the most important it seems is a problem of the interchangeability of fuses of different manufacturers. It is known practice that the fuses of these same basic standart parameters, i.e. dimensions, rated currents and voltages and t-I characteristics can show different operation in similar conditions. From this reason we are never sure whether the protection with the replaced fuse-links agreed with the standarts will remain equal to the originally done. This remark is important practically for such cases like various back-up protection systems, protection of diodes and thyristors and some others. In this respect important are not the standart but rather the actual t-I zones, cut-off currents, pre-arcing and clearing I^2t's, sometimes also the minimum breaking capacity, overvoltages, rated power losses and temperature rises and several others. A disorganization of the protection becomes here due to the rather too wide permissible standart gates of mentioned parameters.

The problem is well known but to accentuate it we will give the following exemplary comments:

- The standart ratio of time operation say at 6 times of the rated current of a 100 A industrial fuse can reach abt 20 [18]. The choosen exemplary overcurrent is close to the usual take-over current of the contactor-thermal relay-fuses assembly.
- The ratio of cut-off currents of equal fuses of different manufacturers can be say 2.
- The ratios of pre-arcing and clearing I^2t's can have magnitudes even greater than 10. The actual situation in this respect among the semiconductor fuses do illustrate the data given in [19] which are actual even now.
- The ratio of rated power-losses and temperature-rises of semiconductor fuses in the utmost cases can approach say 10 [19]. And if replacing the original fuses by more hot ones in a large power semiconductor equipment there may arise a question of an overheating of the whole arrangement.
- The minimum breaking capacity defined by the coefficient k_1 [20] of the fuses type a can have an arbitrary magnitude defined by a given manufacturer. So after replacing of fuses there may arise the problem of the incorrect interrupting of moderate overload overcurrents.
- A jeopardy of the use of semiconductor fuses of higher overvoltages than that generated by the originally installed is an evident case.

Above given examples are far to be complete, especially if we consider a proper utilization of semiconductor fuses.

What kind of the conclusions one can push forward from those examples? First of all it seems that a corollary is to tighten up of the standart requirements, as much as it is needed for the correct service. But we shall move in this direction in a very cautious way in order to not limit excessively a desired margin of the freedom of the fuses designers and consequently to not bring to a stop of the progress of development.

A quite different problem also does exist with t-I characteristics of operation in respect of the service safety of the domestic screw-in fuses of 380 V, type D. This is a case important in systems of small prospective short-circuit currents /say few times of the rated current/. It is a typical case rather for the old tonement houses feaded by weak old networks. When a short-circuit has take place in similar cases the mentioned fuses enable of the existance of a failure earth-leakage current during some decades or even hundreds seconds. The failure current existance in similar case means in turn the appearance of a touch voltage on the houshold electrical conviniences. If this voltage is high enough the service safety therefore can be drastically diminished. In some individul countries described situation can be normal practice over majority of the old dwelling quarters /e.g. in Poland/. Hence it exists the need to create some domestic fuses of 380 V of a rather quick-acting t-I characteristic instead of the time-lag one required by I.E.C. specifications. Here one shall know that the earth-leakage domestic protection as a rule in those countries rather are not available. Situation analogous to described one can observe in the farms poorely equipped within agricultural electrical convinienсes supplied by weak overhead rural high voltage systems and small transformers. In several number of the third world countries are similar situations.

Afore-going exemplary problem is not a lonely exeption but it is a rather an illustration of a more general rule that the adaptation of the I.E.C. requirements may push foreward the needs to design the fuses having not standardized characteristics of operation.

<u>SEMICONDUCTOR H.B.C. FUSES</u> The development of this specific fuses is still stimulated by the uninterrupted improvement of the power semiconductor devices. They are therefore in the very centre of attention of the fuse makers. That's why a couple of detached words could be said on them behinde of some remarks already given above on semiconductor fuses. In following there are summariezed the chief ideas on said fuses published already in [22].

The role of semiconductor fuses as an economical means of protection of power semiconductor devices is to remain in the foreseable future. The problem however still remains how to achieve protection of the newest high power semiconductor devices keeping step with diodes and thyristors in power handling capability also in future.

Already twice in history technology got a violent progress: in the mid-sixties when the beveling-technique the "hokey-puck"-design has been introduced and second one actually due to extremely homogeneous phosphorus doping of silicon single crystals by nuclear transmutation of ^{30}Si into ^{31}P by means of neutron radiation resulting in increase of the break-down field strength what enables already to manufacture semiconductor devices with maximum continuous current ratings up to abt 4 kA and peak inverse voltage of 6 kV in one piece.

But what we have to do with semiconductor fuses in future in face of expected further development of the semiconductor devices?

First of all we need to awake ourself the weak points of the present day's semiconductor fuses. One of them is the nonuniformity of the arc-voltage. A comparison made for several products manufactured in Europe, U.S.A. and Japan shows that actually are available semiconductor fuses with the coefficient of the arc-voltage nonuniformity, understood as a relation of the maximum arc-voltage to the average arc-voltage, in the range of abt 1.05÷1.4. Only very good products indicate that coefficient close to 1. An eventual improvement of the arc-voltage consisting in doing of a uniform arc-voltage shape /rectangular shape/ in some cases can drastically diminish of the arcing I^2t and in consequence of the clearing I^2t too.

The next problem is the power-losses diminishing which was already touched in afore-mentioned section. The urgent need is a further increasing of the rated current density of restrictions of fuse-elements. The possible improvements are innumerable.

The last but not the least problem which we will to mention here is the saving of silver and/or complete replacing it by a less expensive metal. In this last respect the competitive are combined Cu-Ag elements but of course also Al-elements.

Looking more ahead it seems that the conventional semiconductor fuses would be unsuitable due to too large length,as the protective device for high voltage semiconductor devices. The length is nearly proportional to the rated voltage. On the other hand the dimensions of semiconductor devices indicate a weak dependence on the rated votage. Hence utilizing present day's semiconductor fuses the semiconductor invertors designed for high voltages shall have rather large dimensions strongly dependent on the fuses' dimensions. That's why the new principle of semiconductor fuses would be warmly welcomed.

On the background of the problems we have to solve in h.b.c. semiconductor fuses the new two-path fuses [11] it seems to be hopeful.

SOME PROBLEMS OF RESEARCH Generally we may note, the pre-arcing behaviour of fuses was in a very centre of scientific interest during the first 3/4 of period of the fuses existance. But during the last decade or so only, the calculating methods of the steady-state heating and the pre-arcing times, even of the very complicated fuse-element's forms, have been successfully developed by several authors and we do'nt come back to them here. However one point shall be added. Nearly two years ago I did see in dr Wilkins' laboratory /Liverpool Poly./ a nice and a very needed for designers a computer aided engineering procedure which makes possible in an easy way to select the proper fuse-link dimensions in order to get a desired t-I characteristic, rated power-losses and temperature rises of the specific parts of the fuse-link. It is a true success of the implementation of theoretical considerations into the engineering practice.

On the contrary around the arcing processes we focus our attention practically over the last few decades only, despite there are known individual investigations on arcing in fuses say since 50 years /Kleen, Gantenbein, Lohausen, Kroemer, Schuck a. Boehne, Melkumov, Baxter, Johann and several others/.

One can have an opinion that the arcing behaviour shall remain over the nearest period still in the centre of our attention.

A switching arc phenomenon is the most enigmatic one in the switchgear devices. And in the case of h.b.c. fuses the exploration of it is bristling with the difficulties inasmuch this phenomenon takes place inside of a closed volume with a filler. Moreover a period of its duration at short-circuit interruption is very short one. The special diagnostic tools therefrom are necessary such as an ultra-rapid X-ray flash, a rapid spectography, an ultrarapid temperature and pressure measurements a.s.o. That's why only recently more deep laboratory study of an electric arc performance in h.b.c. fuses was developed in several countries.

The temperature distribution along the fuse-element just prior of this element disintegration and the velocity of energy supply to the element are the predicting factors of arc -ignition and to some extent of arc-burning and then arc-extinction.

There are one-arcing and multiple-arcing processes depending upon the fuse-element shape and the velocity of energy supply. Plain wires and strips under heavy overcurrents demonstrate a typical multiple-arcing, i.e. striation. Despite some endeavourings of several authors /e.g. Nasiłowski, Lipski [23]/ there is no clear and universal point of view on the physics of striation. But there is an experimental approach [24] which makes possible to calculate the peak arc-voltage in case of striation.

On the other hand we are of a step ahead with calculations of a single arcing process characterized by a burn-back of the fuse-element as compared with the striation. A number of approaches in this respect are known / more recent are Wilkins' with co-workers and Daalder's and Schreurs' [24]/. These dynamic approaches do open the door to a full calculation of the h.b.c. clearing ability. But before that, keeping still the one-arcing mechanism under considerations, there are several questions to investigate, among them are:

- generation and propagation of the pressures arising during the arcing and their influence on the arcing behaviour in h.b.c. fuses,
- reciprocal action of the parallel fuse-elements in one cartridge over the arcing period.

Speaking about the pressure, the more recent investigations indicate on the two characters of this pressure generation: one is monotonous connected with the slow burn-back process at rather moderate overcurrents [25] and another one is in form of the pressure shock-wave initiated at the instant of arc-ignition. The last is a very typical one when a plain wire or strip transits explosively into the streaks [26].

But interrupting a heavy overcurrent by a notched fuse-element it seems the both characters should exist abreast: the simultaneous arcs ignition in a number of series equal notches can give a suddenly arising pressure shock-wave and then the burn-back process contributes to the further pressure elevation but over this stage in a monotonous manner. If however the burn-back process would be slow enough then this contribution may not exist.

The mutual influence of the parallel fuse-elements placed after all close to each other in a cartridge is also a problem awaiting for investigations. However there are known some fragmentary investigations in this respect [3,27] but the question still waits for its discoverer. We shall pay more attention to that problem since a considerable number of h.b.c. fuses are designed for rated currents above say 25 A in which as a rule the fuse elements are in parallel. Aforementioned mutual influence is a complex interaction of parallel elements in which an important role shall play also the pressure and the overlapping of spaces occupied by the arc-channels.

In connection with this there is a more general reflection on specifically h.b.c. fuses operation during the arcing period. Such fuse is an interrupting device in which the interaction between the fuse-elements, the arc-quenching medium and the fuse-link body, which does reflect those shock-waves, is an essential base of the correct action. All three parts shall be selected and coordinated in an appropriete way as a one whole. This statement is not new and the fuse designers surely know that well from their own experience.

Author had´nt an ambition to exhaust all problems on the arcing in h.b.c. fuses. It would be not possible to do that by one person. But it seems said remarks are sufficient to get the judgement on the tasks awaiting for right solution in the nearest future.

But beyond arcing problems we have also plenty to do with the quite different but how important problems on h.b.c. fuses and their proper selection for applications. Several examples of such problems are given below:
- A number of questios on the ageing due to M-effect, mechanical deterioration, pulsed loading a.s.o.
- We have to investigate a number of problems pertaining to the really full-range-clearing-ability fuses. In this respect we have to note very promising high voltage fuses with the cadmium fuse-elements /Westrom and co-workers, Canada/.
- A number of questions on the proper selection of fuses for various applications. For instance there is not yet solved finally the problem of a correct coordination of h.b.c. fuses with the expulsion fuses in an assembly designed to protection of padmounted and pole-type transformers in U.S.A. H.b.c. fuses are here best applied as back-up fusing devices while the expulsion fuse is used as the first line of defense. H.b.c. fuses in assembly serve also to prevent against a violent rupture of oil filled transformers as result of the arcing inside of the transformers tank.
- Several points are to enlighten in connection with the testing and stan/dartization.

The list could be continued.

FINAL REMARKS Above given superficial observations on the question "what next with the h.b.c. fuses?" it seems to me do indicate that we have still many problems to solve in the research and development. But we have also to improve the manufacturing processes, for h.b.c. fuses shall be produced as far as it is possible independently of the manual ability of workers in order to stabilize the final quality. In this respect for example interesting is a set of manufacturing machinery for the fuse-elements with constrictions in form of the grooves and continuously deposited tin-lead alloy to get time-lag fuses [28,29]. Same machinery for grooves plus another machinery to make the continuous welding of Cu- and Ag-strips [30] enables the mass manufacturing of fuse-elements of semiconductor fuses. Having the consciousness of a not fully exhaustive answer on the question in the title let´s say couple of closing words.

The subject of our common interest i.e. the fuses are destined to serve as a protection of the very different objects. That´s why we shall be prepared to create in a very limited time quite new fuses operational characteristics sufficient to be a good protector of the not yet existing devices. This menial role of fuses, we believe, will still remain for the long years, despite several suggestions to design the electrical installations on the fuseless basis.

Now we see that the Latin word "fundo /fundi, fusum/" does cover a vast field of the electrical overcurrent protective devices we have to deal with. And that our activity in this field is needed for society.

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