WHY THE OPERATION FAILURE OF HIGH BREAKING CAPACITY FUSES IS SO FREQUENT?

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ABSTRACT

High breaking capacity (HBC) fuse is today one of the most used low and medium voltage protective devices. Its operation principle presents two singular current values of difficult interruption, “critical current” and “minimum breaking current". These fuses, in general are not able to break any current that begins the melting process. An introduction about the HBC fuse design characteristics and operation modes is given. Standardized fuse classes are discussed based upon the IEC 60269 and IEC 60282 specifications. The error in the selection of the appropriate class is the most common mistake and the consequences go from damages to the protected equipment up to fuse violent explosion. Real typical cases of incorrect selection are presented, pointing out the consequences and risks. It is concluded that the only way to avoid errors in the selection is by means of the deep knowledge of the methodology of application of the HBC fuses.

INTRODUCTION

The fuse is the oldest protective device against overcurrents, and that of more application today, based its wide use fundamentally on its high reliability. In the South American region, until some years ago the behavior record of the HBC fuses was excellent. However, lately the number of fuse failures have been significantly increased.

The standards that standardize their application are modernized permanently, but their crucial parts have remained unaffected for more than 60 years. What has changed in the electric systems is the high power concentration, higher short-circuit power and space limitations that lead to the reduction of the equipment size. Thus, fuses work at present time nearer their technical limits of temperature, load current, voltage, breaking capacity, etc. These higher exigencies reduce the margins of security with the consequence that any small selection error on users´ part is shown quickly, many times in violent form.

HBC FUSES OPERATION PRINCIPLES

HBC fuses design characteristics

Their interruption capacity roots on the high operation speed that allows cutting the current in sub-cyclic form. Due to its operation principle, the HBC fuse presents two singular values of current of difficult interruption: “critical current” and “minimum breaking current", values that are specified in the corresponding international standards [1, 2]. These fuses, in general are not able to break all currents that start the melting process. As well as is defined the breaking capacity as the maxim current value that the fuse is able to interrupt, it is necessary also to define a minimum operation current.

The most important components of the HBC fuse are:

- Body: usually built of high-density ceramic (or glass-fiber reinforced), material that possesses high resistance to thermal shocks and to internal overpressures.
- External contacts: are of widely varied forms, built with low resistivity materials like copper or brass and covered with silver or tin in order to protect them from oxidation.
- Fuse element: built with copper or silver ribbons, having cross section reductions or restrictions, locating in the central part the low melting point material (M effect).
- Extinguisher material: quartz sand, which function is to collaborate in the heat extraction during the normal use, becoming extremely active during the electric arc extinction process. During the arc quenching, the filler absorbs energy in the process of transformation of quartz sand in "fulgurite". As the sand passes to the liquid state it is expelled outside of the arc area by the high internal pressure, being introduced in the grains interstices [3].

HBC fuses operation modes

Operating with load currents smaller or of the order of the rated one, the fuse element increases its temperature until reaching a value that does not affect neighboring elements, neither compromise the fuse useful life. Such a steady state temperature has limits that depend fundamentally on the material of the fuse element, related with the oxidation and aging phenomena [4, 5].

Figure 1 shows a typical low voltage high breaking capacity fuse, NH type [1].

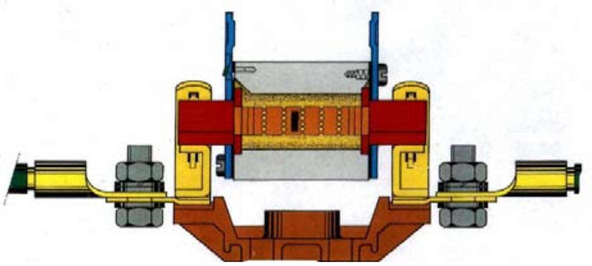

Figure 1, Schematic view of a high breaking capacity low voltage fuse.

In Figure 1 the fuse components can be seen: fuse element (ribbon) with five cross-section reductions and the dark rectangle that represents the deposit of low melting material. Both elements will be studied later.

- Pre-arc period

In this period, the fuse element when traveled by a current higher than the rated one elevates its temperature beyond the limit of steady state operation. As the resistivity of all the metals used as fuse element are proportional to the ribbon temperature, the heating process accelerates until reaching the melting temperature that is of 960 °C for silver and 1,083 °C for copper. This temperature increase takes place with a speed function of the current magnitude, in such a way that two levels of current can be distinguished, overload and short-circuit. The heating in the first case is influenced by the heat loss in axial form, for what the maximum value of temperature is in the center of the ribbon. In the second case, the values of restrictions current densities are so high and the time so short that the maximum temperatures are equally reached in all the restrictions.

The light overload presents one of the most complex problems for the HBC fuse. In such a situation a slow temperature increase takes place, leading the fusible element to reach the melting temperature in its center in very long times. Therefore, in the case of using silver element, the center reaches a temperature of 960 °C, being the fuse filler, body and terminals at temperatures of the order of 500 °C, temperature that damages the neighboring elements, specially conductors and bases.

The solution to this problem is achieved by the application of the “M effect", which allows that the HBC fuse can interrupt currents as low as its minimum melting current (1.25 to 1.3 the rated current). A single electric arc is generated, with a slow heating of the fuse element and consequently a long pre-arcing time [4, 6]. The arcing time is insignificant in duration in comparison with pre-arcing one, nevertheless, some semi-cycles can be required to reach the final interruption. Figure 2 shows current and voltage oscillograms of the operation of a fuse under low overload conditions.

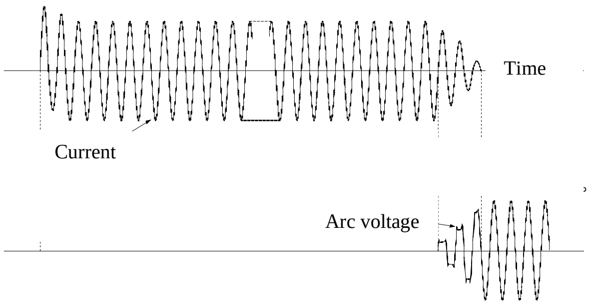

Figure 2, AC overload operation of an HBC Fuse.

If it is an interruption phenomenon with high current values, beyond overload, the high current density in the restrictions area or cross section reductions, quickly elevates the temperature in such points achieving their melting and simultaneous vaporization in all them. This means that an arc is generated in each restriction. If the current is high enough, the melting temperature and the vaporization energy is reached before the natural current peak. The extinction process generates the phenomenon denominated "current limitation", that means that the fault current is prevented of reaching the maximum value, limiting in that way the thermal and dynamic stresses of the protected equipment. This property is characteristic of the high breaking capacity fuse, allowing this way to control very high levels of fault energy in extremely reduced volumes.

- Arc Period

The formation of the arcs among the melted ends of the element is accompanied by a significant increment of the voltage on the fuse terminals, due to the abrupt elevation of the impedance associated with the arc presence. The magnitude of this surge will depend on the characteristics of the protected circuit and of the speed with which the impedance of the arc increases (for example in a highly inductive circuit, quick current variations will cause high voltage peaks). The arc continues burning until the voltage drop between the fuse terminals equals the source voltage, causing the current interruption and thus the arc extinguishes, this period is denominated arcing time.

- Critical current

Corresponds to the current interrupted by a HBC fuse that forces the device to absorb the maximum energy value during the arc process, energy that the fuse should be able to absorb without any damage and without any external indication. With currents lower than the critic current, the arc energy diminishes but with overload values it begins to grow up again. This way, for example, with overload currents of the order of the minimum melting one, the arc energy grows to similar values to those of the critical current and even higher. The difficulty in the interruption of low current values takes place for the transition from multiple arcs to simple arc [3, 4, 5].

Many current limiting fuses, especially the medium voltage ones, cannot interrupt currents below the minimum interruption current specified by the manufacturer, since with low overcurrents the initial arc voltage is too small in comparison with the source voltage seriously hindering the fuse breaking operation.

- Type and class selection

The selection of the type of fuse for each application is helped by the guides given by specific standards that individualize the fuse class based on the equipment or element to be protected.

HBC FUSE CLASSES

Due to the wide field of fuse application, diverse fuse classes exist that are designed for some specific applications. For medium voltage fuses, three normalized classes specified in IEC 60282-1 exist, denominated back-up, general-purpose and full-range whose characteristics are [2]:

- Back-Up: current-limiting fuse capable of breaking, all currents from the rated maximum breaking current down to the rated minimum breaking current.
- General-Purpose: current-limiting fuse capable of breaking, all currents from the rated maximum breaking current down to the current that causes melting of the fuse element in 1 hour or more.
- Full-Range: current-limiting fuse capable of breaking, under specified conditions of use and behavior, all currents that cause melting of the fuse element(s), up to its rated maximum breaking current.

For low voltage fuses, the class is mainly indicated by a couple of letters, the first one minuscule being “g” or “a”, and capital the second [1].

- "g" current-limiting fuse-link capable of breaking all currents, which cause melting of the fuse-element up to its rated breaking capacity.
- "a" current-limiting fuse-link capable of breaking all currents between the lowest of its operating time-current characteristic and its rated breaking capacity.

"a" fuse-links are generally used to provide short-circuit protection, being usually used in conjunction with another suitable switching device designed to interrupt such small overcurrents.

The second letter means: G, general applications (previously L in VDE standards); M, motor circuits; D, delay; N, non-delay; R, semiconductor protection; S, idem R but faster and low power dissipation; PV, photovoltaic cell; Tr distribution transformer and B for mining applications (both in VDE 0636/2011).

The main classes and specific applications are [7, 8, 9]: "gG" full-range breaking capacity for general application; "gM" full-range breaking capacity for the protection of motor circuits; "aM" partial-range breaking capacity for the protection of motor circuits; "gD" time-delay full-range breaking capacity; "gN" non-time-delay full-range breaking capacity; “aR” partial-range breaking capacity for the protection of semiconductor; “gR” full-range breaking capacity for general application and semiconductor protection, optimized to low I^2t values; “gS” full-range breaking capacity for general application and semiconductor protection, optimized to low power dissipation; "gPV" full-range d.c. breaking capacity for photovoltaic energy systems; “gTr” full-range breaking capacity for distribution transformer protection; and “gB” full-range breaking capacity for mining applications.

These wide range of classes and applications, signify that for a successful application the people in charge of the fuse class and type selection need of a deep knowledge on fuses. Besides, any error usually has very serious consequences from the personal and equipment protection risks point of view.

TYPES OF FUSE OPERATION FAILURES

It is considered as a fuse operation failure not only an explosive fault (breaking failure), but any operation outside of the design characteristics, for instance an unintended (nuisance) operation under normal load conditions due to aging or other causes. Cases due to fuse design problems were not included, considering only the failures due to incorrect fuse selection, wrong handling, inappropriate storage, incorrect load, etc.

An extensive study of the main types of high breaking capacity fuses failures, which has taken place mostly in South American electric systems has been carried out.

TYPICAL EVENTS

Several on-field and laboratory fuse fault events are here presented, describing in a summarizing way the fault causes and consequences. For instance, Figure 3 shows the right HBC fuse operation under high current conditions, recorded at the High Power Laboratory of the Electric Power System Protection Institute (IPSEP) of the Rio Cuarto National University, Argentina.

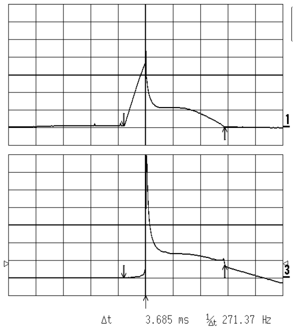

Figure 3, Right HBC fuse operation breaking a high current value (up current, lower voltage).

Figure 4 shows a wrong fuse operation for having low sand compaction due to sand lost caused by a fuse body crack, generated by incorrect handling (kept in the back of the utility emergency maintenance pickup by weeks), recorded at the same laboratory than Figure 3.

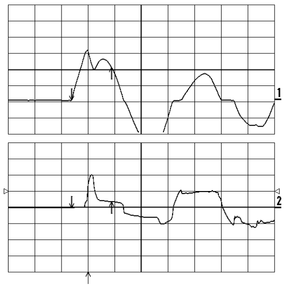

Figure 4, Wrong HBC fuse operation for having low sand compaction (up current, lower voltage).

Figure 5 shows an on-field operation with current lower than the minimum breaking capacity of an aM class fuse. Figure 6 corresponds to a low current operation of a general-purpose HBC fuse after suffering an aging process, recorded at the IPSEP laboratory [10].

Figure 7 shows an effect similar to that in figure 4, but in this case on-field in a capacitor protection application.

Figure 5, Fuse operation outside of its operation range.

Figure 6, Laboratory test of a low current operation failure of an aged HBC fuse.

Figure 7, On-field low current operation failure due to aging.

TYPICAL SELECTION MISTAKES

Several fuse class or type selection mistakes were studied, explaining the right concepts to be used on the selection task in order to avoid the failures. The analysis is based upon current literature and standards.

- **Selection of the fuse rated current too close to the load of the circuit.**

Low and medium voltage fuses of classes "g" and “general purpose" can interrupt overloads higher than 25 % to 30 % which increase the temperature of the fuse element. If this temperature overcomes the dissolution temperature of the M effect, the irreversibility point is reached by what the fuse suffers deterioration. This usual type of overload starts the aging process, leads to the unexpected opening of the low voltage fuse and could take-out the medium voltage fuse from the safe operation zone, with high risk of explosive failure. The aging of the medium voltage fuse usually leads to the sure opening of the associated switch and it is considered as a normal performance [3]. It is frequent that for deficiency of the fuse and/or of the switch, the last does not operate and the consequence is the fuse explosion. That is to say that the aging cause the fuse explosion.

- **Do not consider repetitive load current transients.**

The heating and cooling follows exponential laws, for what the successive overloads can gradually increase the fuse temperature, what leads to the dissolution process of the M effect and to the consequent aging. In these cases, a fuse of higher rated current should be selected, verifying that the fuse is still protecting the equipment intended to protect, being advisable the consultation to the fuse manufacturer in extreme cases.

- **Do not consider non-repetitive load current transients.**

The application of fuses for the protection of motors, capacitors, transformers, etc. requires the study of the connection transient overcurrents that for each one of the mentioned cases possesses distinctive particularities. The mistake of selecting a fuse with rated current too close to the equipment rated current, leads to the aging start. The fuse ratio (relationship between the fuse rated current and the homologous of the protected equipment) should be kept between 1.6 and 2; what is permissible since in these cases the fuse protect the equipment only against short-circuits. Usually the motor protection scheme possesses specific additional protection against overloads, the thermal relay, that can be as simple as a bimetallic device or a sophisticated microprocessor relay. The transformer overloads are generated on the secondary side, where protection is given by fuses with lower fuse ratio (gTr fuse). Capacitors are protected against internal faults by means of the imbalance or neutral displacement relays, thus the fuse is used to protect from short-circuits [3, 5].

- **Use of back-up or “a” fuse class where the fuse can operate under overload conditions.**

The fuses classes back-up or “a” do not possess M effect, for what the overloads can lead the fuse element to too high temperatures as to allow the current extinction and also their temperatures can damage the neighboring elements, as conductors, connections, fuse bases, etc. These fuse classes can be only used together with another device that interrupts the overcurrents before the fuse. The consequences of this situation are very serious [5].

- **To ignore the effect of harmonic currents.**

The existence of harmonic sources as the Adjustable Speed Drivers, soft starters, induction furnaces, switch mode power supplies, etc., equipment widely spread in the industry, jointly with the power factor compensation by capacitors, produces the circulation of harmonic currents between these sources and the capacitors. If fuses are connected on the way of these harmonic currents, abnormal temperature increase and nuisance fuse operations could take place. The situation can be worsened if the fuse is back-up or “a” class. The solution is to block this harmonics circulation or to increase the fuse rated current, without losing protection [3].

- **In the event of a fault, replace only the operated fuse without reviewing the state of the other fuses probably involved in the fault path.**

Statistically most of the distribution system faults are of single-phase type (45 %), followed by the two-phase ones (21 %), and the less frequent one is the three-phase (31 %). So that it is very probable that the fault current has circulated through more than one fuse, being the fault cleared by the first of them that operated, having left the other involved fuse under conditions different to those that had when left the manufacturer premises. For that reason, the fuse state should be verified by means of a simple measurement of the internal resistance.

- **Excessive humidity**

The low and medium voltage fuses are not hermetic, and the filler (quartz sand) is highly hygroscopic, thus in presence of high environmental humidity, the interior of the fuse becomes moist. If it operate under these conditions, the water vapor pressure can cause the explosion and the logical interruption failure. There have been cases of flooded facilities that where dried-off (without fuses drying-off), where the mentioned situation took place. For it should be avoided the use of this type of fuses under extreme humidity conditions [1 ,2].

- Limitations of the heat extraction

The fuse rated conditions are vertical positioning, environment temperature of the order of 25 °C and with free air circulation around the equipment. If the installation conditions change, the rated characteristics should be altered. For space limitation reasons many small metal clad cabinets are built and fuses are contained in smaller spaces. In these cases the load current should be decreased or should be selected a higher fuse rated current, based on the possibility of power dissipation that the cabinet maker gives (in W). If this effect is not considered, the fuse can be driven to operate under dangerous conditions.

- Use of AC fuses in DC circuits

The application in DC presents two crucial differences with regard to AC, the lack of zero crossing and the circuit time constant. There are practical rules that allows the AC fuse derating for DC. If the operation conditions are not deeply known, the utilization of the practical rules can be risky. In DC applications, the derating should be done following the fuse manufacturer recommendations.

- **Semiconductors protection**

These devices require protection against overloads and against short-circuits separately, being the fuses used for this last one. Fuses class “a” are used trusting in the overload's detection for another means, being aided that other means by the signaling of the fuse operation indicator and an associate micro-switch. Most of the faults happened with this protection scheme has been originated on having driven the fuse class “a” to operate under overload conditions, for which has not been designed. This fault usually leads to the externalization of the arc [3, 5].

This listing does not pretend to be exhaustive; there are always cases possible of errors not included here, for what it is always advisable to consult the fuse maker.

CONCLUSIONS

It is concluded the need of a deep knowledge on HBC fuse operation characteristics and on fuse selection good-practices, in order to avoid most of the here described fuse failures.

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