# PERSONAL PROTECTION AGAINST ELECTRIC ARC FLASH IN DISTRIBUTION SYSTEMS, BY SELECTING THE RIGHT HIGH BREAKING CAPACITY FUSE

Juan C. GOMEZ[1] Medhat M. MORCOS[2] Juan C. AMATTI[1] German R. ZAMANILLO[1] Daniel H. TOURN[1]
[1]Rio Cuarto National University, Argentina [2]Kansas State University, USA
jcgomez@ing.unrc.edu.ar

## *ABSTRACT*

*The personnel risk due to electric arc flash is very important today, due to the high number of accidents with consequences suffered by utilities´ personnel. The personnel protection is based on control of the arc released energy, and of the incident energy on the personnel by means of protective clothing. The coordination procedure is presented, considering the arc energy control given by high breaking capacity fuses and circuit breakers. Protective clothing can be selected based on the let-through energy and the personnel' body incident energy. It is concluded that to carry out an appropriate coordination study among arc control elements are justifiable due to the substantial personnel risk reduction.*

## INTRODUCTION

The personnel risk due to electric arc flash is one of the today distribution system hottest subjects, due to the high number of accidents with serious consequences suffered by utilities´ personnel [1].

The accidents take place fundamentally during the maintenance tasks, it is not a significant problem with occasional passerby in the fault zone. The ideal situation is to work with all the circuits disconnected, but in many cases it is impossible, (for economic and/or technical reasons) being forced to live-work (with voltage), using isolated elements and tools, and also appropriate clothing [2]. The new paradigms indicate that everything can be disconnected during the work and just some few exceptions are considered.

The importance of the topic is noted for the high activity developed by the standard institutions and the number of standards that emerge [3, 4]

If the arc energy can be contained inside the cabinet or to be expelled to the exterior by suitable way, there are not risks to the personnel, also for that goal it is very useful the fuse application that as will be shown, reduce the arc energy which allows that the cabinet withstand it without opening up.

The key factor of the victims of burns for electric arc (and any type of burn) is the total surface of the body that is affected. It has been shown that just have 50% of probability of surviving people of between 30 and 39 years when they have burnt 75% of the body surface [5].

The coordination requirements (operation time increase as moves up-stream) elevate the risk of damages to equipment and increase the risk to people, allowing the presence of the arc for longer time durations. Can be adopted a compromise solution in equipment protection but not on people risk. Another coordination type can be required, as the zone-interlocking, adaptive protection, etc. The transitory modification of the protection settings is also used, to just reduce the incident energy during the maintenance works [6].

The highest values of incident energy are usually in circuits of low and medium-low voltage that is in fact where higher number of working hours lapses for the electricians and where the works are mostly live-work, for that reason it is necessary to be centered in those voltages and fundamentally in NH or American type fuses [7, 8, 9]. In general there are not burns in accidents with voltages lower than 300 V [9].

Seemingly, as several researchers indicate, the calculations according to IEEE Standard 1584 are too conservative; being possible that the worker receive incident energy levels two or three times higher, for what it is recommend the limitation by means of the protection with fuses [2].

## ARC FLASH PHENOMENON

The arc phenomenon developed inside locations where utilities´ personnel works or it can have people's eventual presence generate the following risks: burns, wounds, deafness - blindness and high overpressures.

Electric arc is formed by electric current circulating between two electrodes, through ionized gases and vapors whose characteristics temperatures are from 10,000°K to 15,000 °K, durations not bigger to 1 second and liberation of high energy values in form of thermal radiation, high sound and luminous levels, explosive expansion of the air, and expulsion of melted metal at high speed (behaving as true bullets or projectiles) [1, 2].

The energy liberated by an electric arc is the integral of the product of the instantaneous values of current and voltage during the time in which the arc is burning. The electric arc behaves as purely resistive and strongly not lineal.

The available arc energy is smaller than the one calculated in theoretical form due to the influence of the arc impedance, for that the current obtained values of the short circuit calculations (bolted-faults) are not directly applicable and its use can be counteractive since the decrease of the fault current increases the arc duration, thus increasing the liberated energy. In systems of

medium-low voltage (2400-4160 V), the arc current is of the order of 90% of that of grid fault (bolted fault), falling to 65% in low voltage systems (480V) [7].
The maximum energy transfer would takes place when the arc voltage drop is similar to the source voltage drop, what is not completely exact for the arc nonlinearities (non-sinusoidal arc current and voltages), presence of source inductance and voltage dependence of the arc resistance.
Besides, part of the arc energy is used to melt and to vaporize the electrodes and involved parts, and also the form and size of the arc chamber can magnify its effect on the worker (personnel). The best way to precisely know the incident energy value is through measurements and not by pure calculation.

## PERSONNEL RISK

The incident energy is adopted as indicative of risk. The personnel protection is based on three premises: control of the arc released energy, provide means or paths for the energy release without risk, and control of the incident energy on the personnel by means of protective clothing.
It is well-known that the burns on the human skin are due mainly to the skin temperature and the duration of this heating. It has been published that the skin damage begins to take place very slowly, taken several hours when the temperature reaches 44 °C and the lesion speed is greatly increased when the temperature overcome 60°C [1]. Has been determined that 80°C is the threshold temperature of curable burn or of second degree burn (presence of blisters) [10].
An “incident energy-duration characteristic curve” has been proposed with a valley value in 1.2 cal/cm$^2$ (it is frequently given a zone between 0.8 and 1.6 cal/cm$^2$, where it is recommended the use of protecting clothes) with duration of 0.2 seconds for the second degree burn, which is transcribed as Figure 1 [1].

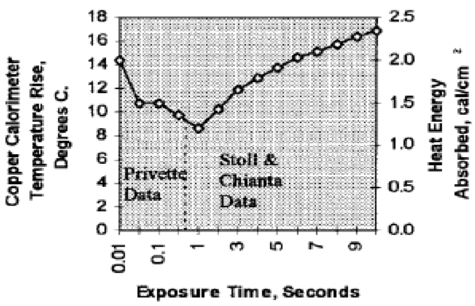


Figure 1, Human Tissue tolerance to second degree burn [10].

Flame resistant (FR) clothing are defined as clothes formed by material (one or several layers) that burns slowly or self-extinguishes and will not fuel a fire. FR materials push oxygen away, starving the flame. The NFPA 70E, Standard for Electrical Safety in the Workplace defines five clothing classes (0 to 4) based upon the incident energy withstand [3].
The clothes protector's function is to avoid that the incident energy on the human skin overcomes the normalized value of 1.2 cal/cm$^2$; offering a barrier to the energy that arrives from the arc, withstanding the energy values specified by its type or FR number.
It should not forget the face and hands protection, by wearing safety-glasses, goggles, face-shields, masks, caps, helmets and gloves.

## HIGH BREAKING CAPACITY FUSES

The high breaking capacity fuse is a protective device that operates in two different ways according to the current value that breaks. If the current is very high, it acts limiting it, preventing that the natural crest is reached, forcing to zero (annulling) the current before the natural zero passage, and reducing in great measure the let-through energy, as it is shown in Figure 2 [11].

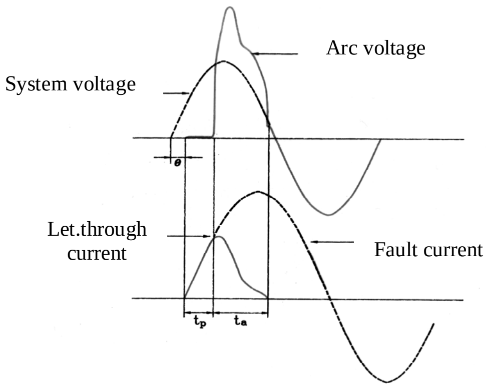


Figure 2, High-breaking capacity fuse limiting operation.

If the fault current is lower than the denominated threshold value, the limiting effect does not take place, circulating the fault current during several cycles without any attenuation until the arc period is reached, definitively interrupting the current in one of the subsequent natural zero passages, what can be seen in Figure 3.

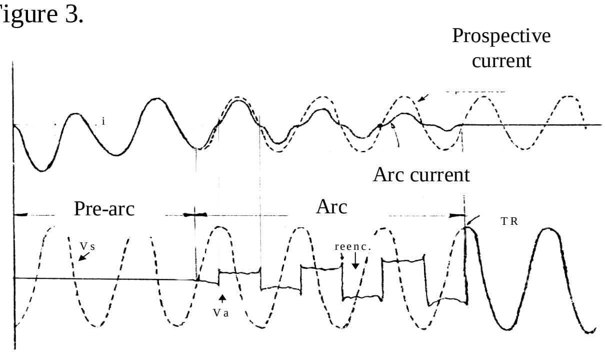


Figure 3, High-breaking capacity fuse non-limiting operation.

Defining as pre-arc period the time of the operation of the fuse in which the current circulates through a conductor in solid state or liquid state (the fuse element), being followed by the arc period in which the current circulation takes place in a gassy environment (metallic vapors) until the current is made zero in definitive form. The instants in those the pre-arc and arc periods concludes are shown in Figures 2 and 3. Also it can be clearly seen that the currents waveforms are non-sinusoidals in the first case and sinusoidals in the second case (except during the arc period).

The information regarding the fuse operation, is fundamentally given by means of three characteristic curves, the time-current characteristic (TCC), the let-through current as function of the fault and rated currents (Figure 4), and that of the let-through specific energy ($I^2t$) as function of the rated current for the pre-arc and arc time periods (Figure 5).

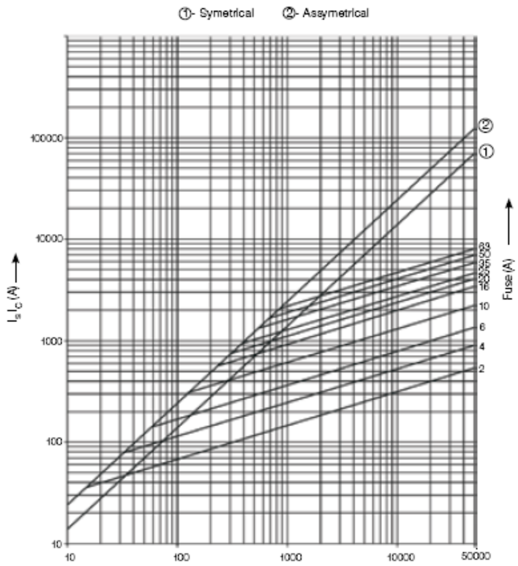


Figure 4, Let-through peak (crest) current characteristic.

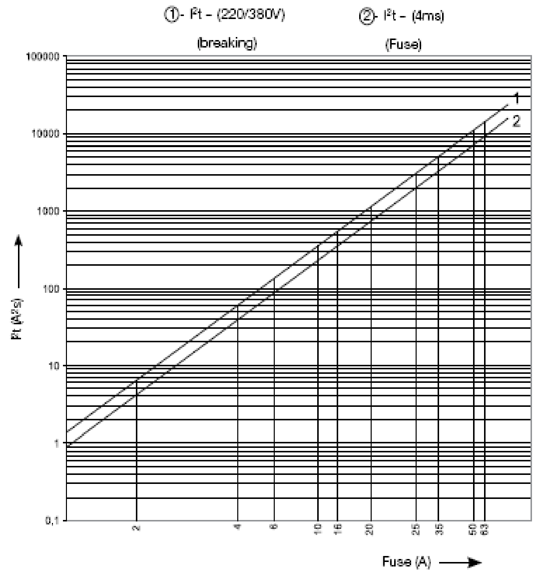


Figure 5, Specific energy ($I^2t$) characteristic.

For fault currents lasting longer than 10 ms, conventionally only the TCC is used, since it is considered that starting from such a time (although it corresponds to half cycle of 50 Hz) the rms values can be used. In other words, the TCC is built using rms current values.

For shorter time durations the TCC loses validity due to the current asymmetry effect that generates a difference between the rms value and the true rms value (non-sinusoidal wave-shape), for it during these short time durations the information of specific energy is used. For such time durations and in some cases times something longer, depending on the fuse type (fundamentally for the fuse element shoulder/notch relationship), it can be considered that the fuse operation during the pre-arc period follows an adiabatic process. This operation without exchange of heat is manifested in the TCC as a straight line with -2 slope. In other words, when in the fuse the heat exchange begins to be detectable, the curve leaves the straight line of constant slope slowly moving toward the long times where it becomes a vertical line, where all the developed heat is dissipated, keeping constant the temperature (situation that is presented for currents lower than or close to the rated value).

When the operation time is long, relatively, the energy that the fuse allows to pass during the arc process is low (as the operation time is longer the participation of the arc is smaller) in comparison with that of the pre-arc. On the other hand for the high currents, the values of pre-arc and arc specific energy begin to be comparable. The pre-arc energy for these currents is constant and it only depends on the fuse element material and dimensions, but the arc energy is strongly influenced by the value of the system voltage by what the energy values should be given in function of the applied voltage.

For short time durations, the fuse operation is informed by the denominated specific energy that is indicated as $I^2t$ that it is really $\int i^2 dt$ that remains the expression that is used to determine the current rms value.

The circuit-breakers that possess the limiting characteristic, also keep constant the values of let-through specific energy, similarly to the high-breaking capacity fuses. For this type of protective device (circuit-breakers), it should also be informed their operation characteristics in very similar form to the corresponding to the high-breaking capacity fuses.

## ARC INCIDENT ENERGY

The three methodologies are described and also the coordination procedure among the mentioned methodologies is presented, considering the arc energy control given by high breaking capacity fuses and circuit-breakers (both current limiters). From this analysis the protective clothing can be selected based on the let-through energy (for critical current) and the personnel' body incident energy.

One of the key elements is the current let-through specific energy characteristics of the overcurrent protective device, where the zones for risky incident arc energy can be draw, as shown in figures 4 and 5.

The calculation of the incident energy can be seen in several publications, where typical conditions are adopted, using as variables the bolted three-phase symmetrical fault current in the under study location, system voltage, rms arc current, distances among electrodes, open or box configuration, grounded or ungrounded system, arc duration, and working distance. The IEEE Standard 1548 indicates the calculation procedure [4, 12].

Several authors indicate that the calculated values can differ in less of the real-word values due to the specified electrodes localization with those for which the constants to use in the calculation of the incident energy were determined [12].

Two methodologies are applied, to determine the incident energy: from the time durations given by the TCC of the corresponding protective device, or by means of the straight line of constant incident energy on the TCC [8, 13].

From the arc modeling introduced in to the circuit model, including the fuse model, it can be concluded that the use of current limiting protective devices, especially fuses, allows reducing the incident energy value to less than 1.2 cal/cm$^2$ [12].

The use of a fuse of a maker or another fuse of another maker for the same rated current and fulfilling the corresponding standard, a very wide variations can be found, for instance from 2 to 7.3 cal/cm$^2$ and from 6.7 to 25.5 cal/cm$^2$ with a 630 A fuse [14]. The slight modification of the TCC curve of a protective device can greatly modify the incident energy [8]. The occurrence index is very important, and must be include in the calculations [8].

To reduce the incident energy it can be acted on the magnitude and duration of the arc current, selecting the type and the curve of the protective device [15].

## PROTECTIVE CLOTHING-LET-THROUGH ARC ENERGY COORDINATION

The advantages and disadvantages of the increment or decrement of the control of the arc energy are analyzed here with regard to the choice or selection of the suitable protective clothing type. If the protective clothing's behavior is physically analyzed, it can be understood from the energy point of view; it is clear that the received energy (incident) it is partly stored, part is conducted (toward the human skin) and part of it is dissipated. It is the typical case of protection of a electric system element o equipment by a fuse.

The coordination work is similar to that of overcurrent protection of an element or electric equipment as a transformer, cable, etc. When an element is protected it should be verified that the energy allowed to let-through by the protector device (fuse) does not reach the damage level in the protected element. The only difference is that here the liberation of the energy and possible damaged part is not inside the same equipment or element. The energy is released from the arc (point in fault) and it is protected of its effect on another element that is the protective clothing (indirectly protecting the worker that wears it).

For the case of fuses, the work is carried out by comparing the TCC or the specific energy values, depending if it is a low or high overcurrent, respectively.

Similarly, as it was already shown, if the overcurrents are of low values the TCC are used, reading the operation times for the different current values, proceeding to calculate the incident energies and of there to select the protective clothing or in the other hand by directly comparing the fuse curves with that of constant incident energy [8, 13]. Under these conditions, the work is directly carried out with rms current values, since the TCC curve begins in times of 0.01 s that corresponds to half cycle (50 Hz) and being a logarithmic graph it passes quickly at times of several cycles where the irregularities that detach the waveform of a pure sinusoidal have already disappeared. This form of working is valid so much for fusible as for circuit-breakers.

Several authors indicate that if the fuse operates in the limiting area, it greatly decreases the incident energy, but they do not deepen in the coordination task where the current is not any more sinusoidal, as can be seen in figure 2.

If the overcurrent is of high value, it proceeds in similar form to the equipment protection, using the specific energy, since the fuse and the issuing arc are strictly in series for what they have the same current amplitude and duration, as only common magnitudes to both (fuse and arc). This control of emitted specific energy redounds in the control of the incident energy, for that the values should be translated from emitted energy into incident energy. The conversion of the value of $I^2t$ values into incident energy values is not a simple calculation, but it can be extended by analogy to the equipment protection using values of $I^2t$.

The specific energy really does not directly correspond to energy values, since they lack of the time-variable resistance values of the fault-arc and of the fuse, but if these values are determined by means of experimental tests, the direct comparison of the specific energy is totally valid, concept that has been used largely in equipment protection analysis. The empiric formulas proposed by standards and commercial software allow to include modeling constants such as voltage, arc length, box characteristics, distances from the arc, etc. that enabling the determination of the incident energy in cal/cm$^2$ for each couple of current-time values [4, 15].

Elsewhere has been presented the concept of Human Damage and its curve HDC that give place to develop the Equal Energy Lines (EEL), given as valid for time durations longer than 10 ms and up to 2 second [13]. Of the analysis of figure 2 of the reference, in which four points are shown, the value of $I^2t$ can be determined considering that until the longest time point (something less than 1 second, it should be remembered that for instance the cables maintain the $I^2t$ constant up to 5 seconds), a straight line can be drawn that allows to calculate the exponent, resulting of -1.52.

In order to speak of constant specific energy, for a double logarithmic graph as the TCC, the line expression exponent should be -2, considering that the difference (between -1.52 and -2) is due to the indirect of the calculation process and to the several taken assumptions. The expression given in IEEE Standard 1584 indicate that the incident energy varies lineally with the time, does it seem to be that the results are valid for time durations longer than 200 ms [4, 15].

For a different arc duration or distance from the arc, the normalized incident energy can be converted into the actual incident energy by using expression (1) [4, 15].

$$E = C_f\, E_n\, (t/0.2)\, (610^x/D^x) \qquad (1)$$

Where E is the incident energy (cal/cm$^2$), $C_f$ is 1.0 for voltages above 1 kV or 1.5 for voltages at or below 1 kV, $E_n$ is the normalized incident energy, t is the arc duration (s), D is the distance (mm) and x is the distance exponent [4]. Independently, without place to doubts it can be affirmed that for time durations shorter than 10 ms, the energy is constant, for what can be extrapolated with a straight line of -2 constant slope or by using the values expressed directly in $A^2s$.

It is incorrect the use of the let-through (peak or crest) current graphics to determine the equivalent rms current. The elsewhere presented procedure is as follows: entering to the mentioned graph with the fault current, moving vertically the limited crest value is obtained and dividing it for $\sqrt{2}$ gives what is denominated rms equivalent. The mistake is to consider that the coefficient $\sqrt{2}$ is valid in this application, but the coefficient is only applicable to transform from crest to rms values on sinusoidal waves, and this wave is more triangular than sinusoidal. If it is wanted to find the true rms value, it should be applied the analytic expression of definition of rms value. For it the let-through current curve (maximum let-through values) is not directly applicable to this coordination study. The solution roots in the application of the specific energy and virtual time concepts, methodology used from many years for the extension of the fuse TCC for time durations shorter than 10 ms [11].

## CONCLUSIONS

It is concluded that the consideration of the arc consequences and to carry out an appropriate coordination study among arc control elements are broadly justifiable due to the substantial personnel risk reduction. The high breaking capacity fuse in spite of being an overcurrent protector is a suitable protection device for the personnel protection against arc-flash hazard. The use of the relation between let-through specific energy and incident energy is a useful tool for the coordination study for the arc-flash personnel protection. The sub-cycle fuse operation characteristic of keeping constant the pre-arc and arc specific energy is a very useful advantage for the control of the incident energy. For longer arc durations the TCC can be used.

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