OVERCURRENT PROTECTION OF CABLES BY FUSES: CONSIDERING LIFE LOSS AND M-EFFECT

Juan C. Gómez, Gabriel N. Campetelli, Marcelo A. Basilico, Marcos Felici.

National University of Rio Cuarto, Engineering Faculty, (IPSEP)
Ruta 36, Km. 601, (5800), Río Cuarto, Córdoba, ARGENTINA
Telephone / Fax: 54 358 4676171 or 54 358 4676251
Email: ipsep@ing.unrc.edu.ar

Abstract:
A methodology to be used in the studies of low voltage cable protection by fuses has been developed. The procedure includes the cable life loss calculation following Arrhenius law and the estimation of the fuse M-effect diffusion. The method is applicable for steady state loads as well as cyclic or transient calculations, considering load intervals of 5 minutes and taking account of the environment temperature changes, for example in sinusoidal way. The pre-load conditions for both elements can be included in the calculation. The M-effect behaviour low was experimentally determined, being the best one the exponential with the coefficient as temperature function and a time proportional exponent. Such law was applied to the calculation of fuse resistance under variable current density; being determined a critical resistance value, which is a reversibility limit. The experiments included oven M-effect diffusion under constant temperature and fuses low current melting for times between a few hundred seconds and several hours. The comparison between the experimental and analytical results is good which confirm the applicability of the proposed law. The calculation needs the knowledge of some fuse constructive characteristics, which can be supplied by the fuse manufacturer or determined by very simple tests. The methodology is of very easy use for most of the practical cases, allowing the study of cable protection for overloads inside the M-effect operation zone.

Keywords: Cable, HBC Fuse, protection, overload, short-circuit,

1 - INTRODUCTION

The protection of conductors and electric cables is one of the topics less analysed in the specific bibliography, giving the impression that the same one was already out. In spite of it, our experience indicates that the professionals involved with the topic meet with too much frequency in front of damaged conductors, for inadequate performance of the protection, due fundamentally to the ignorance of the requirements to complete for the same one.

The cables are elements classified as of high time constant whose real meaning is that they possess considerable capacity to support overloads, allowing in such a way to overcome conditions of emergency of the system. Obviously that such a capacity possesses a limit that should be kept in mind by the protection, being a normal practice the exploitation of such an ability not only in emergency but even during the load pick hours.

It should be had in mind that the deterioration of the cable, originated in the electric current takes place exclusively for high temperatures during long times. In other words, a conductor possesses a certain useful life (for example 20 to 40 years according to the type), with a load state generally called rated current. If the conditions of electric load are but high a consumption of useful life takes place to bigger speed and the inverse one its durability extends.

For it the good protection would be that that measures temperature indicating the operating time, but due to economic and technical reasons, in the great majority of the cases the protection acts on the base of the current - time relationship. In this work it will be analysed the characteristics of the protection of cables exclusively using fuses, be already of high rupture capacity like of expulsion.

The protection is studied from two aspects, as it is conductor internal or external fault, if it is external, the protection of the cable acts like back-up to the corresponding to the failed element, should operate before deterioration takes place in the cable for it protected.

The treatment conducive to the selection of the protection should be begun once the characteristics of the cable and the installation conditions are perfectly known.

There are several calculation programs that allow to determine the conductor load capability in function of the installation conditions, indicating in some cases the form of protecting them, procedure that doesn't allow to keep in mind special states of load neither to give consumption of useful life. [1]

2 - CABLE STUDY

2.1 - Overload and short-circuit capability

The characteristics of the current cables have improved notably in the last years, nevertheless the catastrophe risk continues being important, and neither they are exempts of damage for overheating caused by overcurrent and short circuits.

2.1.1 - Steady state or slight overload

The protection is made on the base of the consumption of useful life, using for it the modified expression of the law of Arrhenius. Such a principle considers that the driver can be used to his maximum temperature of work during all his useful life, consuming it in a regular form. Also, the increment of the temperature in 8 ° C reduces its life in half and a decrease of temperature in same value duplicates the life of the cable. [2]

The equation of the law is the following one:

$$C_v = \frac{1}{2^{\left(\frac{\theta_a - \theta_n}{8}\right)}} \qquad (1)$$

Where:

C_v = consumption of life in p.u.

θ_a = Temperature reached in °C

θ_n = Work temperature or continuous regime in °C

The acceptable temperatures for the most important types in cables, vinyl policloride (PVC), polyethylene thermoplastic (PE), cross linked polyethylene (XLPE) and etilen-propilen rubber (EPR), are shown in Table 1.

Table 1: Acceptable temperatures

Tempera-ture	Steady state	Emergency overload	Short circuit
Type		t <100 hs./year, t<500hs./life	Time < 5 s
	° C	° C	° C
PVC ≤ 300mm^2	70	100	160
PVC > 300 mm^2	70	100	140
PE	75	90	150
XLPE	90	130	250
EPR	90	130	250

A differentiation should be made in the study, when cables of low and medium voltage are considered. Firstly, in medium voltage the cables usually possess a copper electrostatic screen. The word shield is used when the screen also has as purpose to protect to the cable of the external electric influences. This gives a path to earth for the fault current, with their rising limitation of temperature - time, should keep in mind that most of the faults in cables is or they begin as monophasic. [3]

2.1.2 - Short circuit solicitations

The short circuits cause a very intense heating in the cables for effect of the heat generated in the conductor. Due to the short time since the fault settles down until the moment in that this should be interrupted, we can suppose that all the generated heat is used in elevating the temperature, we consider for it an adiabatic phenomenon, valid supposition until times of 5 seconds.

The expression corresponding to the adiabatic process, is the following one:

$$v.C\ d\theta/dt = r\ i^2 \qquad (2)$$

whose solution is:

$$(I/s)^2\ t = C/(\rho.\alpha)\ \ln((\theta_2 + 234)/(\theta_1 + 234)) \qquad (3)$$

Where:

I = current in A.

s = section in mm^2.

t = time in s.

C = specific heat in J/°C mm^3.

ρ = specific resistivity ohm / mm.

α = resistivity variation with the temperature in 1 / °C.

v = volume in mm^3

θ_1 = initial temperature in °C

θ_2 = maximum temperature allowed in °C

If we consider the cable (screen or armour) working to a temperature θ_1 and knowing the values of the conductor's constants (copper, aluminium, etc.), we can calculate the time necessary t to elevate the temperature at θ_2, when the current has a value I, using the mentioned expression. The equation allows the determination of the times so much for conditions of cold conductor like for any load state, even overload.

For example for a conductor isolated in XLPE, considering preload of 100%, the expression given by the maker is:

$$I\ (A) = k\ S\ t^{0.5} \qquad (4)$$

With the section in mm^2, the time in s. and the constant k similar to 143 for copper conductor, 94 for aluminium one and 128 for copper screen.

There is a very precise work, which considers to the mentioned magnitudes, resistivity, thermal conductivity, longitude, density and heat specific variables with the temperature in quadratic form, not being justifiable its complexity for normal cases. [4]

If the corresponding temperatures are placed for nominal work and supported maxim, together with the conductor cross section, the current - time expressions become values of constant specific energy, that is to say, I^2t = constant. Such a value can be traced in the graph current - time of the protection device, being represented by a straight line with slope equals to minus two (-2) whose validity extends only until times of 5 seconds.

According to the short circuit current in the installation place, the times of the current limiting fuse operation will be different, should use in the equations the values corresponding to the sub-transient asymmetric short circuit one when the performance is in the order of less than 100 ms., using the permanent value of the current if the device takes more than the given time.

2.1.3 - Rigorous overload solicitations

This problem originates in the excess of conductor connected loads, increase of the consumption, openings of rings, transfer of loads, etc., producing a phenomenon different to the one studied previously. The thermal capacity of the cable is important for what this overload can be allowed during considerable times, for which the supposition of adiabatic regime is not any more valid. The calculation is but complex, being been able to make by means of some of the available analytic tools, like finite differences, finite elements, etc. or using the expressions given in the Standards.

The standard ANSI/IEEE n° 242, Chap. 8, it specifies an equation that allows to determine the maximum current of the cable in function of the time, for any preload state, applicable from slight overloads until short circuits.

$$\frac{I_E}{I_z} = \frac{(\theta_E-\theta_o)/(\theta_z-\theta_o) - \left(\frac{I_o}{I_z}\right)^2 e^{-t/K}}{1-e^{-t/K}} \cdot \frac{230+\theta_z}{230+\theta_E} \qquad (5)$$

Where:

I_E = cable emergency load
I_o = cable preload current
I_z = cable rated current
θ_E = cable load emergency temperature
θ_z = cable normal load temperature
θ_0 = ambient temperature
t = time after the overload's outburst in hours
K = constant of time of the cable in hours

The value 230 is really an average of 234 corresponding to the copper and 228 of the aluminium.

The time constants can be defined in the following way: [5]

0.5 small cables in air
1.0 cables of medium or small size in air or not directly buried
1.5 big cables in air or directly buried small cables
2.5 direct and not directly buried medium cables
4.5 big buried cables
6.0 big directly buried cables

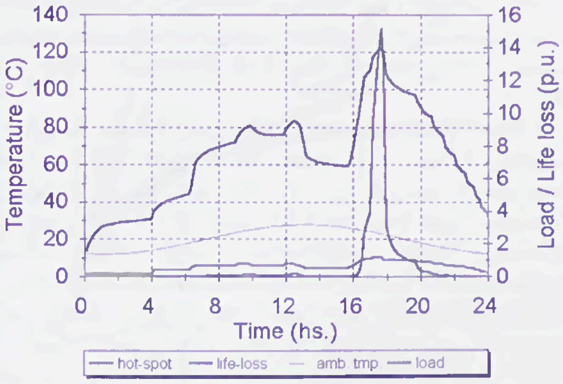

Figure 1, Cable life loss

The given expression allows building the cable time - current characteristic curve, which can be directly compared with the homologous one of the protection device.

2.2 - Cable life loss calculation

The elevation of temperature of the cable can be determined by means of the application of the exponential expression whose final value is proportional to the current squared, its time constant takes the previously given suitable values. Knowing the law of variation of the ambient temperature, the load state and the time constant, the cable temperature can be easily calculated along the under analysis period of time. Applying the law of Arrhenius, the consumption of useful life in the under study interval can be predicted. In the Figure 1 the carried out work is shown.

3 - FUSE STUDY

The protection of the cable on the part of the fuse in the area of rigorous overloads and short circuit only means the comparison of the characteristic curves, on the other hand when it is a light overload, it is necessary the employment of the concept of loss of useful life. The reaction of the fuse in front of those small overloads is based on the M-effect that will be studied next.

3.1 - M-effect diffusion

In the usual materials of fuse elements, copper and silver, the previous temperature to the arc establishment in the case of overload can reach the 1080 and 960 °C respectively, reducing the thermal differences and thus complicating the energy extraction. The solution to the one mentioned inconvenience was achieved in 1939, with the incorporation of the denominated M-effect, presented by Metcalf. [6]

Such an incorporation consists on the adding of a low melting point material deposit, with what descends the temperature of the filler in the moment of arc initiation, to less than 250 °C. This addition allowed to extend the performance field in front of slight overloads, until values so low as 1,2 times its nominal current, diminishing the heating to steady state regime and simultaneously reducing the power loss.

The complete operation of the fuse at the present time can be calculated by means of the application of analytic models of enough complexity, what allows the investigator and professional of high specialisation to achieve extremely reasonable approaches. Unfortunately the handling of calculation tools and modelling as powerful as they are the finite differences, finite elements, TLM, etc. is not within reach of the normal user.

The modelling of the diffusion process will allow to verify the protection against overload of power equipment in general and of cables in particular, especially in those cases in that the circuit is subjected to recurrent loads.

Independently of the number of section reductions and of the restriction relationship (quotient among shoulder and restriction dimensions), the maximum temperature takes place in the central area of the fuse, because the main one via for the dissipation it is through the extreme contacts. It is in fact in this central area where the material of low melting point is deposited (M-effect), usually tin, lead and cadmium alloys whose melting temperatures are function of the alloy, being between 170 and 200°C. [7].

When the M-effect reaches the melting temperature, it dissolves the bases material (fuse element), either copper or silver, in way of forming an amalgam with more resistivity and with effect initiator, unchaining an accumulative process that eroded the metal bases increasing its resistance and generation of heat until the total melting and consequent electric arc start.

In the case in that the quantity of liberated energy is not enough to liquefy to the M-effect, the breakup process doesn't take place. If there are load picks or high recurrent loads, it can begin the breakup and to advance for stages, until the fuse is melted with even smaller currents that its rated value, process that is denominated ageing. [8].

3.1.1 - Behaviour under steady state conditions

The fuse is composed of very varied materials with different thermal constants, however the heating and cooling processes can be assimilated to the heating of a homogeneous body, provided the temperatures of melting of the M-effect is not overcome [9].

For it, the fuse element average temperature responds to an exponential law fixed for:

$$T = T_f \left(1 - e^{-t/\tau} \right) \qquad (6)$$

Where:

T_f = reached final temperature.

t = time.

τ = fuse thermal time constant.

The variation of the fuse resistance, experimentally determined in a heating test, based on the measurement of the voltage drop with constant current, follows a similar law to the mentioned equation, therefore one can affirm that the resistance is a trustworthy indication of the temperature average of the fusible element. [10]

Starting from the graph obtained experimentally, the values of "time constant" and "final temperature" can be determined, this last one proportional to the value of the squared current density. Such values allow to predict the temperature changes and thus the average element resistance, when the fuse is subjected to preload cycles, loads, cooling, etc..

The explained method allows studying the behaviour when the fusible element doesn't possess effect M, determining the temperatures, resistances and voltage drop.

Without the M-effect, anything prevents that the temperature in the hottest point in the fuse reaches the melting point of the copper or silver according to the case, that which will damage to other components of the circuit, like they are the fuse holder, connection conductors, protected device, etc.. [9]

3.1.2 - Behaviour during the dissolution

The break-up begins when being overcome the M-effect melting temperature. In order to be able to connect the simple model previously explained to the break-up conditions it is required to know the relationship among the external magnitudes: voltage drop and current, with the interior temperature of the hottest fuse element point that is in fact where the deposit of low melting point is placed.

This knowledge will indicate if the break-up process has begun, being to determine like it progresses and that way is affected by overload's conditions.

3.2 - Experiments

The study of the diffusion process was made in two ways, firstly by testing on samples fuses operated with overloads of until 200% of the nominal load and later on determining the penetration depth in function of the time and temperature.

3.2.1 - Fuse samples

As the objective it is to develop a simple model and of easy application, fusible samples so similar were built those of industrial use as it was possible, type VDE 0636, class gL, size 1, 500 V with rated current of 160 A.. [11]

The fuse in if it consists of a steatite made ceramic body, copper knives, aluminium lids, copper ribbons 99,9% and quartz sand as filler material of grains among sieves 30 and 50 (ASTM standards). The low melting temperature deposits that was applied to 85% of the samples it was carried out using an tin-cadmium alloy 80/20, welded on the bases element by using a butane gas torch.

3.2.2 - Fuses low current operation

As first measure the internal resistances of the samples were determined, using the voltmeter - ammeter method whose average value was 4,45 E-04 + / - 0,05 E-04 ohm.

The fuses were installed in the fuse holder, located in vertical form, connected to copper cables, with dimensions responding to the mentioned standards. Constant loads between 130% and 200 % were applied, allowing their stabilisation with the ambient temperature or waiting the operation of the fuse.

During overload's processes the voltage drops were measured in function of the time, with times of sampling inversely proportional to the currents, in order to be able to determine the heating and later diffusion as they processes.

3.2.3 - Oven diffusion

Was carried out on samples built with copper ribbons of uniform cross section, purity 99,5%, with the following dimensions: length 60 mm, wide 18 mm and thickness of 0,1 - 0,2 and 0,3 mm. In the central part of the ribbons, the alloy of low melting point (tin-cadmium 80-20) was deposited in cylindrical form of 5 mm of diameter. The process of fixation of the material was carried out using electric solder torch. The samples built in such a way underwent heating in electric oven, with constant temperature (maintained +/- 1 °C), remaining in the oven different samples during growing times that freeze the phenomenon when being extracted. The process was studied for temperatures between 220 and 305 ° C, with times being increased of 10 in 10 minutes. The samples treated in this way were injected in resin. The test samples became polished until reaching the mirrored surface, by means of the employment of abrasive with sizes from 200 up to 800 (ASTM), being made a finished with alumina. Later on the diffusion depth was measured by means of a metallograpic microscope having a magnification of 200, being studied two hundred samples approximately.
In order to check the statement that the penetration is interrupted when the temperature is lower down, remaining without being restarted until the maximum previously reached temperature is overcome, penetration cycles were made with three to five samples in simultaneous form, retiring some, reinserting them later on. The result confirmed the previous enunciated one.

3.3- Results

The Figure 2, shows the experimental values of voltage drop during heating - melting tests with 220 V of a gL type fuse of 160 A., using copper fuse element, with ambient temperature of 25 °C. It is experimentally proven that the voltage drop and the average resistance (directly related with the temperature) they follow a law like the one shown in the Figure, which corresponds to a series of fuses without any preload and under overloads of 137, 156, 169, 175, 181 and 187%.

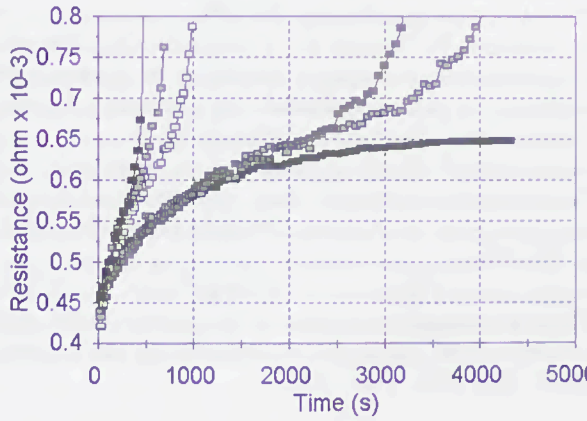

Figure n° 2
Resistances increase for diffusion

From the graph the value of the resistance limit can be deduced that is in the order of 0,65 mohms that correspond with the maximum temperature before the diffusion initiation, 177 ° C.
The penetration depth in function of the time, for variable oven temperatures, is shown in the Figure 3. In the Table II the coefficients and the average quadratic errors of the equations are transcribed that approach the curves of Figure 3, where it can be proven the law of exponential variation of the break-up phenomenon.

$$P = a \cdot e^{b.t} \qquad (7)$$

Table II
Coefficients of the exponential equation

Temperature	Coefficients		R^2
° C	a	b	
220	10.7	0.0053	0.9886
235	10.1	0.0066	0.9878
265	6.7	0.0063	0.9856
280	12.3	0.0062	0.9348
290	13.6	0.0067	0.9892
305	17.4	0.0074	0.9948
average		0.0064	0.9801

The employment of potential equations to the experimental results gives bigger errors, being the exponents variable between 0,45 and 1, that that partly coincides with other authors' results. [9], [10]
In order to verify the compatibility from the experimental determinations of diffusion to constant temperature and elevation of the resistance in function of the time, it was proceeded to calculate the voltage drop incorporating inside of the exponential heating equation, the variation of current density in function of the penetration expression deduced previously.
In the Figure n° 4, the analytic values are shown jointly with the experimental ones for the case of current of load of 187%.

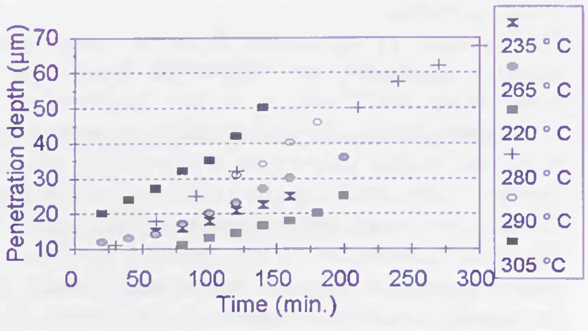

Figure 3, Diffusion as time function

The obtained coincidence is enough for our objective, in case it is wanted to improve it the increase of generation of heat by the variation of the resistance with the temperature could be included. Such an improvement implies a series of analytic complications.
With the shown results, it is possible the building of a model that simulates the behaviour of the fuse, under conditions variables of temperature, preload and overloads.

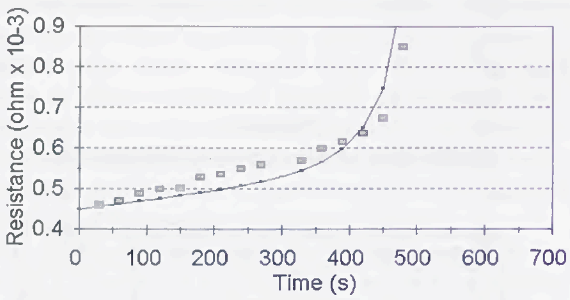

Figure n° 4
Analytic and experimental comparison

4 - CONCLUSION

By means of the application of the proposed methodology, the loss of useful life of the conductor can be determined as function of the temperature and time of work, being in hands of the operator of the system the determination of the acceptable value of consumption of life. The control of consumption of life can be left to the protection with fusible whose model of long time indicates the allowed duration of the one mentioned overload.
In what concerns to the fuse modelling, it can be affirmed of the existence of a resistance or voltage drop limit values, starting from which begins to be noticed the diffusion, overcome the one which at one time long or short, depending on the intensity of applied current, the fuse will operate. This value represents an irreversibility limit that turned out to be 0,65 mohms in our case example, the one that can be calculated easily by means of the resolution of the typical equation of heating, in function of the time constant, preload and overload values.
The variation of dissolution depth or penetration to constant temperature are exponential function of the time whose coefficient is in turn function of the temperature, being the independent exponent of the same one. As the temperature it is gradually increased the dissolution speed it is also increasing, as function of the temperature and depth (or lapsed time).
The direct introduction of this variation law inside the term of generation of heat of the heating equation, gives for result an enough approach for most of the calculations of protection with fuses.

The law of variation of the dissolution, result of the M-effect allows the development of a model that determines the times of operation of fusible H.B.C. under overloads from the minimum one that causes the melting until the maxim of performance of the M-effect, jointly with the prediction of the ageing caused by recurrent overloads, permanents or not, being able to keep in mind the ambient temperature and the preload state. The method offers the answer about the behaviour of the fuse, in form similar to the way in that the cable overload studies, therefore the times of performance of the fuse can be determined to be compared directly with the ability of supporting such an overload on the part of the conductor in study. For their use it is only required to know the characteristic constants of the process which can be determined starting from simple experiments. Such values, cable and fuse time and heat generation constants, and fuse diffusion constant, can be given by the maker as catalogue data, in such a way that the user can get quickly into such an information.

References

1.- Pirelli Cabos S.A., Dimensionamento de conductores elétricos, Makron books, Brasil, 1994.
2.- Naot,Y (1984): How far is an insulated conductor protected by a fuse. 2nd ICEFA 1, 87-94.
3- IRAM 2178-1990, Cables de energía aislados con dieléctricos sólidos extruidos para tensiones nominales de 1,1 kV a 33 kV.
4.- Morgan,VT (1971): Rating of conductors for short-duration currents. Proc. IEE 118, 555-570.
5.- IEEE Std. 242-1986, Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems, New York, Sixt Printing, 1994,
6.- Metcalf, A.W.; A new fuse phenomenon; BEAMA Journal, Vol. 44, 1939, pp. 109-112.
7.- Hofmann, M.; Experimentelle und rechnerische Untersuchung von Ansprechkennlinien und Alterungsvorgangen bei Sicherungsscchmelzleitern; PhDTesis;1987.
8.- Daalder, J.E., Kulsetas, J. y Rondeel, W.G.J.; Aging in fuses with M-effect; Fourth Int. Symp. on SAP, Lodz, Poland, September 1981, pp.295-299.
9.- Ordoqui, E., Zorzan, C., Campetelli, G. y Gómez, J.C.; Efecto de la precarga estable en la respuesta de fusibles de alta capacidad de ruptura; Revista Electrotécnica, Mayo-Junio 1994; pp. 85-89.
10.- Rondeel, W.G., Kulsetas, J. y Bodsberg, K.; Dimensioning criteria for fuses with M-effect; Fourth Int. Symp. on SAP, Lodz, Poland, September 1981, pp.289-294.
11.- VDE 0636-DIN 57636, Niederspannungssicherungen NH system, Kabel und Leitungsschutz bis 1250 A und 500 V/440V sowie 660V., Mai 1984. Teil 1, 21/ 22.