Study of the behaviour of a n-metal cable screen subject to an adiabatic short-circuit

Jose María **DOMINGO CAPELLA;** Grupo General Cable Sistemas SL, Spain, jmdomingo@generalcable.es

ABSTRACT

This paper presents a method to calculate the effects of a short circuit under adiabatic conditions in a cable screen which is connected in parallel with other conductor components with close concentric geometry, such as metallic armours or metallic barriers for radial obturation.

KEYWORDS

Short-circuit calculation, cable screen, IEC 60949, cable design.

INTRODUCTION

The standard IEC 60949 *"Calculation of thermally permissible short-circuit currents, taking into account non-adiabatic heating effects"* considers only one current carrying component to determine the admissible fault current and duration for a given cable design, as can be seen in the expression found in its clause 3 (page 9 of the document). The Amendment 1 of this standard indicates the possibility of taking into account several carrying conductor components when they are connected in parallel, distributing the fault current among them in inverse proportion to their resistances.

This presents a problem whose resolution is not obvious, since components made of metals with different electrical resistivities, temperature coefficients and heat capacities will grow their respective temperatures and resistances at diverse rates. Consequently, during the fault time the proportion of current carried by each single component will be in constant evolution, leading the whole screen to a situation that will diverge from that obtained assuming fixed current ratios.

The lack of a clear procedure showing how this calculation should be made leads very frequently to dimension one of the components to withstand alone the entire fault current. This results into cables that are more expensive, and also a little heavier than necessary. Additionally, a design optimisation would reduce the power losses when the cables are installed in solid-bonding configurations, due to smaller induced currents in the screen.

This study first shows that the expression of the clause 3 of the standard can be deducted from physical laws. And then it proposes using the same physical laws to solve the case of several conductor components working in parallel. The result is an analytical expression whose exactitude has been checked with a numerical algorithm that generates a sequence whose limit is the exact solution of the problem. The equation found in the point 3 of the standard is a particular case of the solution of the "n-metal" problem.

The main limitation to this study is the assumption of concentricity between all the components involved in the calculation, so it should not be used for taking into account the common armour of three core cables, for instance. This is due to the fact that the mutual inductances between the conductor and the screen and other components connected in parallel have not been considered, and in an eccentric configuration they will not be compensated, thus altering the distribution of the current between the different metallic components.

EXPRESSION IN POINT 3 OF IEC 60949

The expression found in the standard for the calculation of the effects of an adiabatic short circuit on a single current carrying component can be deducted from physical laws.

Taking:

- The equation of the adiabatic rise of temperature in a conductor due to the Joule's law (energy balance):

$$I^2 R' = S \times 10^{-6} \times \sigma_c \frac{d\theta}{dt}$$

  where:
  - t is the time (s)
  - I is the short-circuit current (A)
  - R' is the DC resistance per unit of length of the conductor component (Ω/m)
  - S is the geometrical cross-sectional area of the conductor component (mm²).
  - σ_c is the volumetric specific heat of the conductor component at 20°C (J/K·m³). It is assumed that this parameter do not experience relevant variations in the range of temperatures studied.
  - θ is the temperature of the conductor component.
- The expression that links the resistance of a conductor component (per unit of length) with its temperature:

$$R' = \frac{\rho_{20} \dfrac{\theta + \beta}{20 + \beta}}{S \times 10^{-6}}$$

  where:
  - ρ_{20} is the electrical resistivity of the conductor component at 20°C (Ω·m).
  - β reciprocal of temperature coefficient of resistance of the conductor component at 0 °C (K).
- And the definition of the parameter K taken from point 3 of IEC 60949:

$$K = \sqrt{\frac{\sigma_c(\beta + 20) \times 10^{-12}}{\rho_{20}}}$$

A system of equations is obtained, and its solution is:

$$I_{AD}{}^2 t = K^2 S^2 \ln\left(\frac{\theta_f + \beta}{\theta_i + \beta}\right)$$

where:

- t is fault duration (s)
- I_{AD} is the short-circuit current (root mean square over duration) calculated on an adiabatic basis (A).

$$I_{AD} = \sqrt{\frac{1}{t}\int_0^t I^2 \cdot dt}$$

- *i and f* are subscripts that refer to the initial and final stages of the short circuit, respectively. θ_i is supposed to be known, as it can be calculated through IEC 60287.

This solution is the general form of the adiabatic rise formula found in IEC 60949.

SOLUTION OF THE N-COMPONENT CASE

In the case of several conductor components connected in parallel, the system of equations is more complex, as there will be one differential equation for each component.

The initial system of equations that must be solved when several components share the fault current is formed by:

- The expression that links the resistance of each current carrying component (subscript *j*) with its temperature:

$$R'_j = \frac{\rho_{j20}\dfrac{\theta_j + \beta_j}{20+\beta_j}}{S_j \times 10^{-6}} G_j$$

where G is the geometry factor, defined as the quotient between the DC electric resistance per unit of length of the component and its DC electric resistance per unit of length of cable. When only one current carrying component is considered this parameter has no influence on the result, but in the presence of other conductor components, the current distribution will depend on this parameter. Depending on the construction of the conductor component it can adopt the following values:

- In components with straight geometry, such as metal foils longitudinally applied or tubular sheaths, this parameter will always be 1.
- In components formed by helically applied wires, either isolated or braided this parameter will be:

$$G = \sqrt{1 + \left(\frac{\pi \cdot d}{P}\right)^2}$$

where:

  - d = mean diameter of the wire screen or armour (mm)
  - P = helix pitch of the wires (mm). In the case of significant uncertainty with this value, it has to be selected the value which generates the most unfavourable final result.

- In components formed up by helically lapped tapes, the inter-turn and inter-tape contact cannot be predicted or guaranteed, especially after some time in service or when the cable is bent. It is then necessary to assume that the current will flow around the helix. Therefore, the cross section of the component must be calculated as the product of the quantity of tapes with their width and their thickness, and the geometry factor can be calculated as in the case of helically applied wires.
- For other non-straight configurations, such as corrugated metal sheaths, the geometry factor must be calculated in accordance with the above definition.

- The energy balance in each component :

$$I_j^{\,2}\frac{R'_j}{G_j} = S_j \times 10^{-6} \times \sigma_{\mathrm{cj}} \frac{d\theta_j}{dt}$$

- The inverse proportion existing between the partial currents in the conductor components and their resistances,

$$I_1 R'_1 = \ldots = I_j R'_j = \ldots = I_n R'_n$$

- And the fault current as the sum of the partial currents:

$$I = \sum_{j=1}^{n} I_j$$

The solution of this system of *3n* equations (where *n* is the number of current carrying components involved) is:

$$I_{AD}^{\;2} t = \sum_{j,k=1}^{n} S_j K_j S_k K_k \ln \frac{R'_{jf}\, S_j K_j + R'_{kf}\, S_k K_k}{R'_{ji}\, S_j K_j + R'_{ki}\, S_k K_k}$$

where subscripts *i* and *f* refer respectively to initial and final stages of the system fault.

APPLICATION OF THE SOLUTION

Calculation of the admissible fault current or duration

The performance of the screen is limited by the first component that reaches its maximum admissible temperature. It can be identified as that with the smallest value for this expression:

$$\left[\frac{KG\rho_{20}10^6}{(20+\beta)}\right]^2 \left[(\theta_{\max}+\beta)^2 - (\theta_i+\beta)^2\right]$$

where θ_{max} is the maximum admissible temperature for the conductor component under fault conditions. It must be determined in accordance with IEC standards 60724, 60986 or 61443, depending on the nominal voltage of the cable.

Let *A* be the liming element. Once it has been identified, it is known that its final resistance will be:

$$R'_{Af} = \frac{\rho_{A20}\dfrac{\theta_{A\max} + \beta_A}{20+\beta_A}}{S_A \times 10^{-6}} G_A$$

Then, the final resistance of any other current carrying component *j* can be calculated with this expression

$$R'_{jf} = \sqrt{\frac{S_A^{\,2} K_A^{\,2}}{S_j^{\,2} K_j^{\,2}}\left(R'^{\,2}_{Af} - R'^{\,2}_{Ai}\right) + R'^{\,2}_{ji}}$$

and substituted in the solution of the system of equations.

Calculation of the final temperatures given the fault parameters and screen design

The calculation of the final temperatures requires an iterative process. We can take the following expression:

$$I_{AD}{}^{2} t = \sum_{j,k=1}^{n} S_j K_j S_k K_k \ln \Psi_{jk}$$

where Ψ_{jk} is:

$$\Psi_{jk} = \frac{\sqrt{Q + R'_{ji}{}^{2} S_j{}^{2} K_j{}^{2}} + \sqrt{Q + R'_{ki}{}^{2} S_k{}^{2} K_k{}^{2}}}{R'_{ji} S_j K_j + R'_{ki} S_k K_k}$$

It is necessary to find the value of Q that equals the two sides of this equation with enough precision. Then, the temperature of any component *A* after the fault can be calculated as:

$$\theta_{Af} = \sqrt{Q\left(\frac{20+\beta_A}{10^6 \rho_{20A} K_A G_A}\right)^2 + \left(\theta_{Ai}+\beta_A\right)^2} - \beta_A$$

Screen dimensioning

In the case that a given *n-1* component screen design is unable to withstand the required fault, the cross sectional area of the additional necessary component *n* can be calculated through the following expression:

$$S_n = \frac{\sqrt{\Phi} - \sum_{j=1}^{n-1} S_j K_j \ln \frac{R'_{unf} K_n + R'_{ujf} K_j}{R'_{uni} K_n + R'_{uji} K_j}}{K_n \ln \frac{R'_{unf}}{R'_{uni}}}$$

where:

- R_u is the DC resistance per unit of length of cable of one square millimetre of the component *j*:

$$R'_{uj} = R'_j S_j = \frac{\rho_{j20} \frac{\theta_j + \beta_j}{20+\beta_j}}{10^{-6}} G_j$$

- $$\Phi = \left(\sum_{j=1}^{n-1} S_j K_j \ln \frac{R'_{unf} K_n + R'_{ujf} K_j}{R'_{uni} K_n + R'_{uji} K_j}\right)^2$$

$$+ I_{AD}{}^{2} t \ln \frac{R'_{unf}}{R'_{uni}}$$

$$- \ln \frac{R'_{unf}}{R'_{uni}} \sum_{j,k=1}^{n-1} S_j K_j S_k K_k \ln \frac{R'_{ujf} K_j + R'_{ukf} K_k}{R'_{uji} K_j + R'_{uki} K_k}$$

Picture of a cable with copper wire screen and aluminium foil for radial obturation.

EXAMPLE OF CALCULATION

This point shows a practical case of application of the proposed method. We can consider the calculation of the maximum allowable fault current with a 0.5 s duration in the screen of a cable with:

- a copper wire screen formed by 59 wires with 1.04 mm diameter, helically applied (helix pitch 430 mm) and mean screen diameter of 65.25 mm.
- an overlapped and longitudinally applied aluminium foil connected in parallel with the copper wires, with a thickness of 0.2 mm and a width of 225 mm.

It is considered for both components an initial temperature of 70 ºC and a maximum of 250 ºC after the fault.

Needed parameters

From table I of IEC 60949:

Parameter	*Cu wires*	*Al foil*
K (A·s$^{1/2}$/mm²)	226	148
β (K)	234.5	228
σ_c (J/K·m³)	3.45 x 10^6	2. 5 x 10^6
ρ_{20} (Ω·m)	1.7241 x 10^{-8}	2.8264 x 10^{-8}

From the definition of the problem:

Parameter	*Cu wires*	*Al foil*
t (s)	0.5	0.5
θ_i (ºC)	70	70
θ_{max} (ºC)	250	250

Calculated with the above information:

Parameter	*Cu wires*	*Al foil*
S (mm²)	50.1197	45
G	1.1078	1
R'_i (Ω/m)	4.5595·10^{-4}	7.5835·10^{-4}

Identification of the limiting component

The expression used to identify the first component reaching its maximum admissible temperature gives a value of 40.856 J·Ω/m^4 for the copper wires and 40.123 J·Ω/m^4 for the aluminium foil. Since the value for the Al foil is smaller, this will be the limiting component. This allows the calculation of its resistance after the fault, and with this parameter it can be obtained the final resistance of the other component (the copper wires screen):

Parameter	*Cu wires*	*Al foil*
R'_f (Ω/m)	7.2154·10^{-4}	1.2164·10^{-3}

Calculation of the admissible fault current

With the use of the solution of the system of equations it is obtained $I_{AD}{}^2 t$ = 1.5011·10^8 A²s. Considering t = 0.5 s it can be calculated I_{AD} = 17.32 kA, which is the solution of the problem.

The final temperature of the aluminium foil is its maximum value: 250 ºC. The value for the copper wires can be calculated from its final resistance: 247.36 ºC.

In this case, the admissible current (adiabatic calculation) if only the copper wires had been taken into account would be 10.91 kA.

ADDITIONAL CONSIDERATIONS

- In the previous example, the aluminium foil turns out to be the first component reaching its maximum temperature. However, the difference in temperature with copper was small and in fact an increase in the helix pitch of the Cu wires can easily invert the situation. In those cases in which there are components with comparatively low conductivity (such as lead) or elements with high geometry factors (such as bronze tape armours with small helix pitch), these components will be far from their limit temperature at the end of the shortcircuit. For instance, in a Cu wires and lead tube configuration, when the wire screen reaches 250 ºC, the Pb sheath is usually in the range of 120 to 130 ºC.
- This fact gives a clue for cable designers: if, for instance, the default design thickness of the lead sheath offers a result that is near to the required value in terms of short-circuit transmission, it can be preferable a slight increase of the cross sectional area of the Pb tube rather than supplementing it with copper wires. Once the first copper wire has been added, all the lead will have to work way under its possibilities. And the needed section of copper to compensate this effect may end in a more expensive cable.

Picture of a cable with copper wire screen, extruded lead sheath and aluminium wire armour

- The non-adiabatic effects, which are not considered in this study, will have these two sources in the case of a composed screen:
  - The heat transmission to non-metallic adjacent materials.
  - The heat transmission between current carrying components when there is contact between them.

  The second source can take a small fraction of the heat generated in the hottest component to the coldest one. The heat transferred will depend on the difference between the two metals and on the surface of contact of them. The temperature difference will be very small in a typical aluminium-copper interface and will present important values only when one of the components in contact is made of a low conductivity metal (such as lead) or has a high geometry factor. As these components, as indicated in the first point, will be far from their temperature limit, this effect cannot be expected to create problems.
- The non-adiabatic factor described in the IEC 60949 standard cannot be applied to the results obtained following this study.

REFERENCES

[1] International Electrotechnical Commission, International standard 60949 (1988) and its Amendment 1 (2008-2009), Bureau Central de la Commission Électrotechnique Internationale 3, rue de Varembé, PO Box 131 CH-1211 Geneva 20, Switzerland.