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Thermal model for current limiting fuses installed in vertical position

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ABSTRACT

This paper presents a new mathematical model developed for the designing process improvement of high voltage current-limiting fuses, which is able to solve the heating process of fuses installed in vertical position.

Once the transient heating process has been solved, this model allows obtaining the values of the power dissipated and the heat transfer coefficients corresponding to the steady state conditions. From these values, the temperature distribution at the surface of the complete fuse is calculated and so, it is possible to verify whether international standards are fulfilled or not.

The new model proposed has been validated by comparison of the numerical values calculated from the model with those obtained by testing real fuses.

1. Introduction

High voltage current-limiting fuses are largely used for protecting against short circuit and overloading in power systems. Fuses allow the flow of current through the circuit while its value is kept below an established limit. If this limit is exceeded, the main components of the fuse, the fuse elements, melt and the current flow is interrupted in order to protect the installation.

The operation of the fuse is always a thermal process where Joule losses and installation conditions play a relevant role as they are responsible for the fuse heating. Besides, the thermal behaviour not only determines the operation of the fuse, but it also establishes the maximum current through the fuse elements during the steady state. Excessive Joule losses may produce overheating of the fuse as well as of other elements in the installation. For that reason, this situation is regulated in international standards in order to prevent damages. That regulation consists on limiting the temperature of the fuse, under the rated current and an ambient temperature of 40 °C [1]. For temperatures greater than 40 °C, due to the existence of high ambient temperatures or caused by the installation of the fuse in an enclosure, it may be necessary to reduce the current flowing through the fuse below its rated value (fuse derating), to comply with temperature limits.

The steady state thermal process in electric fuses has been tackled by different researchers [2–10]. In general, installation conditions are not specifically addressed and so, the thermal performance of fuses fixed vertically is only explicitly considered in [7].

When the fuse is fixed horizontally, the temperature distribution obtained is symmetrical with respect to the fuse midpoint, where the highest temperature is reached. But when, for space reasons, the fuse is fixed vertically, the temperature distribution loses the symmetry. So, although the highest temperature is getting near the midpoint of the fuse, now the temperature reached by the upper cap is greater than the temperature of the lower cap. Therefore, temperatures at the lower cap and at the midpoint can be below the values established by standards, but may not be true with the temperatures at the upper cap.

This paper presents a new mathematical model for the analysis of the steady state thermal behaviour of medium voltage current-limiting fuses, fixed vertically. The model proposed solves the transient heating process of fuses until the steady state condition is reached. Afterwards, a new procedure to calculate the heat transfer coefficients to the environment is included. Thus, it is possible to know the highest surface temperature of the fuse, as well as the temperature reached by both end-caps. Considering those values of temperature the compliance with limits under the rated current, as established by international standards, can be checked.

Additionally, it also makes possible the optimization of the design, because the model proposed allows analysing the effect of changes in the initial design, as well as the simulation of different operation conditions. This way, it is possible to reduce the need of prototypes development and testing. Finally, this paper compares the results obtained with this new model with those obtained from real tests developed by a fuse manufacturer and with those obtained from the finite element method.

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2. Methodology for the calculation of the temperature distribution

Back-up fuses are fuses that must be able to interrupt all currents between a minimum value specified by the manufacturer and the full rated breaking capacity. As many of the current-limiting fuses, which are produced are in the back-up category [11], this work has been focused on back-up fuses with rated voltages from 3.6 kV to 36 kV.

This section describes the methodology proposed to analyze and define the thermal behaviour of the fuse installed in vertical position, once the steady state is achieved. As currents equal or below the rated current are considered, the fuse elements do not melt. The data required to implement this methodology are: ambient temperature, current and voltage rated values, dimensions data and physical properties of the materials used.

The temperature calculation at the outer surface of the fuse constitutes a 3D problem. Because of this characteristic, the complexity of the model increases but some simplifications can be introduced to reduce the difficulty of the problem, making it a 1D problem. These simplifications are:

- As the fuse length is much greater than its diameter, the heat transfer in the radial direction compared with the transmission in the longitudinal direction can be considered negligible to calculate the temperature distribution along the fuse length,
- The fuse length is large enough to neglect the edge effect. So, heat transfer in radial direction can be assumed to calculate the temperature distribution in the different layers of the fuse.

The new model has been developed by tackling the analysis in different phases:

1. Development of the equations governing the heating process of the fuse, until the steady state condition is reached. These equations allow obtaining the Joule losses, the surface temperature at the midpoint of the fuse and its heat transfer coefficient.
2. Achieving the heat transfer coefficients at the upper and lower endcaps.
3. According its materials, division of the fuse in different zones.
4. Achieving the global thermal conductivity for each zone.
5. Determining the temperature distribution along the fuse length.

Each of these phases is described below, with particular emphasis on the calculation of heat transfer coefficients.

This methodology is based on the method proposed by [12] for the analysis of the thermal behaviour of fuses fixed horizontally, but significant modifications must be introduced to take into account the thermal particularities when the fuse is placed vertically because an asymmetry appears in the temperature distribution between the top and the bottom endcaps.

2.1. Modelling the transient heating

As the temperature of the fuse depends on the heat generated by Joule losses, produced in the fuse by the circulating current due to the fuse resistance, the power dissipated by the fuse must be calculated. However, it should be noted that the fuse resistance varies with temperature (1), which is unknown, so the power dissipated is a priori an unknown parameter, which has to be calculated.

$$P(T) = R(T)I^2 \tag{1}$$

As a consequence, to obtain the temperature distribution in the fuse, it is necessary to calculate previously the evolution of the transient process until the steady state, characterized by a constant temperature value. Due to the lower resistivity with regard to other components of the fuse (star-core, porcelain tube, etc.), the fuse resistance can be considered solely due to the fuse elements. Thus, the resistance of the fuse depends on the temperature of the fuse elements (T_f) [13], according to (2).

$$R(T_f) = R_{20} + R_{20}\cdot\alpha\cdot(T_f - 20) \tag{2}$$

where R_{20} is the fuse resistance at an ambient temperature of 20 °C (Ω) and α is the temperature coefficient of the fuse elements (°C^{-1}).

Moreover, the heat generated during the transient process by the current flowing through the fuse elements increases the temperature of every component of the fuse, being also dissipated to the environment [14,15], as it is shown in expression (3).

$$E = \left(m\cdot Cp\cdot\frac{dT}{dt}\right)_{\text{fuse}} + \bar{h}_m\cdot S\cdot(T_p - T_{\text{amb}}) \tag{3}$$

where m is the fuse mass (kg), C_p is the fuse specific heat (J/kg K), S is the outer surface (m^2), T_p is the porcelain tube temperature and $\bar{h}_m$ is a global heat transfer coefficient (W/m^2 K) at the midpoint of the fuse.

According to the real tests, when the fuse is placed vertically, the maximum temperature is reached slightly above the midpoint. As the error is not significant, for simplicity, it has been assumed that the highest temperature is obtained at the midpoint of the fuse.

The change in the internal energy of the fuse during a time interval Δt can be expressed as the sum of the terms corresponding to the change in internal energy experienced by the fuse elements, the quartz sand, the star-core and the porcelain tube. As short time intervals (Δt = 1 min) are considered to represent the evolution until the steady state, it may be assumed that the change in temperature, experienced by the different components of the fuse, is of the same order [12]. On this way, they can be replaced by the change in the temperature of the porcelain tube. So, expression (3) can be written as expression (4)

$$RI^2 = \sum(m\cdot C_p)\frac{\Delta T_p}{\Delta t} + \overline{h_m}AL(T_p - T_{amb}) \tag{4}$$

where A is the cross-sectional area (m^2) and L is the length (m),

Integrating the above expression, the temporal evolution of fuse surface temperature is given by (5).

$$T_p(t) = T_{\text{amb}} + \frac{RI^2}{\bar{h}_m AL}\left(1 - e^{-\bar{h}_m AL/\sum mC_p\cdot t}\right) \tag{5}$$

The resistance value included in (5) depends on the temperature of the fuse elements, according to (2). As a consequence, it is necessary to find a relation between that temperature of the fuse elements and the porcelain temperature. This relation is obtained from the Fourier's law ($Q = -\lambda A dT/dx$) [14,15], taking into account that the heat dissipated from the fuse surface, must reach the surface by radial conduction during the transient period (6).

$$T_f(t) = T_p(t) + \frac{R(t-1)I^2}{2\pi L}\left[\frac{Ln(r_{ip}/r_f)}{\lambda_{qs}} + \frac{Ln(r_{ep}/r_{ip})}{\lambda_p}\right] \tag{6}$$

where r_f, r_{ip} and r_{ep} are the external radius of the fuse elements, and the inner and the outer radius of the porcelain tube (m) respectively.

Once the temperature of the fuse elements at the midpoint of the fuse in the instant "t" has been obtained, their resistance to that temperature is recalculated. Then, the power due to Joule losses and the heat transfer coefficient at the midpoint of the fuse can be calculated.

This iterative process, as it is shown in Fig. 1, is followed until the steady state is achieved. This situation is considered to be reached when the temperature increase is equal or lower than 1 K in one hour.