Analysis of Thermal Phenomena in High-Voltage Fuse-Links Based on Thermovision Equipment

VALER GIURGIU
SC ICPE SA Bucharest
ROMANIA
hvfuses@icpe.ro

COSTIN CEPISCA
Politehnica University of Bucharest
ROMANIA
costin.cepisca@upb.ro

GHEORGHE OARGA
SC ICPE SA Bucharest
ROMANIA
hvfuses@icpe.ro

SORIN DAN GRIGORESCU
Politehnica University of Bucharest
ROMANIA
sorin.grigorescu@upb.ro

LILIANA STEFANESCU
SC ICPE SA Bucharest
ROMANIA
metrologie@icpe.ro

Abstract: - This paper proposes a method for experimental study of the H-V electrical fuses based on the thermal imaging equipments. The detection of fuses temperature by contact methods (RTD and thermocouples) affects the temperature being measured, especially in this case when the resistive element has important geometrical dimensions. The paper analyses theoretical methods for the determination of H-V fuses temperature and results of a thermovision measurement method.

Key-Words: - Fuse-links, high-voltage, temperature measurement, thermovision

1 Introduction
A high-voltage fuse is a simple electrical apparatus and relatively cheap and because of her features it is used in a wide variety of applications for protection against short-circuits currents, for example protection of the motors, transformers or capacitors [1], [2]. High-voltage fuse-links have been developed, in general on the basis of experimental methods, because the processes which govern the operation of the fuse-links are many and very complex. In Figure 1 is an example of the fuse-links for transformer protection.

Fig.1 High-voltage fuse-links \( U_n = 24 \text{kV} \);
\( I_n = 31.5 \text{ A} \) and 40 A.
Since a current-limiting fuse is a "blind" assembly, it is impossible to visually inspect its internal construction after it is assembled. Therefore, small flaws that can occur during the production process could significantly affect the operating characteristic of the fuse.

Resistance measurements can be quite sensitive, but the realities of production impose a broad tolerance on fuse elements. An acceptance test is one which verifies the minimum melt $I^2t$ of the fuse.

A contact temperature measurement method (thermocouples) is used in the laboratory experimental studies, with important errors [3], [7].

Thermal imaging has evolved into one of the most valuable diagnostic tools used for the study of temperature distribution on fuses [4]. Portable infrared (IR) imaging systems scan the fuse surface and instantly convert the thermal images to visible pictures for quantitative temperature analysis. The paper presents results of thermal imaging study of high-voltage fuse-links.

2 Theoretical aspects

Analysis of temperature distribution in the fuse-elements, in the case of an adiabatic process (operation in the case of the short-circuit current), it can be made easily on the basis of the mathematical modelling, but the situation is very complicated in the case of the prearcing times longer than those corresponding with an adiabatic process, when the distribution of the temperature in the body of the fuse-link depends on influence of various component parts, like fine-grain filler (quartz sand), outer isolating tube body, end contacts, connecting cables. (Figure 2).

Figure 3 presents an example of a temperature distribution in the region of reduction section of the fuse-element (silver) in the case of the mathematical modeling in adiabatic regime (finite difference method).

In the case of stabilized conditions, for long times and a cylindrical body of fuse-link, the distribution of the temperature between the radius $r_1$ at temperature $T_1$ and $r_2$ at temperature $T_2$ is governed by the following equation:

$$T_1 - T_2 = \frac{Q}{2\pi k} \ln \frac{r_1}{r_2}$$

where: $Q$ – dissipated energy in the radial direction from fuse-elements, per unit length, $k$ – conductivity of the quartz sand.

If the diameter of the insulating tube is $d$, and the $\Delta T$ is the difference of the temperature between the outer surface $S_e$ of the insulating tube and the environmental medium, then the energy transmitted by convection per surface unity of the insulating tube is given by the equation:

$$Q_c = \frac{\lambda_a m \Delta T (G_r P_r)^n}{d}$$

where:

$\lambda_a$ – thermal conductivity of the air;

$m = 0.54$, $n = 0.125$

$G_r = \beta d^2 \gamma \Delta T / (\mu^2)$ – Grashoff number

$P_r = \mu/gc / \lambda_a$ – Prandtl number

At the atmospheric pressure of 765 mmHg and at 20°C, the air have the following parameters:

$\gamma = 1.164$ kgf/m$^3$  \quad $\lambda_a = 0.0265$ W/(m°C)

$c_a = 0.242$ kcal/(kgf °C)  \quad $\mu = 1.86 \times 10^{-6}$ kgf s/m$^2$

In these conditions, equation (2) becomes:

$$Q_c = 0.01363 \Delta T (G_r P_r)^n S_e$$

If the temperature at the surface of the insulating tube is $T_e$ and the temperature of the ambient air is $T_a$, then the energy transmitted by radiation from fuse-link will be:
\[ Q_r = 5.77 \ c_r \ S_e \ (T_e^4 - T_a^4) \times 10^{-8} \]  

(4)

where \( c_r \) represent the radiation coefficient of the material of the external surface of insulating tube (paint, resin etc.).

For example, in Table 1 are shown measured and calculated values of energy dissipated by convection and by radiation from a fuse-link for motor protection, in the case of temperature-rise testing at rating current of 250 A and withstand testing (sequence no.1-100 cycles of 1h and sequence no.2-2000 cycles of 10 min).

Table 1 – Measured and calculated values for dissipated energy from external surface of fuse-link

<table>
<thead>
<tr>
<th>Testing type</th>
<th>Rating current</th>
<th>Withstand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium temperature-rise ( \Delta t [^\circ C] )</td>
<td>68</td>
<td>32</td>
</tr>
<tr>
<td>( Q_c ) [W]</td>
<td>59</td>
<td>23.4</td>
</tr>
<tr>
<td>( Q_r ) [W]</td>
<td>57</td>
<td>20.4</td>
</tr>
<tr>
<td>( Q_{\text{calculated}} ) [W]</td>
<td>116</td>
<td>43.8</td>
</tr>
<tr>
<td>( Q_{\text{measured}} ) [W]</td>
<td>112</td>
<td>43.52</td>
</tr>
</tbody>
</table>

It can be seen that the difference between measured and calculated values are acceptable, but in practice it is useful to know the temperature distribution in many points of the fuse-link, especially in the case where the temperature-rise obtained by experimental testing is close of the limits established by international norms.

### 3 Measurement method

In Figure 4 there is an example of a circuit for the testing at temperature-rise of fuse-links. There are many possibilities for measuring that temperature-rise in different points of the isolating tube or on the contacts (with thermocouples [3], thermometers etc.), but in the present the best measurement method is a thermal imager, like FLUKE Ti20, for accurate measurements in any points of the fuse-link.

In Figure 5 there are some examples of the results obtained with this thermal imager, in the case of the temperature-rise testing for a fuse-link. That method is very useful, because very much result can be stored and then through the software installed on PC can be extract maximum details. A thermocouple or a thermometer can give the value of temperature in a single point (which can be a point where will not be reached the maximum temperature), on the other hand the imager offer a multitude of values in many points.

![Fig. 4 Scheme and real circuit examples for temperature-rise testing.](image)

![Fig. 5 Measurements of the temperature at the end of the test for a fuse-link type EITp 24 kV/40 A.](image)
In research activity must be achieved detailed analyses, and in Figure 6 is an example of in time analyse, by mean of the possibilities offered by thermovision, utilizing a grid for temperature. Thermographic systems are used for electrical inspections. As electrical connections become loose, there is a resistance to current that can cause an increase in temperature [5],[6]. This increased temperature can then cause components to fail, potentially resulting in unplanned outages and injuries.

4 Conclusion
The thermovision method is very useful in research activity of high-voltage fuses realization, with best results and accurate. By mean of this technique must be performed detailed studies, with very important diminution of the experiments and research time. Windows-based image analysis and reporting software integrated with modern IR cameras allow thermographers to create quick reports, make critical decisions and recommend repair action about the fuse inspected.

References: