Experimental evaluation of the magnetic pressure in thin wire elements during fusion process

Assoc. Prof. Constantinos S. Psomopoulos, Assoc. Prof. George Ch. Ioannidis, Assist. Prof. Stavros D. Kaminaris, Dr. Petros Karaisas

Piraeus University of Applied Science, Department of Electrical Engineering, Egaleo, Greece, cpsomop@teipir.gr

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Abstract

The physicochemical process during the operation of fusible wires under high currents densities presents complicity and seems not to be completely known. According to the related literature, there is magnetic pressure involved in the process during pre-arcing and possibly during arcing periods. In this paper, the investigation of this physical quantity is attempted. The evaluation is carried out using calculations based on measurements of the current and voltage waveforms during fusion process of exploding wires, which are stressed by common industrial power supply directly feed from the network of 50Hz. The measured quantities were the voltage drop and the current during the current interruption process and the total duration of the fusion. Surrounding medium was air and SiO_2 fine granules used in NH fuses, and the magnetic pressure is calculated using typical physical equations. The measurements were conducted using fast digital oscilloscopes connected with computer and the observed phenomena are investigated focusing on the resistivity variation as a result of the high current densities and arc formation. The total time duration (pre-arcing and arcing periods) of the fusion process was measured and the results for different current densities and lengths of the thin wire elements are presented and analysed. The results may support the efforts for better understanding the physicochemical processes during fusion.

Introduction

Fusible wires and electrically exploded conductors are frequently used in fuses that protect the electrical installations of the low and medium voltage distribution network and in a wide variety of power applications. They generally operate either at current lower than of their nominal value or momentarily under excess or sort-circuit currents. During the operation under nominal current or less, the Joule heating produced on fuse element dissipates to the surrounding area of the element and thermal equilibrium is attained after a time period (Barrow et al. 1991; Cheim and Howe 1994; Wright and Newbery 1995; Psomopoulos and Karagiannopoulos 2007; Gounaridis et al. 2014).

For the case of operation under excess or heavy fault currents, the design of fuses is based on the well known fundamental principle that they must interrupt these currents in a very short time period. The phenomena developed are in brief as follows: The increase of the fuse elements resistance causes the temperature to raise rapidly, until the melting point is reached. The latent heat of fusion is produced gradually by the current during the melting time until the material is completely vaporized (Cheim and Howe 1994; Wright and Newbery 1995; Gounaridis et al. 2014). When the material of the element vaporizes, electric arcs struck between the remaining solid parts of the element. This dynamic process gives rise to a rapid temperature increase, while the current decreases rapidly until its flow is interrupted. The fundamental fuse operation has been described extensively in the relevant literature (Vermij 1980; Barrow et al. 1991; Cheim and Howe 1994; Wright and Newbery 1995; Bussière 2001; Psomopoulos and Karagiannopoulos 2002a ,2002b, 2007; Gounaridis et al. 2014).

Even though the related phenomena have been studied in literature, the majority of the research work was executed using typical and standard current pulse generators, while in a few cases, to our knowledge, typical industrial power supply from a typical installation were used. At this point it should be noted that fuselinks actually operate using such types of power supplies and not typical current pulses as in the majority of the experiments which have been conducted so far. In this paper, the investigation of the magnetic pressure development, during the fusion process in thin wire elements simulating fuselinks, operating under industrial power supply of 50Hz, is attempted. Even though international literature focused on fusion process of thin wire elements describe the role of magnetic pressure in the process, no one to our knowledge present experimental data on the subject. In the experimental investigation two environments were used: air and SiO_2 thin granules which are the same with the ones used in practical applications.

Experimental Set-Up and Measuring Procedures

In Figure 1 the simplified schematic diagram of the experimental set-up, for the estimation of the voltage drop across a fuse element under sort-circuit conditions is presented. The voltage source was a common sinus industrial supply with a 1:1 transformer for safety reasons. Thin wire elements, representing the fuselinks, were connected to terminals with appropriate heat and current sink characteristics. An ohmic load of 0.45kW was used to simulate the operation under light load conditions of the circuit (Psomopoulos and Karagiannopoulos 2002a).

The measurements were performed using a digital oscilloscope of a frequency bandwidth of 100MHz and a sampling rate capability of 1GSa/s. During the measurements the sampling rate was set to 100kSa/s per channel and maximum voltage of 16V peak to peak (2V/div). The vertical sensitivity of the instrument is 2mV to 5V/div. Any possible capacitance of the experimental setup (coaxial cables, etc.) can be neglected due to its very low value. Also, all the resistances used presented only ohmic behavior. All measurements were performed on thin cylindrical cooper wire conductors of two main thicknesses of 120um and 140um made from copper 99.99% The lengths for the experimental measurements varied from 25mm to 50mm with a step of 5 mm for each set.

The measured values from the oscilloscope were transferred to a computer used for storage, further processing and analysis. Also, each set of measurements was repeated in order to clarify that the expected patterns reemerged in all initial conditions of the sinus curve.

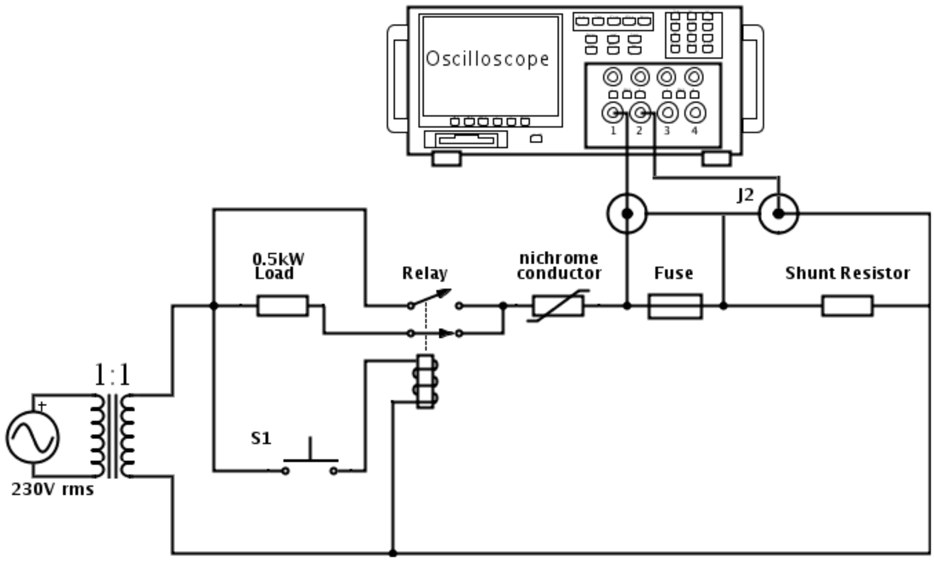

Figure 1. Simplified schematic diagram of the experimental set-up.

Results and discussion

The total time duration and characteristics of a representative fusion process are presented and analyzed. In Figure 2 and Figure 3, a set of measured and calculated magnitudes are presented. In Figure 2, air is used as an insulating material while in Figure 3, SiO_2 is used. Each single measurement has identical lengths and thicknesses of the copper wire.

On top of Figures 2 and 3 the actual *I=f(t)* and *V=f(t)* are presented in a common axis system. In these graphs the sort-circuit's duration, the voltage drop across the element, the current value (impulse and continuous sort-circuit currents) can be clearly seen. Furthermore, the voltage and current waveforms observed on these Figures have the same characteristics as the ones presented in the relevant literature (Vermij 1980; Wright and Newbery 1995; Bussière 2001; Psomopoulos and Karagiannopoulos 2002a, 2007; Gounaridis et al. 2014). Similar characteristics can be observed in spite of the differences in this study (the measurements presented were taken in random positions of the sinus curve of the voltage source). Additionally, magnetic pressure *PB=f(t)* has been calculated and presented in both Figures 2 and 3.

At the end of the pre-arcing period, an exponential rise in voltage is observed. In this moment at which the rate of voltage starts to increase radically, the beginning of the arcing period is started. The current even though up to that moment is decreased, heat still continues to accumulate. At some instant before the material is completely vaporized, the metallic coherence within the wire is interrupted and an arc is formed (Vermij 1980; Wright and Newbery 1995; Bussière 2001; Psomopoulos and Karagiannopoulos 2002a; Gounaridis et al. 2014). On that relative matter other researchers (Psomopoulos and Karagiannopoulos 2002b; Gounaridis et al. 2014) have shown that devises with no serious production defects and a symmetry within tolerate margins (as these presented here) will most likely fuse in the central region, as the highest probability suggests, due to the temperature distribution on the metal element. The silica sand, if any, fuses along with the metal parts. As a result, metal droplets and vapors dissipate towards the rest of the chamber, a gap is then created and the arc is instantly initiated (Bussière 2001).

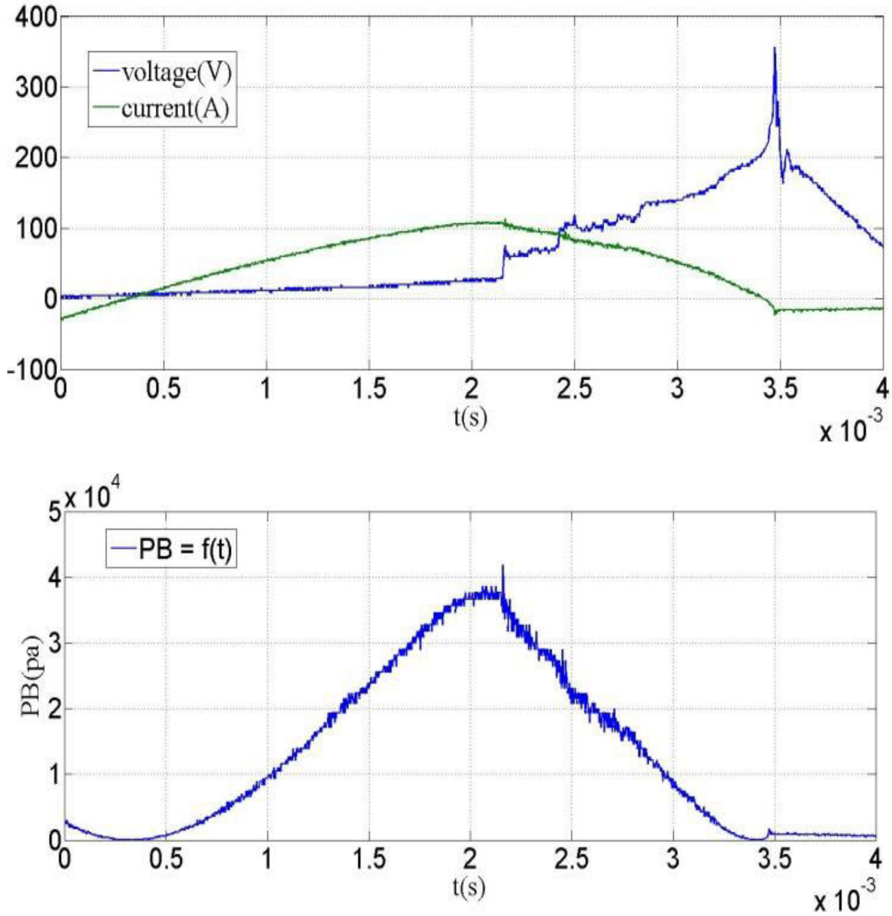

Figure 2. Top graph: voltage and current waveforms in thin wire element (length = 35mm and diameter = 0.14mm) with air as surrounding medium. The calculated maximum current density in arc is 11.19kA/mm^2. Bottom graph: Evolution of the magnetic pressure.

The thermal ionization of the surrounding area assists the arc formation. Assuming the chamber of the case has only air as the arcs expand, it produces both elevated temperature and pressure within the plasma and hence an active environment. There is a rapid change in arc dimensions, which is a function of the rate of burn-back of the metallic parts (arc elongation). This dynamic process gives rise to rapid increase in the electric resistance of the arc and its eventual extinction (Barrow et al. 1991; Cheim and Howe 1994; Wright and Newbery 1995; Psomopoulos and Karagiannopoulos 2007; Gounaridis et al. 2014).

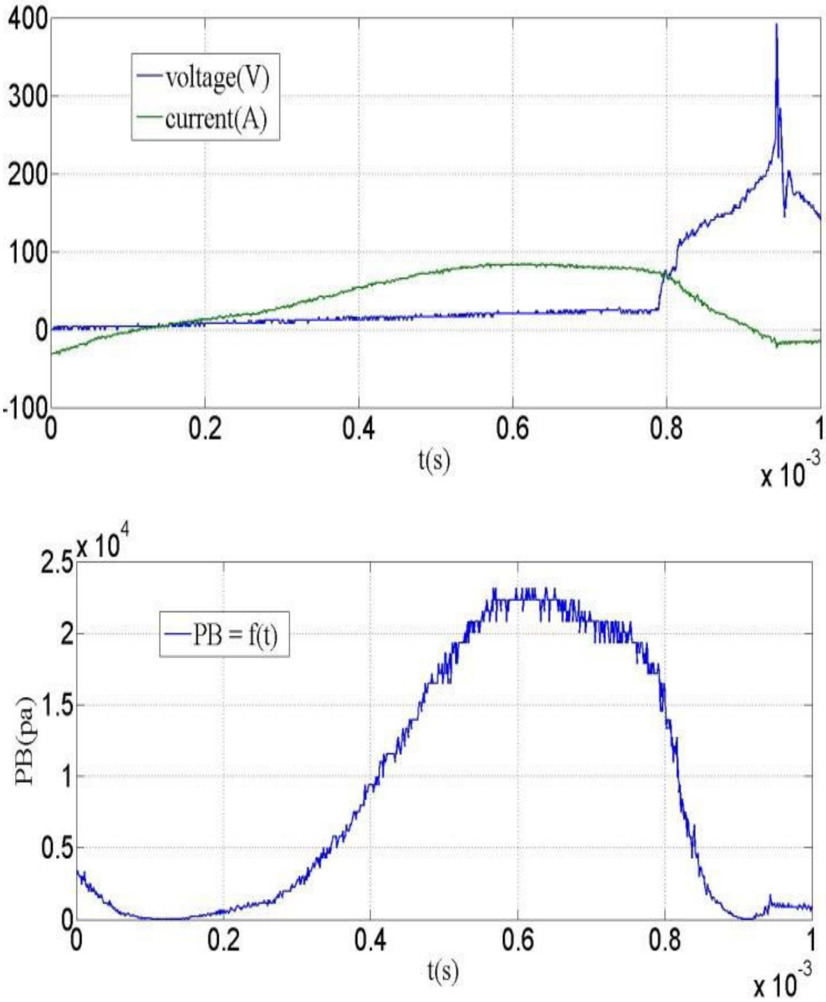

Figure 3. Top graph: voltage and current waveforms in thin wire element (length = 35mm and diameter = 0.14mm) with SiO_2 surrounding medium. The calculated maximum current density in arc is 7.46kA/mm^2. Bottom graph: Evolution of the magnetic pressure.

In the examination of the chambers filled with silica sand, as the arc plasma is initiated some metallic vapours along with the silica vapours are produced because the arc continuously interacts with the surrounding insulators. Physical quantities such as: temperature, electron density and pressure in the chamber and in the inner parts of the arc plasma depend on the material removed during melting and vaporization. The very high pressure of the eruption causes the dissipation of debris (liquids and vapours) to spread within the grains of the sand and fill them. The arc plasma is then sustained for a short period of time due to the continuous contribution from the surroundings until the dissipated energy is not sufficient enough and the erosion of the material stops (Bussière and Pascal 2001; Gounaridis et al. 2014).

However, it is doubtful whether this phenomenon will occur in a regular way or whether the liquid cylinder will explode under the mechanical action of the vapor pressure (Vermij 1980; Wright and

Newbery 1995; Gounaridis et al. 2014). According to the literature there is another action that could lead to arcs formation in fusible wires. A cylindrical wire completely melted by an electric current flowing through it, experiences a pressure in connection with the surface energy and a magnetic pressure created by the electric current. If the diameter of the melted wire shows small variations the magnetic pressure is largest at the smallest diameter. As a consequence of the surface tension and the magnetic pressure, a cylindrical current-carrying liquid conductor stretched in air will deform into a number of globules (undoloids) (Taylor 2002). If the source voltage of the circuit is sufficiently high, small arcs arise between these globules. This phenomenon is referred as “multiple arcing” and it has been observed by other researchers (Vermij 1980; Barrow et al. 1991; Cheim and Howe 1994; Wright and Newbery 1995; Psomopoulos and Karagiannopoulos 2002a; Gounaridis et al. 2014). That reason led to the employment of the following equations for the calculation of the magnetic pressure:

$$P_B = \frac{B^2}{2\mu_0} = \mu_0 \frac{I^2}{2\pi^2 d^2}$$

where $B = \mu_0 I(\pi d)^{-1}$, *d* is the diameter of the wire and *I* is the current flowing through the conductor. It was more than expected that the magnetic pressure would be proportional to the square of the current flowing through the element.

The results showed that the magnetic pressure developed in the elements during fusion was always higher in elements exposed in air. The lower magnetic pressure developed in the element with SiO_2 compared to the one in air, can be easily explained by the lower current flowing in the case of SiO_2. It can be concluded that the reduction of the maximum current due to the use of SiO_2 results on the mitigation of the magnetic pressure and the arc formation in the fuse elements. These results are in agreement with the ones presented in the existing literature (Wright and Newbery 1995; Bussière and Bezborodko1999; Saqib and Stokes 1999; Bussière 2001; Taylor 2002; Psomopoulos et al. 2007; Gounaridis et al. 2014).

Conclusions

The variety of physical processes makes it difficult to build up an accurate model and for a conclusive description of the fusion process in thin wire elements and electric fuses. Breaking phenomena, plasma development, energy dissipation through heat and radiation, material diffusion, physical properties of the arc plasma which defines the energy supply in the energy dissipation mechanism, are important parameters that are mainly experimentally investigated. The magnetic pressure which is developed during fusion stresses the thin wire element and seems to play a very important role on the whole process. The surrounding medium, as well as, the current density are among the major parameters that affect the magnitude of the magnetic pressure, directly the first one and indirectly the second one. The experimental investigation of these parameters is started and it seems that has a potential to contribute to the existing knowledge and development of more accurate models of the process.

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