Resistivity variation during fusion process of thin wire elements

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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. The work presented in this paper investigates the resistivity variation during fusion process of exploding wires using common industrial power supply directly feed from the network of 50Hz. The measured magnitudes were the voltage drop and the current waveforms 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. The measurements were performed through fast digital oscilloscopes connected with PC and the observed phenomena are investigated focusing on the resistivity variation as a result of the high current densities and arc formation. The results could support the efforts for better understanding the physicochemical processes during fusion.

Introduction
Electrically exploding conductors such as fusible wires are frequently used in fuses and other applications basically to protect the electrical installations and apparatus against overcurrents. They generally operate either under a minus value of their nominal current or momentarily under excess or sort-circuit currents. In nominal 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 (Gounaridis et al. 2014; Psomopoulos et al. 2007; Wright and Newbery 1995).

In the case of fuse operation under fault current the fuselink overheats, melts and is interrupted, cutting off the current flow in the circuit under protection minimizing the damage from the high power flow. The main principle is that the fuse will open the circuit. It is a basic and relatively simple function that derives from fundamental phenomena. An overcurrent causes an increase in the resistance of the fusible component and therefore a rapid rise in temperature until the melting point. The latent heat continues to accumulate due to the passing current, while in the melting period up to a point that the material is partially or completely vaporized (Gounaridis et al. 2014; Psomopoulos et al. 2007; Wright and Newbery 1995).

After the vaporization of the previous conducting wire, electric arcs struck between the anode and cathode of the remaining solid parts of the element. This dynamic process gives a sudden rapid rise in temperature as the current decreases rapidly until the flow is eliminated. During these conditions it was observed that the temperature scale of the rupturing caused phenomena is within 2000K~20000K and current densities can put under exceeding stress any material. The fundamental operation of the fuses has been extensively described in the relevant literature (Gounaridis et al. 2014; Psomopoulos and Karagiannopoulos 2002a, 2002b, 2007; Wright and Newbery 1995).

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 a few to our knowledge, used typical industrial power supply from a typical installation. And it must be noted that the actual operation of the fuselinks will be under such types of power supplies and not with typical current pulses which have been used in the majority of the experiments conducted so far. The work presented here is an attempt to investigate the resistivity variations during the fusion process in thin wire elements simulating fuselinks, operating under industrial power supply of 50Hz. These variations seem to be the least investigated parameters during fusion in the related international literature. In the experimental investigation two environments were used: air and SiO_2 thin granules that 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 measurement 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 where 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. In Figure 2 the schematic of the above mentioned fuse test devise is shown.

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

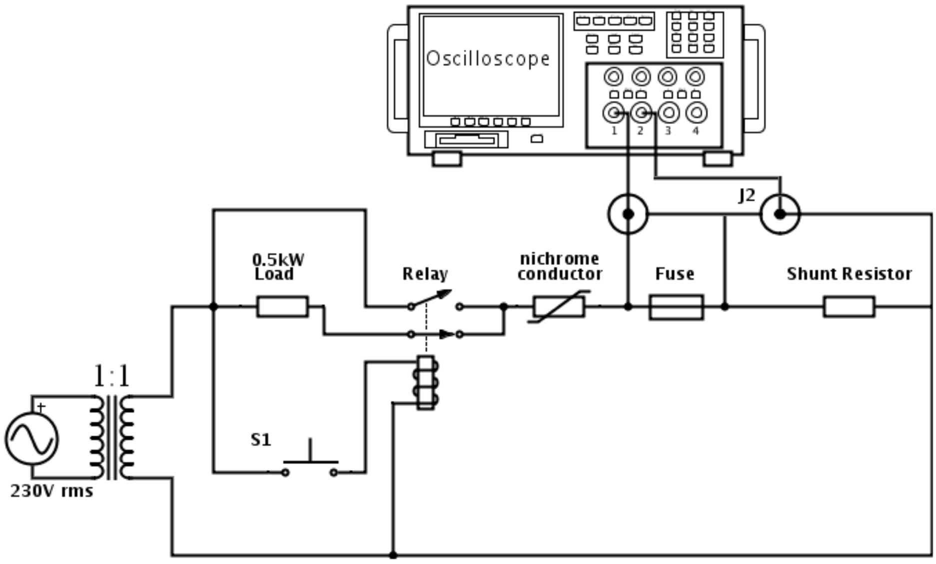

Figure 1. Simplified schematic diagram of the experimental set-up.

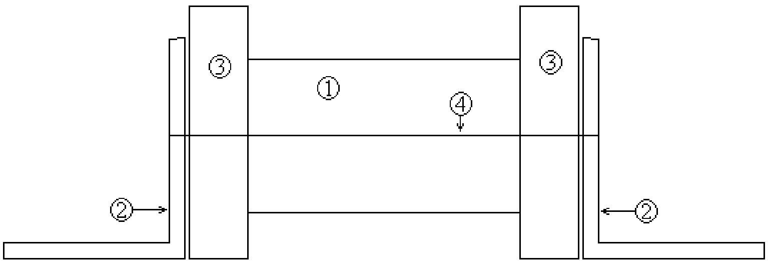

Figure 2. Simplified illustrations of the side view of the test devise. Parts: 1) Cavity capable of filling with silica sand, 2) Electrode clamps, 3) Shutters of the filling cavity, 4) Fuse element in copper

Results and discussion

The total time duration and characteristics of a representative fusion process are presented and analyzed. In Figures 3 and 4 a set of measured and calculated magnitudes are presented. The surrounding medium during these measurements was the air. In Figures 5 and 6 the same measurements are presented using a SiO_2 as a medium. Each single measurement has identical lengths and thicknesses of the copper wire. In each case, in Figures 4 and 6 only a part of the total measurement (shown in Figures 3 and 5 respectively) are presented, focusing on the part that presents the significant variances.

The resistivity variation during the arcing period seems not be investigated extensively in the existing literature during the fusion process, even though the transient conditions are being investigated extensively. The findings of this experimental work could have some interest in the scientific community due to the extreme variations that the resistance presents during the whole process, as it can be easily seen in Figures 4 and 6. These ones are presented for the first time according to our knowledge. In both cases strong continuous variations after a smooth period of increasing can be observed. These variations can be easily identified by the experience researcher as formation of N-type of Negative Differential Resistance (NDR), a common phenomenon during the plasma formation in arc flashes (Psomopoulos and Karagiannopoulos 2007). This particular observation is just another verification of the fusion process with the formation of arcs. But the surrounding medium seems to affect the whole process (Psomopoulos and Karagiannopoulos 2002a, 2002b, 2007; Saqib and Stokes 1999; Bussière 2001; Bussière and Bezborodko1999; Taylor 2002).

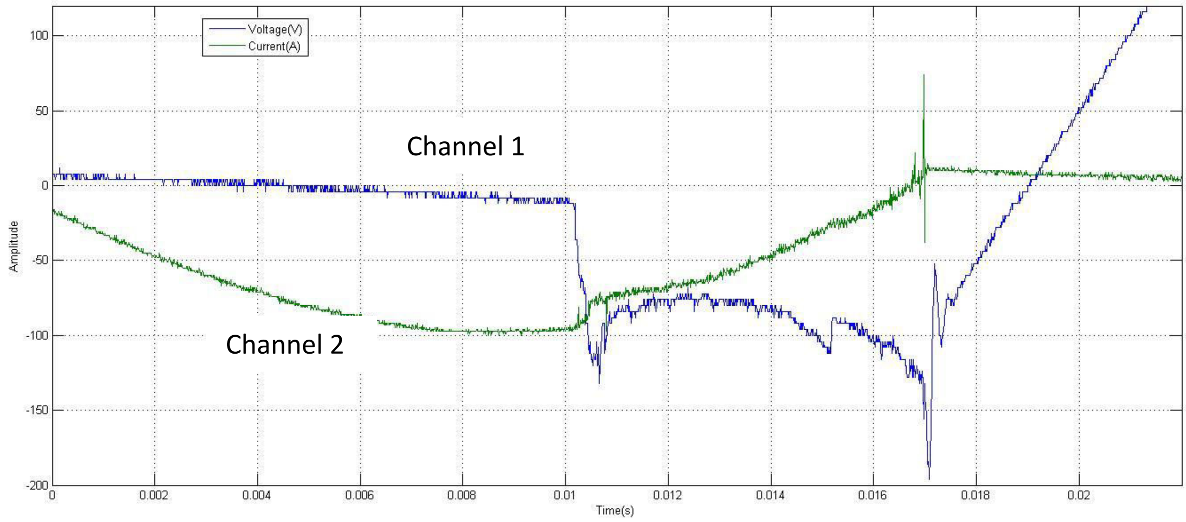

Figure 3. Typical measurements of the fusion process in thin copper wire elements in air. Channel 1: voltage drop across the element, Channel 2: current during fusion process. The thin wire element had length 40mm, diameter 0.16mm.

From Figure 4 it is clear that the first period after the short circuit (occurred in 10ms), which lasts some ms (around 6-6.5ms), the increment of the resistance is smooth and can be easily explained from the increment of the wire element absorbed power until the point of the first state transition in the material. The rather long time can be explained by the fact that the point on the curve at which short-circuit occurs the voltage is on its lowest magnitude and increasing. After this period, which is the commonly known pre-arcing period of the fusion process, a rapid increment and reduction (N type NDR) are present. This series of continuous N-type NDRs is responsible for the ignition of arcs along the wire elements as it has been observed in literature (Psomopoulos and Karagiannopoulos 2002a, 2002b, 2007; Saqib and Stokes 1999; Bussière 2001; Bussière and Bezborodko1999; Taylor 2002; Wright and Newbery 1995).

From Figure 6 it is clear that in the first period after the short circuit (occurred in 12ms), which lasts some ms (around 20-22ms), the increment of the resistance is smooth and can be easily explained from the increment of the wire element absorbed power until the point of the first state transition in the material. The rather long time can be explained by the fact that the point on the curve at which short-circuit occurs, the voltage is on its lowest magnitude and increasing. At the same time, the existence of the silica granules seems to reduce the number of hard variations during the second stage which represents the reduction of the short-circuit energy as the SiO_2 is a well known and widely used material for this purpose.. Thus the results seem to be in accordance with the work of others (Psomopoulos and Karagiannopoulos 2002a, 2002b, 2007; Saqib and Stokes 1999; Bussière 2001; Bussière and Bezborodko1999; Taylor 2002; Wright and Newbery 1995).

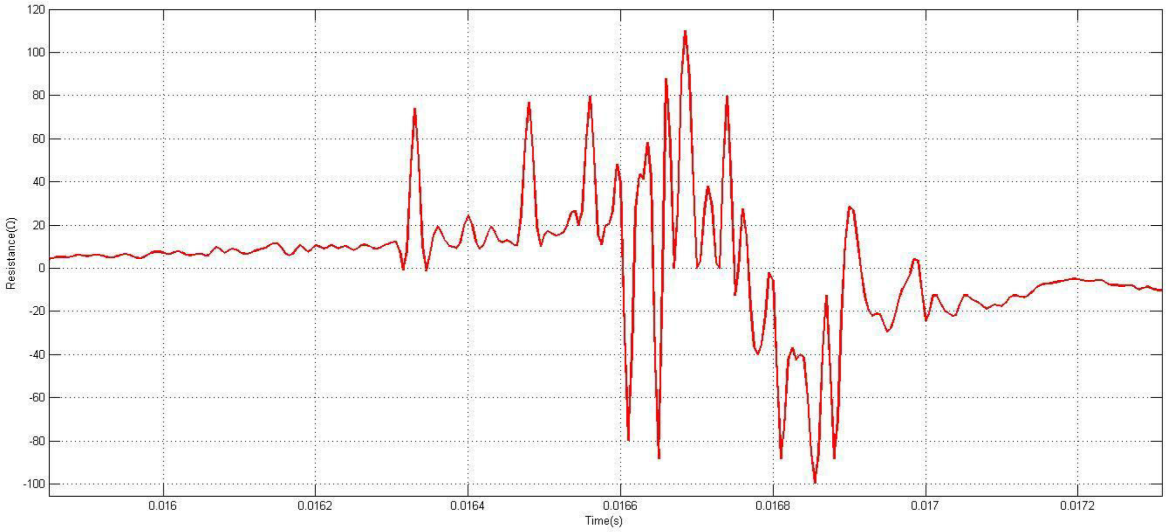

Figure 4. The waveform of the of the fusion process resistance R=f(t) of the measurement of Fig.3

General, the waveforms observed in the literature can be divided in two basic areas known as pre-arcing period and arcing period. In this investigation, certain initial conditions where duplicated and their experimental results were observed. The basic parameters which control a potential outcome are: the quadrant of the sinus in which the pre-arcing begins, the imperfections of the surface and the inner crystalline structure of the copper thread, the medium or set of mediums, that in each case insulate the fuse, the geometry of the conducting fuse element in relation to the materials and finally the quality and the geometry of the rest of the devise. The geometry of the fuse material was consistently simple as in all fuses as thin cylindrical copper wires where used. That was in the direction of having a common reference, a more solid basis, for the rest of the parameters (Psomopoulos and Karagiannopoulos 2002a, 2007; Saqib and Stokes 1999; Bussière 2001; Bussière and Bezborodko1999; Taylor 2002; Wright and Newbery 1995). The experimental results are in accordance with the findings of other researchers, but the use of resistivity variations can be a view of the phenomena from a “slightly different angle”, which may provide additional information towards to better understanding and modeling of the fusion process.

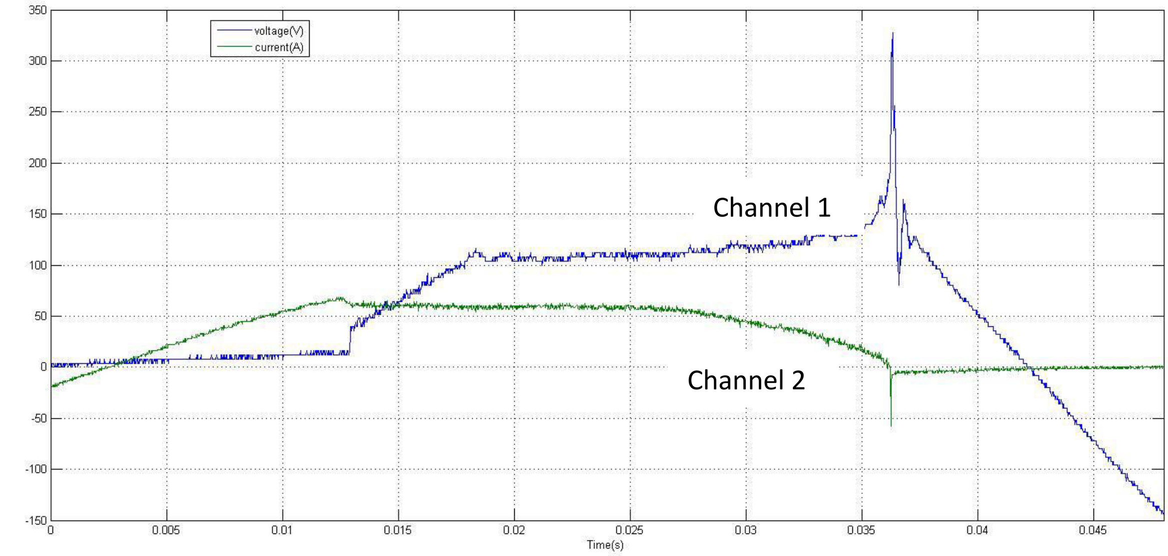

Figure 5. Typical measurements of the fusion process in thin copper wire elements with the quartz sand as a medium. Channel 1: voltage drop across the element, Channel 2: current during fusion process. The thin wire element had length 60mm, diameter 0.14mm.

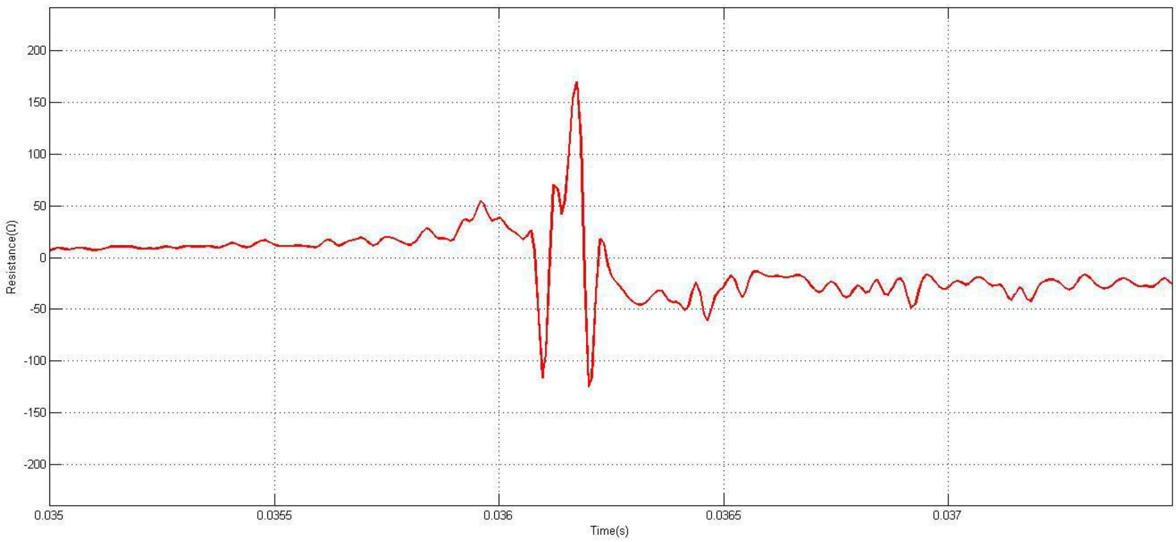

Figure 6. The waveform of the of the fusion process resistance R=f(t) of the measurement of Fig 5.

Conclusion

The variety of physical processes makes it difficult to build up an accurate model for a conclusive description of the fusion process in thin wire elements and electric fuses. Important parameters as: 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 mainly experimentally investigated. The resistivity variation is an additional parameter that could provide additional data for the modeling of such a complex phenomenon, especially through the visualization of the current and voltage curves variations. The experimental investigation of this parameter could contribute to the existing knowledge and develop more accurate models of the process.

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