

# EXPERIMENTAL INVESTIGATION OF THE FUSION IN CYLINDRICAL EXPLODING WIRES USING HIGH CURRENT DENSITIES WITH INDUSTRIAL FREQUENCY

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**Abstract:** The physicochemical process during the operation of fusible wires under high current densities presents complicity and seems not to be completely known. The work presented in this paper investigates the 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. The measurements were performed through fast digital oscilloscopes connected with PC are presented and the observed phenomena are investigated. The total time duration (prearcing and arcing periods of fusion) of the fusion process was measured and the results for different current densities and lengths of the thin wire elements are presented and analysed.

**Keywords:** Fusion process, arc formation, exploding wire, high current densities, heavy ionised metal vapour column, arcs in air.

## 1. Introduction

The 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 under a minus value of their nominal current or momentarily under excess or short-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 [1,2,3,4]. For the case of the operation under excess or heavy fault currents the design of fuses is based on the well known fundamental principle, that they must interrupt those 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 rise 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 [2,3,5]. 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 [1÷12]. The understanding of this operation relies mainly on work on exploding wires and sand fuses mostly performed from 1960s to 1980s [3÷12]. Several theories have been developed to explain the disruption of fuse elements, but no conclusive proof has been found in favour of one of them. Hence new ideas on the exploding wires phenomenon and the sand fuse operation often appear [1÷3, 13÷16].

Present research activities are focused mostly in the arcing period and a number of models have been developed to simulate the fundamental operation. This operation is well understood in general, but all the physicochemical processes during the arcing period seem not to be completely known [12÷14]. However some models have been developed which can simulate fuses operation under fault current during the arcing period [1,6, 12÷14].

In this paper, measurements of the voltage drop across fuse elements and the current, using fast digital oscilloscopes connected with PC are presented. The fusion total duration is measured for a variety of thin wire elements lengths and different current densities. To our knowledge there are no similar measurements in the related bibliography especially considering the method used here were the fusion process was measured using actual industrial voltage (230V, 50Hz), which is simulating actual conditions for the circuit and the exposed fusible wire. In the related literature the experiments are carried out usually with pulse voltages or currents. The measurements in this work were performed in random position of the supply voltage curve. These measurements give the possibility to investigate the

physicochemical process during the pre-arcing and arcing periods. An identification of the existing knowledge in the measurements performed, and a further interpretation of the phenomena during sort-circuit is attempted.

## 2. Experimental Set-up and Measurement Results

### 2.1. Experimental Set-up

Fig. 1 shows the simplified schematic diagram of the experimental set-up, for the estimation of the voltage drop across a fuse element under sort-circuit conditions. Thin wires simulating the fuse elements, were connected to the circuit using appropriate terminals. A typical ohmic load of 0,5kW, connected in parallel with an open switch was used to simulate the nominal current operation and sort-circuit conditions respectively. A measuring resistance  $R_m$  was used to estimate the current through the fuse element. The material used for the measuring resistance had zero value coefficient of variation of resistivity with temperature ( $\alpha \approx 0$ ). The variable resistance  $R$  was of a similar material as  $R_m$  and used to determine the peak current value during sort-circuit.

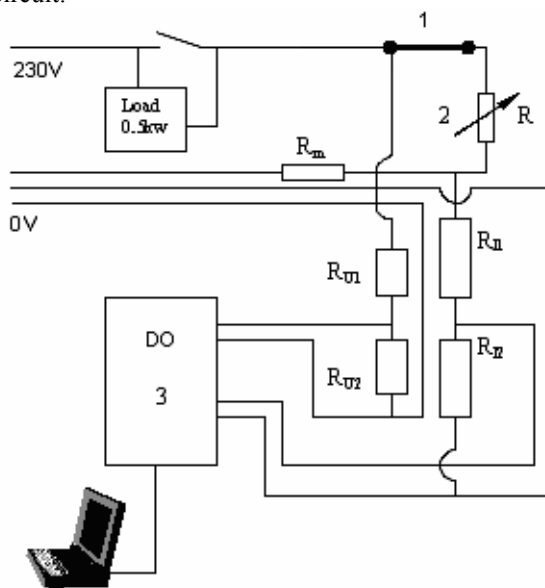


Fig. 1. Simplified schematic diagram of the used experimental set-up.

- 1) Thin-wire element
  - 2)  $R$  : variable resistance for determine the current peak value,
  - 3) Digital oscilloscope with an RS-232 connection to the PC,
- $R_{U1}$ ,  $R_{U2}$  voltage divider for the voltage across the element,  
 $R_{11}$ ,  $R_{12}$  and  $R_m$  voltage divider and measuring resistance for the current through the element.

The measurements were performed through a digital oscilloscope with high sampling frequency up to 100MHz per channel and maximum voltage of 40V pick to pick (5V/div). The sampling frequency was 0,1MHz. The oscilloscope was directly connected to PC, via an RS232 port, for direct transfer of the measurements. The two voltage dividers were used in order to reduce the voltage peak value provided to the oscilloscope. The software of the interconnection could transfer the values and the curves in excel sheets (generally a spreadsheet software) directly with spreadsheet software format, and the measurement on the oscilloscope screen, as image independently inserted in the spreadsheet with common bmp format.

### 2.2. Measurements Results

Measurements were performed on conductors stretched in air. The conductors were thin cylindrical copper wires (99,9% Cu), with several diameters. Figures 2 and 3 show the voltage drop, the current and the resistance waveforms during the current interruption process in fuse elements with diameter of 0,14mm and 0,16mm and length which was varied between 35mm to 100mm with a step of 5mm. The current density was changed through the variable resistance ( $R$ ) of the circuit.

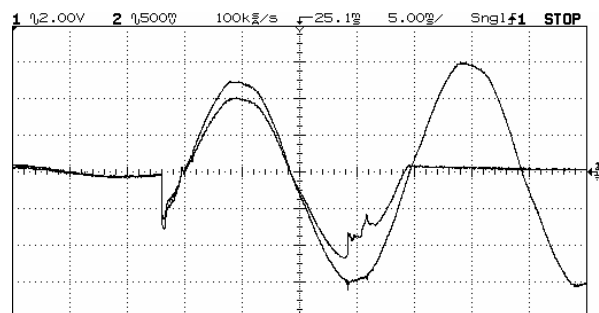


Fig. 2. Typical measurements of the fusion process in thin copper wire elements. Channel 1 is the voltage drop across the element (the sinus waveform), channel 2 is the current during fusion process (rapidly decreases to zero while voltage remains). The calculated maximum current density was 4,54kA/mm<sup>2</sup>. The thin wire element had length 60mm, diameter 0.14mm.

## 3. Discussion

In figures 2 and 3, which present actual measurements from the oscilloscope's screen, it can be clearly seen the sort-circuit's duration, the voltage drop across the element, the current value (impulse and continuous sort-circuit currents). From the waveforms presented in this figures it can be notice that they follow the form of the ones in literature, and similar characteristics can be observed. Here the

difference that exists is that the measurements presented in this work were taken in random positions of the sinus curve of the voltage source.

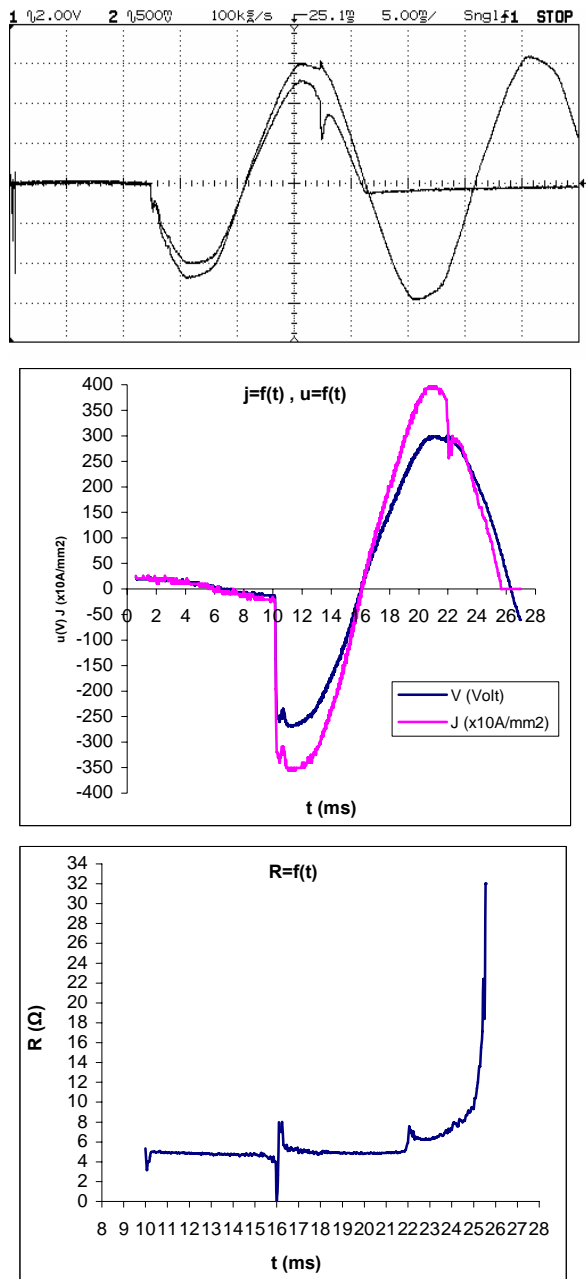


Fig. 3. Typical measurements and the respective actual values calculated from experimental set up characteristics, of the fusion process in thin copper wire elements. The waveform of the of the fusion process  $R=f(t)$  is also presented. Channel 1 is the voltage drop across the element (the sinus waveform), channel 2 is the current during fusion process (rapidly decreases to zero while voltage remains). The calculated maximum current density is 4,54kA/mm<sup>2</sup>. The thin wire element has a length 40mm, diameter 0.14mm.

Another difference concerned the voltage source, which was a common industrial sinus sapped waveform exactly the same one with the one that the equipment it is supplied, and not a laboratory produced voltage. With these two mentioned here basic conditions the fusible wire is exposed to the actual conditions of a network and thus the phenomena observed are closer to the actual ones in practical applications.

General, the waveforms observed in the literature can be divided in two basic areas known as pre-arcing period and arcing period. In the measurements presented here the following can be observed: In the beginning of the pre-arcing period it can be seen the peak value of the sort-circuit current (impulse current). After few  $\mu$ sec, the current is almost stabilized (continuous sort-circuit current). The voltage across the element's edges, after a very fast rising period was also almost stabilized. This value was lower than the source peak value ( $\approx 310$ V).

During this period and after the first 0,5–1msec the waveforms presented the following behavior: The voltage drop was almost stabilized with increasing tense while the current although it was almost stabilized showed decreasing tense. These can be explained by the increasing of the specific resistance due to overheating. The graduated increase of the wire's specific resistance follows the well known relation  $\rho = \rho_0(1 + a\Delta\theta + b\Delta\theta^2)$  and considering the sort-circuit conditions and the above mentioned, seems to give an explanation to the measured high voltage drop in the element's edges [8,12].

At the end of the prearcing period it can be observed a sinking of the voltage drop and the current for a sort time duration (0,25-0,75ms). This sinking may be explained from the accelerated temperature rise until the melting point of the fuse wire's material, and the changes from solid to liquid conditions (the wire starts to liquefy in the inner parts) [3,6,12,16]. During the sort times here in question and the surface tension, the gravitational forces do not play any role according to literature and thus the liquid wire material will remain in place and be heated further to the temperature of vaporization. At some instant before the material is completely vaporized, the metallic coherence within the fuse wire is interrupted and an arc is formed. [3,7,12]. 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. [3,7,8,12].

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 (unduloids). 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 [1,2,3,7,16].

With the volatilization and interruption of the metallic coherence, electric arcs are formed (arcing period) between the remaining solid parts of the conducting material, in an environment of metal vapors. In this complex environment, as the arcs expand produce both elevated temperature and pressure within the plasma and hence an active environment. In these conditions thermal ionization can be expected. 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 [1,2,3,6,12].

The metal vapor column, which arises during the evaporation process of a fusing wire surrounded by air, expands very rapidly due to the high pressure in this vapor, as has been made visible with cylindrical wires in the past [7]. The theoretical and experimental investigation concerning the exploding wires showed that fuse elements, after reaching the evaporation temperature under atmospheric conditions, could become highly superheated in the liquid state [9÷11,17]. At the actual evaporation temperatures the metal vapor column possesses a resistance which is much larger than that of the fuse element at the same temperature, but in liquid state. The fuse resistance in these circumstances is determined by the cross-section of the metal vapor column, the length of this column and the specific resistance of the ionised metal vapor. Experiments showed that the cross-section of the metal vapor column depends on the current [1,2,7,17]. In this metal vapor column the arcs are formed. In these conditions, to sustain a high electron density, a small electric field strength is needed and there is a small electrode fall (~10÷50V) [1÷3,17].

Figure 4 represents the total time duration of the fusion process in thin wire elements exposed in open air. It can be easily observed that the smallest is the length of the wire the higher is the time duration of the fusion process. This seems to be explained by the high volume of the metal structure that supports the element which operates as a heat dissipater and since the wire has small length the supporting absorbs a significant amount of the produced heat in the element [3,4,12,13,18]. Further more to this explanation, as it is mentioned above, during the interruption of the metallic coherence of the wire is followed by an electric arc. Thus the ionised metal vapor column has smaller length so its elongation is

very small considering higher lengths, and at the same time the current density presents high values (see fig. 3). During this process, the heavily ionised surrounding air is considered that is operating in the smaller gap (smaller length) [1,5,7,10,11,16, 17]. The development of the wire fragmentation in exploding wires and the plasma formation in experiments above mentioned have been observed, and described also in M.J. Taylor’s recent works. These experimental results presented the resistance change and the plasma formation and expansion through x-radiological image, photographic study and measurement of the current and voltage waveforms of the used pulses [19,20].

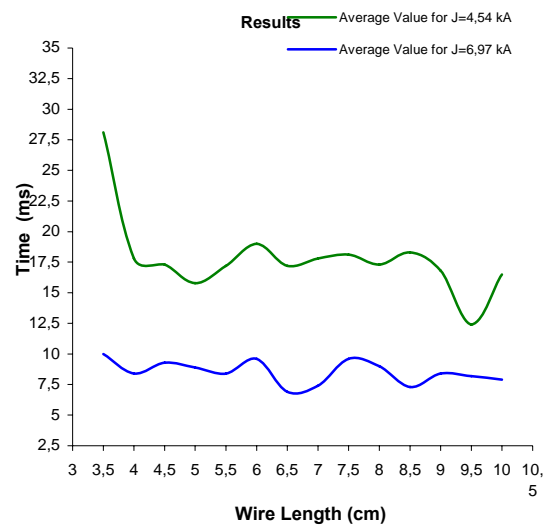


Fig. 4. Waveforms of the average mean value of the fusion process duration in relation with the wire length. The parameter of the current density is also presented. The copper fusible wire has a diameter of 0,14mm.

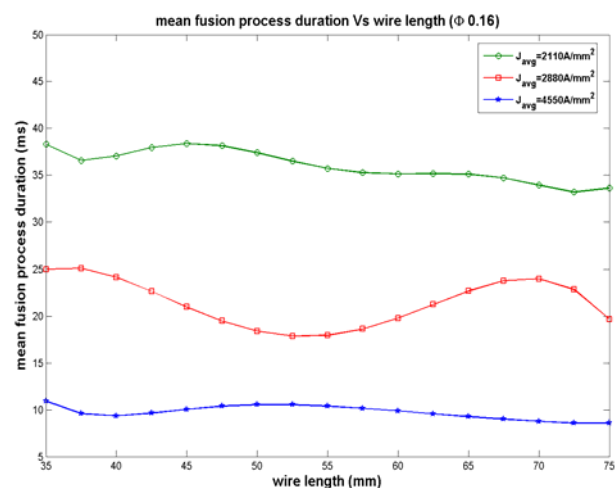


Fig. 5. Waveforms of the average mean value of the fusion process duration in relation with the wire length. The parameter of the current density is also presented. The copper fusible wire has a diameter of 0,16mm.

The resistance waveform in figure 3 present significant similarities with the ones in literature and especially with the ones of M.J. Taylor [19,20] even though the experimental procedures were completely different. The differences exist in the waveforms can be easily attribute to the different geometric characteristics and different waveforms. But the similarities provide strong evidence for the plasma formation and disruptions of the electrical coherence occur due to similar physicochemical procedures in both experiments.

In fig. 4 and 5 also it is observed that the higher the current density is the lower the fusion duration is. This could be easily explained from the above mentioned, since the produced heating power is analog to the term  $j^2$ , where  $j$  is the current density (Joule relation) [3,4,16,18].

In these figures it can be easily observed also that in lower current densities the smaller the length is (lower than a threshold value) the higher is the duration of the fusion process. This seems that can be explained from the following assumptions: The heat from the produced Joule energy is lower per time interval. At the same time the energy that is transferred from the thin wire through the end tags is almost stable per time interval and depends from the materials and the volumes. Thus the energy used for melting and arc ignition is lower per time interval, and as a consequence the required time is rising [8,13,18]. Furthermore the lower current densities produced lower magnetic pressure values and thus the thin wire seems not to be exploded. In this smaller gap between the electrodes (smaller distance between the end tags, when the wire has smaller length) the metal vapour expands [7]. Here it must be notice that in small lengths of the gap between the end tags, the electric field is higher as it can be easily concluded from the abovementioned [1÷3,17]. Thus it seems that the metal vapours which are ionized expand not as rapidly as it has been observed in cylindrical wires with higher lengths where the field is lower and the metal vapours do not remain constrained [7]. These assumptions explain also the differences up 25% that can be observed in the total short circuit duration, in higher lengths of the wire elements and low current densities.

Similar observations have been made in all performed measurements, with differences concerning the fusion duration and the related current density. Important role in the fusion duration seems to have the time instant in which this occurs regarding the value of the source voltage. The lower was the source voltage in the starting of the short-circuit the longer was the duration. This can be explained from the resulted small current density in the beginning of the phenomenon which results a greater pre-arcing period, according to the aforementioned. Of course, differences existed because of the different geometric characteristics of

the fusible elements. Those differences, as it can be easily presumed are the consequences of [8,12,14] : Different wires' volumes which require different energy values to melt.

Different wires' resistance and thus different current densities in the elements.

The higher current densities have as a consequence smaller affect of the length in the fusion duration.

## 4. Conclusions

The measurements through fast digital oscilloscopes combined with PCs, can provide a more accurate approximation and understanding of the phenomena during the operation of the fuse elements. Another parameter that contributes to the above is the use of common industrial voltage source and random sinus values in the experiments. The resistance measurements combined with the voltage drop and current densities measurements can provide a more accurate approximation and understanding of the phenomena involved. The observed fast oscillations for different wire lengths and current densities provided useful information concerning the fusion process duration and thus for short-circuit, which fuse the thin wire. The fusible elements' geometric characteristics affect only the fusion's process duration and the values of the measured magnitudes, for small current densities. The results could be useful in fuses' design.

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