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Experimental Study of the Pressure Exerted in the Body of a High-Voltage Fuse and Metal Enclosed Switchgear

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Abstract - **This article presents the importance of analyzing the breakdown behaviour of high voltage fuses and high-lights the pressure values at the fuse ends. The theoretical basis, test scheme structure, design and sizing elements of fuse components, and numerical simulations performed in Matlab/Simulink are presented. The extinguishing environment is not modelled as it is considered to be a vacuum Starting with the oldest overcurrent protection device and continuing with the importance of high voltage fuses for operational safety, the study presents the behaviour of high voltage fuses during short-circuit current interruption. The key element is the value of the pressure on the contacts of fuses, which is often ignored in favour of the pressure of the middle element. When fuses change from solid to liquid state the inner parts are hotter than the outer parts and melt first, and the melting zone extends to the periphery. The study found that the pressure is much higher and is an important value for designers. Experiments showed that the maximum pressure is reached during the arcing period, a significant finding for the design process of the contacts of a high-voltage fuse. The research was then extrapolated to check the pressure in metal enclosed switchgear containing fuse combinations.**

Cuvinte cheie: *siguranțe de inalta tensiune, presiune, curent de scurtcircuit, timp de arc electric, element fuzibil, celule electrice, combinatie separator-sigurante fuzibile*

Keywords: *high-voltage fuses, pressure, short-circuit current, arcing time, fuse element*, *switchgear*, *load break switch-fuse combination.*

I. INTRODUCTION

The oldest protection device against high currents is the fuse and today it is still the main protection used in many applications due to its high reliability at voltages starting from 7.2 kV to 66 kV. The design of fuses is apparently simple, but the phenomena that occur during its operation are quite complex. For this reason, fuse research and development has tended to rely on empirical methods, requiring a great deal of expensive experimentation and testing. To overcome this, the current global trend is to turn this empirical research into science.

Standards used by the applications with fuses are constantly improved, but the basic parts remained unchanged for more than half of century [1-5]. Electrical systems nowadays require higher short-circuit power concentration and space limitation; therefore, modern fuses operate at the maximum technical limits for which they were designed. Increasing of the safety requirements mean safety limits decrease and the smallest selection error can have serious consequences [6-12].

Fuses are found in many electrical circuits around the world and their main function is to protect electrical equipment such as distribution transformers, motors and capacitor banks from overload currents.

One of the global objectives is to design fusible seals that will operate safely in air with limited heat dissipation when used in gas insulated switchgear.

The fuse has to detect and isolate the faulty equipment from the rest of the circuit, therefore it is connected in series with the protected equipment. The simplest fuse consists of a metal wire connected between two insulated supports. Modern fuses are encased in a ceramic enclosure and the fuse wires are mounted inside an insulating support, they are also equipped with a striker, a signaling device that also acts as an actuator for other electrical devices. The ceramic casing is filled with an arc-quenching exothermic material that is most commonly quartz sand. Other metal components may be made of copper, iron, brass, and can be silver-plated or nickel-plated and must be capable of functioning under the thermal, mechanical, or electrical conditions encountered in service.

Medium-voltage switchgear equipped with load-break switches and fuses (combinations) in metal enclosures are common and reliable, and their design limits the mechanical effects of excessive pressure surges. In order to assess the effects of pressure on the metal envelope, experiments were carried out on the unsuccessful opening of fuses which were deliberately designed with defects and which did not limit short-circuit currents, thus creating pressure in the metal envelope.

II. LITERATURE REVIEW

The behavior of fuses at maximum breaking current has been extensively analyzed over time. The fuse wire melting process is shown in Fig. 1.

At the end of the liquid phase (the pre-arc period) the voltage increases exponentially, as shown in Fig. 1. The moment wh en the voltage rate begins to increase abruptly marks the beginning of the arc period. Heat continues to grow even though the current has dropped up to that moment. The metallic coherence within the wire is interrupted, before the material is completely vaporized, and an arc is formed [1,3, 9-16]. Researches [8,13] have shown that devices without serious manufacturing defects and with symmetry within tolerable limits will most likely melt in the central region, as suggests the temperature distribution on the metal element.

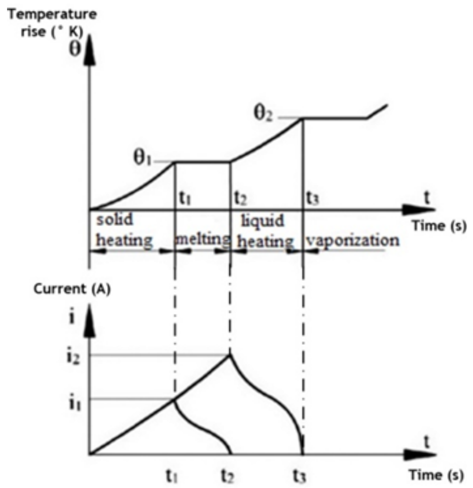


Fig. 1. Fuse wire melting process

Quartz sand fuses with metal parts. Fuse melting leads to metal droplets and vapors that dissipate into the rest of the ceramic casing, creating a gap and instantly initiating the arc [14].

Thermal ionization of the containing medium contributes to arc formation. If there is only air in the ceramic case, when the arc flashes expand, they create both high temperature and high pressure in the plasma, therefore an active medium. The size of the arc is a rapidly changing as a function of the burning rate of the metal parts (arc elongation). This process leads to rapid increase in the electrical resistance of the arc and its eventual extinction [1-3,7,9]. Another study of plasma-wall interaction [6] shows that the electrical conductivity of the plasma σ is basically given by the current (i) and the voltage (u), assuming that the plasma fills the ceramic casing with a given radius R:

$$\sigma = \frac{i}{u}\frac{l}{\pi R^2} \tag{1}$$

Doubts arise whether this phenomenon will occur regularly or whether the cylinder of liquid will explode under the mechanical action of vapor pressure. [3, 9, 16, 17]. From specialized literature it is known that a cylindrical wire completely melted by an electric current passing through is subjected to a pressure directly related to the surface energy and a magnetic pressure created by the electric current. The magnetic pressure will be higher at the smaller diameter of the fused wire. A cylindrical, current-carrying liquid conductor stretched in air deforms into a series of globules (wavelets) as a result of surface tension and magnetic pressure. Small arcs will occur between these globules if the source voltage of the circuit is high enough. This phenomenon is called "multiple arcs" [1-3, 10, 16]. For this situation the following equations have been used for the calculation of the magnetic pressure:

$$P_B = \frac{B^2}{2\mu_0} \tag{2}$$

$$B = \mu_0 \frac{I}{2\pi r} \Leftrightarrow P_B = \frac{\mu_0 I^2}{8\pi^2 r^2} \tag{3}$$

where μ_0 is the magnetic permeability constant:

$$P_B = \left(\frac{10^{-7}}{2\pi r^2}\right) I^2 = kI^2 \tag{4}$$

This parabolic equation explains the graph: $P_B = f(I)$.

The evaporation process of the molten wire creates a column of metal vapor in an air environment that expands very rapidly due to the pressure created by this vapor [16]. Theoretical and experimental studies of melting wires have shown that fusible elements can overheat in the liquid state after reaching the evaporation temperature under atmospheric conditions [18-20]. At the actual evaporation temperatures, the metal vapor column has a much higher resistance than that of the fusible element at the same temperature but in liquid state. The safety resistance in this case is determined by the cross-section of the metal vapor column, the length of the column and the specific resistance of the ionized metal vapor. Experiments have shown that the cross-section of the metal vapor column is dependent on the current [1, 2, 16-23].

Arcing occurs in the metal vapor column and it is a self-sustained electrical discharge in which the plasma is at high temperature, high pressure, and the surrounding environment is in local thermodynamic equilibrium. The most important characteristic of the arc is its temperature [1-3, 16, 23]. Under these conditions, a low electric field strength is required to maintain a high electron density and also there is little electrode drop [1-3, 23].

In the literature, the methods used to determine plasma temperature are generally those described in [2, 6, 22], but research findings vary. The work of these authors focuses on materials other than copper, such as silver and aluminum.

Chikata et al along with Cheim and Howe [7] estimate that the temperature remains constant throughout the phenomenon at about 20000 K and 24000 K, and the electron density is about 1018 cm^3. Saquib [20] noticed a drop from the maximum temperature of 22000 K generated by the arc to 15000 K 4.1 ms later. Maximum electron density was 2x1018 cm^3.

In paper [6] the values obtained point a maximum temperature at about 21000 K and a decrease to 11000 K at the end of the arc period, the temperatures are evaluated using the Boltzmann diagram, the electronic density differentiated by other researchers has a maximum value of 2x1019 cm^3. In the experiments and research of M.J. Taylor were observed and described the fragmentation of exploding wires and the formation of plasma [24-26]. During his experiments, he mainly used capacitor-based pulsed power supplies and also made time measurements of the voltage on the wire and the current. The wire material used was high purity copper (99.9%) with larger geometric characteristics (1.0 mm in diameter, with a length ranging from 150 to 180 mm). These experimental results showed the change in resistance and plasma formation and expansion of the current and voltage waveforms of the used pulses by X-ray imaging, photographic study and measurement [27-32]. Detail of the development of plasma spots was studied using photographic images.

There are papers [35] which highlight the conflicting claims of [37] to [33] and explain the consequences with regard to the use of fuses in combination with circuit breakers containing sulphur hexafluoride as an extinguishing medium. In fact, important and wellestablished applications for fuses are virtually excluded by [37].

Alternative proposals for resolving the conflicting situation in International Standards are presented.

In the medium-voltage ring network configuration, the typical medium-voltage switchgear of medium-voltage and low-voltage substations is a compact and often non-extendable 3-function RMU, consisting of two interrupting switchgear units plus a protection unit connected to the medium-voltage/low-voltage transformer. The protection unit can be a combination circuit breaker-fuse or a circuit breaker. For such public distribution applications, the protection of medium-voltage/low-voltage transformers by a combined medium-voltage circuit-breaker/fuse provides an optimised solution. The circuit breaker/fuse has its place in smart grid investments [35].

The main objective of the paper [36] is to experimentally investigate the DC switching characteristics of a combination DC circuit breaker. The DC circuit breaker is a combination of a DC isolator and a fuse and is preferred in some DC switching applications.

III. Experimental Testing for Pressure Verification

It has been observed that the temperature level of the phenomena caused by breaking is between 2000 K÷30000 K and the current densities can subject any material to excessive stresses.

This article presents an experiment in which the values of the pressure exerted from the inside on the fusible fuse contacts and the porcelain outer casing are evaluated. The fuse is a classic design where the extinguishing medium is quartz sand.

The lower end of the fuse (without striker) has a special port to accommodate a pressure transducer (Fig. 2).

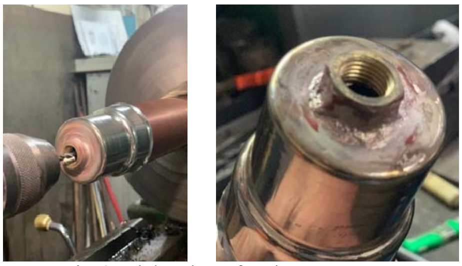


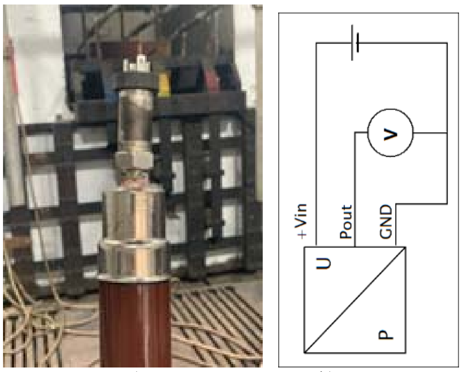
Fig. 2. High voltage fuse bottom contact

It was then fitted with an STS Sirmach ATM pressure sensor – Fig. 3.

The pressure sensor used in the experiments and mounted on the high-voltage fuse (Fig. 3) has the following technical characteristics: pressure measuring range: 2÷25 bar; analogue output: 0÷10 V; supply voltage: 15÷30 Vdc; operating temperature: -25÷85°C; accuracy: ≤ 0,5 / ≤0,25 / ≤ 0,1; response time: ≤ 1ms.

The acquisition system (Fig. 4) consisted of single-channel HV 6600 analog-to-digital converters (ADC) coupled via fiber optics to an high-speed transient recorder (TR) with a sampling rate of 25 MS/s at 16-bit resolution.

The acquisition system has an analog +/-0-100 VDC input, fully galvanically isolated with fiber optics and high immunity to electromagnetic interference. Perception software platform compatible with HBM GENESIS acquisition system. The correlation between pressure and voltage in the experiment: 2÷25 bar/0÷10V => 2,3 bar/V => p = 2,3* (Pout)+2 pressure sensor.



a) b)

Fig. 3. Pressure sensor (a) pressure sensor mounted on high voltage fuse; (b) pressure sensor wiring diagram

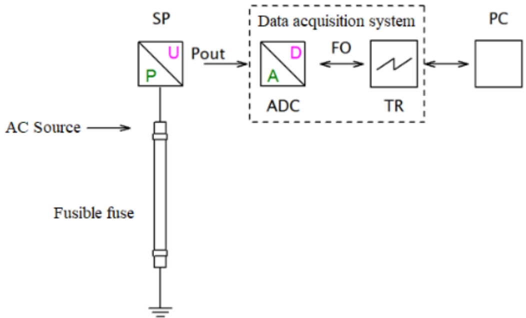


Fig.4. Data acquisition system

The circuit shown in Fig. 5 was used in the experiments and consists of: G - high current AC source 2500 MVA generator; XR - shock coils with 400 mΩ; MB1, MB2, MM – switchgear (MB1-master breaker computer controlled, MB2 – master protection breaker set to work after 200 ms, MM – master maker set to close in the zero of voltage to obtain the maximum peak of current); T - 80 MVA step-up transformers; R-C - transient recovery voltage regulation circuit (200 mΩ and 87 µF); O1 - current measurement; O2 - transient recovery voltage measurement; O3 - source voltage measurement; O – the tested fuse (24 kV, 25 kA, 50 A) equipped with pressure measurement as in Fig. 4.

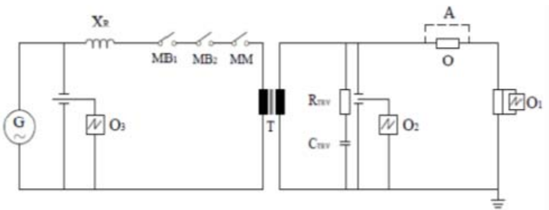


Fig.5. Circuit used in experiments

The signals from the current, voltage, and pressure transducers are acquired by an automatic measuring system and further processed.

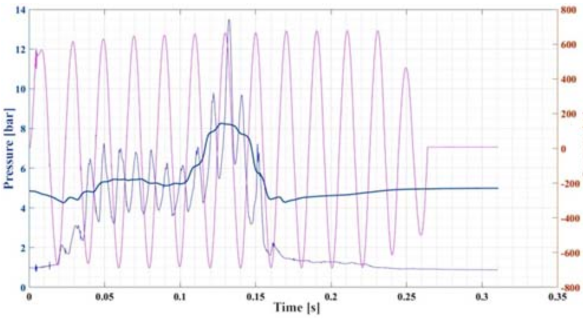
Before the experiments, the same circuit was developed in MATLAB Simulink and the oscillograms in Fig. 6 were obtained.

The extinguishing environment was not modelled in the simulation because it was considered empty. The voltage and current values, taking into account the connection at an angle of φ=18 electrical degrees, are consistent with the assumed values, but the values obtained for the pressure are several times higher than the assumed value.

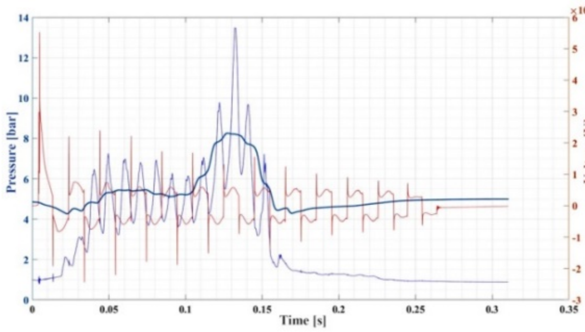
As we have already seen, the stresses that act on the porcelain casing of a fuse when an overcurrent occurs are: dielectric, thermal and mechanical, due to the pressure that builds up inside.

Almost everything is known about the dielectric stresses caused by operating overvoltage, but very little is known about the thermal and mechanical stresses, because the design of thermal and pressure transducers needs to be adapted. Making this structural adjustment is not easy, and these expensive transducers can be destroyed if the fuse blows.

Also, any design modification of the fuse body that deviates from the standard conditions and its characteristics may affect the breaking behavior, but there is no alternative.



a)



b)

Fig. 6. Oscillograms obtained from pressure simulations as a function of current (a) and voltage (b)

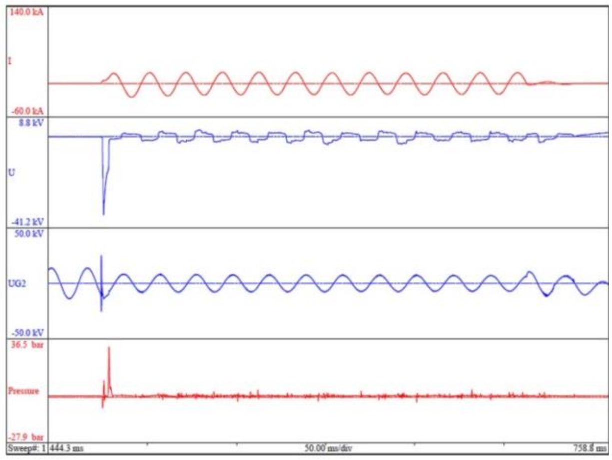
Measuring the pressure inside the fuse body can only be done invasively, and it is known that the porcelain casing of fuses is tested at a static pressure that can withstand several tens of atmospheres, but the processes during the breaking of a current are dynamic, resulting in much higher pressure shocks that lead to its rupture. Normally, when the current is correctly interrupted, the pressure in a fuse does not exceed 2 bar when the fuse melts, which is completely harmless for the casing and the caps, regardless of the arc energy developed, except, of course, for the thermal stress.

What happens inside the fuse if the arc fails to extinguish within 3-4 ms after being initiated? This can be seen graphically in Fig. 7 when a pressure surge in excess of 30 bar occurs with devastating effects on the fuse and surrounding equipment. In the experiment shown in Fig. 7, a breaking test is performed for a current of 14 kA_{rms}, assumed at a voltage of 36 kV_{rms} under the conditions defined by [33].

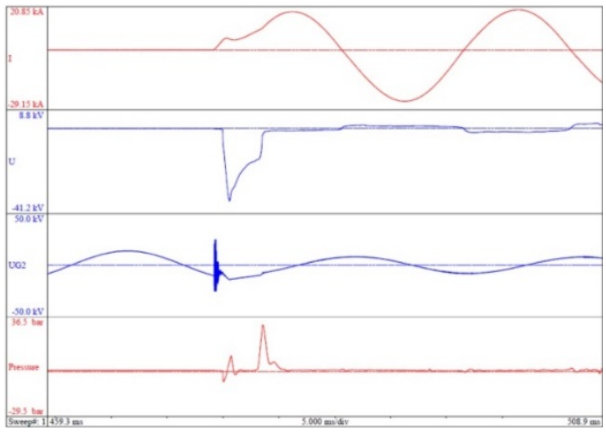
In the first part of the experiment, the fuse tries to limit the short-circuit current to a value of 5.6 kA in accordance with its limiting characteristic, but the conditions for extinguishing the arc in 3-4 ms were not met, and since the arc energy is high, 165 kA^2s, it leads to the explosion of the fuse. It can be seen how the high energy creates a pressure surge of more than 30 bar, causing the fuse body to break and the arc to last until the end of the test.

For comparison with Fig. 7, Fig. 8 shows an ideal test in which the fuse interrupts with minimal arc energy (area A) and another test, Fig. 9, in which a higher energy B is developed that cannot generate dangerous pressure on the fuse body.

Fig. 10 shows a low-amplitude ($500A_{rms}$) current breaking test for a fuse also equipped with a pressure transducer. The fuse, according to the limiting characteristic, should cut the current in about 10 ms, but it fails and the arc lasts for 260 ms, leading to thermal rupture of the fuse body (see Fig. 11) without the pressure exceeding 3.5 bar and pulverizing the fuse body, as happened in the experiment in Fig. 7.



a)



b)

Fig. 7. Oscillogram obtained from practical experiment (a) full duration of the current; (b) zoom on the occurrence of current

Values obtained at a current making angle of ϕ=48.4°: I_l= 5.6 kA; I_{rms}= 14.1 kA; t_k = 0.24 s; P= 31.4 bar; U_c= 35.4 kV; t_{pa}= 0.8 ms; t_{arc} = 3.5 ms; E_{total}= 170.4 kA^2s; E_{arc}= 165 kA^2s.

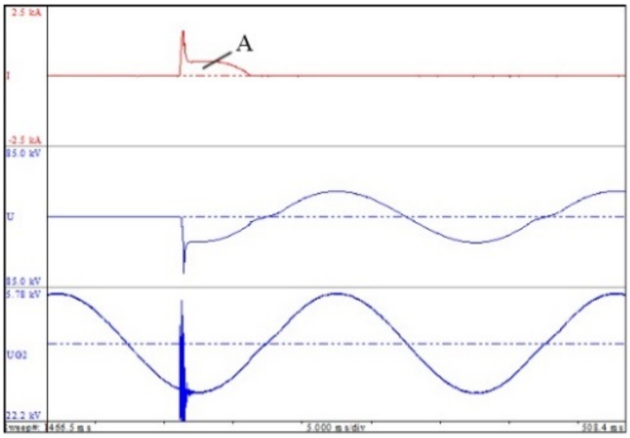


Fig. 8. Normal fuse behavior

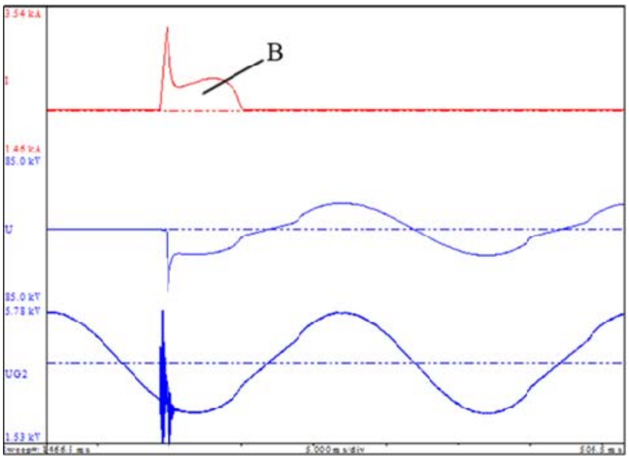


Fig. 9. Experiment on the release of high energy

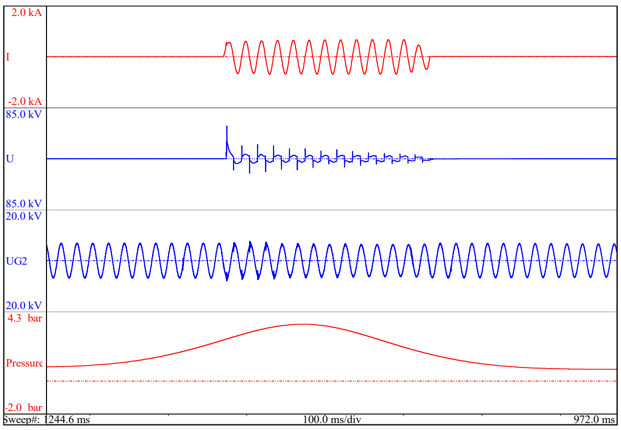


Fig. 10. Experiment for checking pressure

Fig. 10 shows the values obtained at a making angle of ϕ=7.1°: I_{pk}= 0.57 kA; U_c= 55.2 kV; Energy = 55.1 kA^{2}s; t_k= 0.26 s; P= 3.3 bar.

The real-life values obtained are higher (the pressure is 31.4 bar compared to 8 bar obtained in simulation, rest of the values are similar) that those obtained in simulation, because in the simulation it was not considered the extinguish environment.

The literature points that the maximum pressure point is in the middle of the fuse, proven wrong by real life experiments with pressure measurements and high-speed video recording. The maximum pressure is obtained at the extremities of the fuse.

Fig. 11. Experiment for checking pressure

IV. Experiments To Verify The Pressure In Switchgear With Fuse Combinations

It is well known that successful breaking of high currents does not create dangerous pressures in the fuse body. For the purpose of the experiments, fuses were designed with imperfections so that they could not limit and break the current, and the metal envelope of the switchgear was fitted with a membrane to limit the pressure during the short-circuit. Pressure transducers have also been fitted to the body of the metal envelope to measure envelope pressures.

The values of these pressures generated in the envelope depend very much on the value of the short-circuit currents and their duration as well as the shape and volume of the envelope.

The values of these pressures are not known in the theory, because the electric arc that generates the pressure has an unpredictable evolution due to the electric circuit, the insulating parts and the ferromagnetic walls of the envelope and the electromagnetic forces that occur.

In addition to the pressure transducers, the sealed metal envelope is equipped with a valve (diaphragm) that bursts at a certain pressure level, preventing it from reaching values of tens of bars and limiting its disintegration with consequences and losses in the installation.

The experiments include tests strictly complying with the requirements at different parameters: I = 16 kA$_{rms}$, U = 24 kV$_{rms}$; 36 kV$_{rms}$, in single-phase and three-phase circuits, following the behaviour of the envelope under pressure.

The position of the experimental test equipment and the fuse socket is shown in Fig. 12.

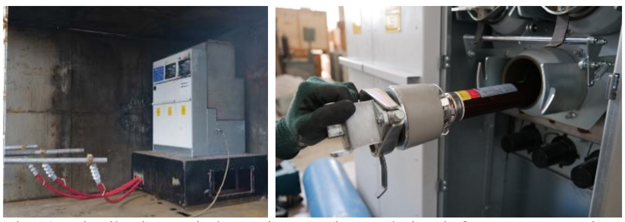


Fig.12. Distribution switchgear in experimental circuit for pressure testing. Fuse placement on a side phase.

A single phase experiment is shown in Fig. 13. A single fuse placed on a side phase ignites the arc in the enclosure at I = 16 kA$_{rms}$, arc voltage drop U = 0.5 kV$_{rms}$, t = 1 s and produces an energy of 280 MA^{2}s, resulting in a pressure shock P = 1.5 bar.

Within 20 ms of the pressure shock, the diaphragm (pressure valve) operates and limits the effect of the pressure on the envelope.

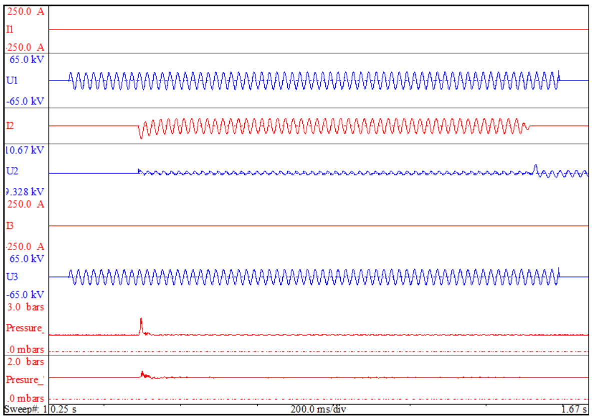


Fig. 13. Single phase experiment to check the pressure on the first lateral phase

The second experiment, shown in Fig. 14, is also a single phase test on an intermediate phase with the parameters I = 16 kA$_{rms}$, U = 0.5 kV$_{rms}$, W = 283 MA^{2}s, t = 1 s.

Two pressure transducers were mounted on this test specimen, one close to the fuse and the other as far away as possible, and the pressure values P_1 = 2.44 bar, P_2 = 1.5 bar were recorded, proving that the extremely dynamic pressure manifests itself dangerously close to the arc, as in the first experiment. The pressure valve operates in 20 ms, preventing the metal envelope from exploding.

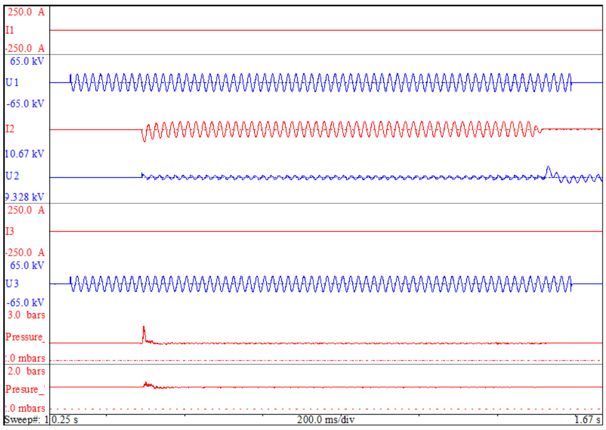


Fig. 14. Single phase experiment to check the pressure on the second lateral phase

The three-phase test (three fuses were installed) with parameters I = 15 kA$_{rms}$, U = 0.6 kV$_{rms}$, t = 0.5 s, giving an energy W = 118 MA^{2}s, P = 4.5 bar, is shown in Fig. 15. The pressure membrane works and limits the effects of pressure, but as in all experiments, the arc does not extinguish and continues to produce thermal and electrodynamic effects until the end of the test.

The experiment in Fig. 16 is similar to the previous one with the parameters I = 16.5 kA$_{rms}$, U = 0.55 kV$_{rms}$, t = 0.5 s, W = 130 MA^{2}s, P = 4.72 bar, and the result is similar and the pressure valve works after about 80 ms, releasing the pressure.

In the experiment in Fig. 17, a three-phase test is carried out with three fuses in the circuit, producing a three-phase arc with the parameters I_{med} = 16 kA, U = 0.5 kV, W = 300 MA^{2}s, t = 1 s. Two pressure shocks of about 4 bar are produced, because the pressure valve did not release all the pressure, being locked in the middle position, then the pressure began to rise again for 100 ms, and when it was high enough, it completely released the discharge surface, limiting the destruction of the metal envelope.

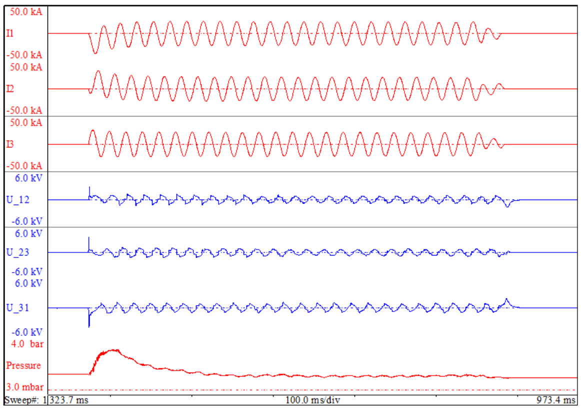


Fig. 15. Three-phase experiment for pressure verification

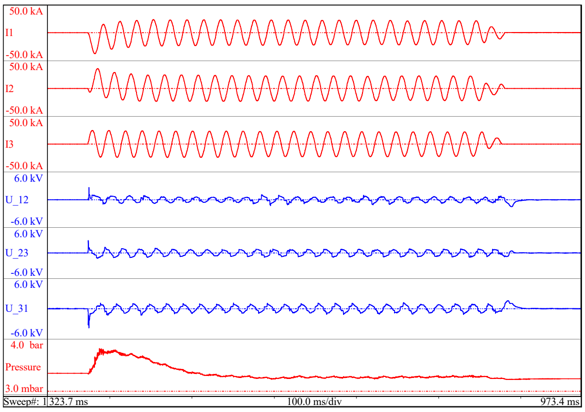


Fig. 16. Three-phase experiment for pressure verification

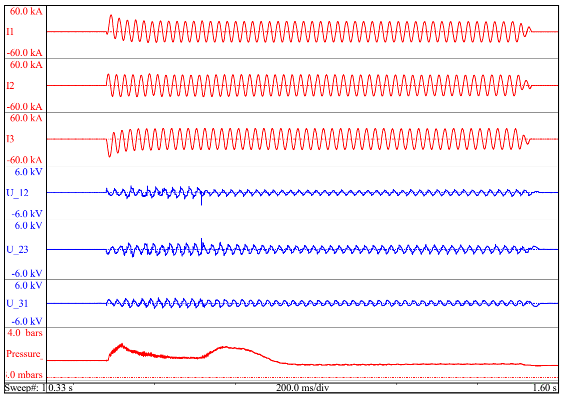


Fig. 17. Three-phase experiment for pressure verification

In all the experiments carried out so far, the pressure relief valve (diaphragm), set at a value above 2.5 bar, has functioned correctly, limiting the effects of an arc. However, there are also situations where it is not properly adjusted and the pressures in the metal envelope are devastating, as shown visually in Fig. 18.

Fig. 19 shows the oscilloscope recording for the destructive test, using similar parameters to the previous experiments: I = 16 kA$_{rms}$, U = 0.55 kV$_{rms}$, W = 290 MA^{2}s, t = 1 s, the pressure was not immediately released, resulting in the destruction of the switchgear.

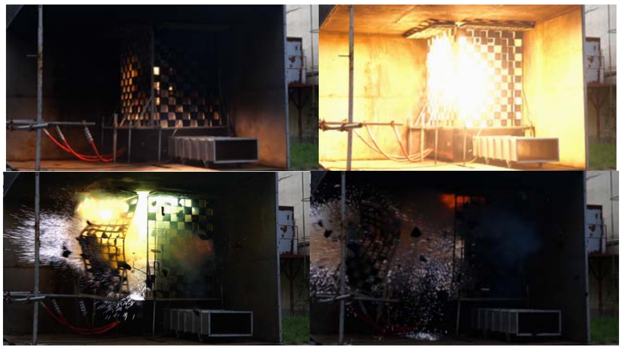


Fig. 18. Destructive experiment for pressure verification - photo steps

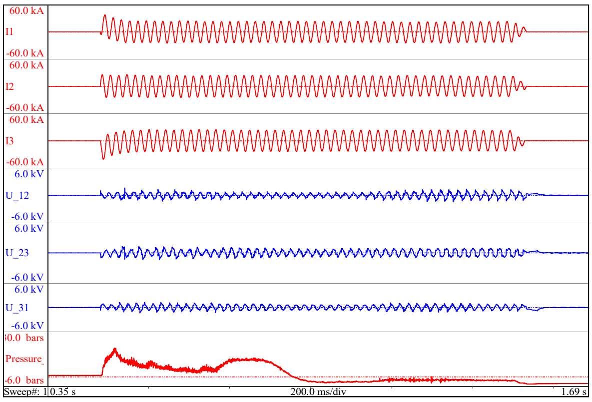


Fig. 19. Three-phase destructive experiment for pressure verification

On the basis of tests carried out on distribution switchgear containing fuse/load break switch combinations, the following pattern of events can be observed. In the first phase, the short-circuit current causes the fuse temperature to rise from a nominal value to the first-state transition point in the material. An increase in resistivity can therefore be estimated as a small linear gradient of increase and is manifested as a slight increase in voltage from the zero values recorded at the element terminals. This voltage rise occurs approximately at the beginning of a half sine period. The fact that the voltage increases non-linearly with resistivity indicates that the material is in the same state of matter as before, but the transition from solid to solid melting point is about to occur. A sudden increase in voltage lasting 0.2 ms indicates that the liquefaction temperature has been reached.

V. CONCLUSIONS

This article presents the importance of analyzing the breaking behavior of high-voltage fuses and emphasizes the pressure values at the ends of the fuses, important values in the design process.

The waveforms obtained can be divided into the pre-arc period and the arc period. A series of initial conditions were replicated in this study and their results were observed in the experiments. Parameters that control a potential outcome are the sinusoidal quadrant where the preliminary arc starts, the surface imperfections and internal crystalline structure of the copper wire, the surrounding environment, the geometry of the conductive fuse relative to the materials, and finally the quality and geometry of the rest of the device. The geometry of the fuse material was simple and all fuses used the same type of fuse elements, providing a common reference for the rest of the parameters.

Based on the presented experiments, it can be observed a pattern of events. First, the short-circuit current causes the temperature of the fuse to rise from a nominal value to the transition point from the first state of the material. Thus, an increase in resistivity can be estimated as a small linear gradient of increase manifested by a slight increase in the voltage at the element's terminals. This voltage rise occurs approximately at the beginning of the first half of the sine wave period.

The fact that the voltage increases in a non-linear manner due to resistivity indicates that the material is in the same state of matter as before, but the transition from the solid to the melting point is about to occur. A sudden voltage increase in 0.2 ms indicates that the pour point has been reached.

As fusible elements go from solid to liquid the inner parts are hotter than the outer parts and melt first. Then the melting zone extends to the periphery.

At melting temperature, the resistivity of the molten material is much higher than the solid material one, and increases as melting continues. (Specific resistivity data for copper are: solid at melting point 10.2×10^{-6} Ohm-cm, liquid at melting point 21.3×10^{-6} Ohm-cm, and molten 13.8×10^{-6} Ohm-cm) [3, 7-10].

As it can be observed from the figures, the step increase in voltage is followed by another voltage increase that can last 2~6 ms.

Whether this increase is linear, a combination of linear increases of any duration depends on the phase of the sine wave and the power that passes through the wire and is converted. The equations for the temperature distribution estimation on the fusible elements can be found in the literature [8].

One of the key findings is the value of the pressure exerted on the caps of a high-voltage fuse, which has not been tested before. It also confirms the theory that the pressure at the ends of the fuse is directly proportional to the recovery voltage.

Analysis of fusible elements after experimental testing and fulgurite distribution confirms that the electrical conductivity of quartz sand to a fused conductor is very low at the pressures evaluated.

Experiments have shown that the maximum pressure is reached during the arcing period, an important finding for a high-voltage fuse contacts design and for a full understanding of the phenomena that occur inside it during the opening of the electrical circuit.

The evolution of fuse element disintegration over different time periods can be controlled by controlling the Joule energy in the fuse wires, which is directly proportional to the pressure in the fuse contacts.

The scientific contribution consists in the calculation and realization of the test circuit for pressure verification, solution for creating the experimental model, study of the most unfavorable situation, solution for the acquisition of the pressure values and the results interpretation.

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