THE ARCING VOLTAGE IN HIGH VOLTAGE FUSES

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Abstract.
Prime parameters governing the arc voltage of fuse elements are investigated. The dependency of the electric field-strength on current is analysed and checked by experiment. The arc channel growth was observed from fulgurite structures. These results, in combination with data on burn-back were used to predict the arc voltage.

INTRODUCTION.

In principle the arc voltage of an operating fuse can be calculated by (neglecting electrode effects):

$$U_{arc} = \int_0^{\ell} E\,dx = \int_0^{\ell} \frac{\rho I}{A}\,dx. \qquad \text{Here } \ell \text{ is the arc length,}$$

ρ the specific resistance of the arc plasma, A the arc cross-section, and E and I the column field-strength and the current respectively. The solution of this equation however is complex as ℓ, ρ and A vary with current, position and time. Also the current may vary from kA to zero in a few msec.

In this report we describe some theoretical and experimental results on these main parameters which control the arc voltage. Arc lengthening by burn-back and arc expansion by volume increase due to melting of silica have been investigated together with the dependency of the field-strength of the arc plasma on current. These results were combined and used to calculate the arc voltage for specific conditions.

THE ARC MODEL.

Wheeler [1] and Gnanalingam [2] developed one-dimensional and stationary models of fully ionized arcs. They calculated the field-strength E starting from a simple energy balance where Joule heating is solely balanced by thermal conduction. In a one dimensional approximation (see fig. 1; $D \ll b$) the power balance can then be written as:

$$\frac{d}{dy}\left(\lambda \frac{dT}{dy}\right) = -\,G E^2 , \quad \text{where } \lambda \text{ is the thermal conductivity,} \qquad (1)$$

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G the electrical conductivity and T the temperature. Spitzer's [3] relations for electrical and thermal conductivity of an ionized plasma are used, together with the boundary conditions:
$(x = 0;\ \frac{dT}{dx} = 0;\ x = \pm\ 0{,}5\ D;\ T = 0)$. The power balance can be solved semi-numerically and analogous to a method used by Wheeler [1].
The result is [2, 4]:

$$E = 3{,}4.10^{-2}\ [Z \ln \Lambda]^{0{,}4}\ I^{0{,}4}\ b^{-0{,}4} D^{-1}\ [Vm^{-1}] \qquad (2)$$

Z is the ion charge and Λ the Coulomb cutt-off. Dependant upon the plasma temperature and density Z may range between 1 and 4 whereas $\ln \Lambda$ may vary between 5 and 10.
Eq. (2) shows that provided the arc dimensions remain the same the field-strength E is proportional to $I^{0{,}4}$. The validity of this result was investigated by experiment, in which the fuse arc was short-circuited [4].

Copper strips (cross-section 5 x 0,2 mm^2) are mounted in a cartridge which is filled with pure sand. After compacting the sand the cartridge is placed in a critically damped LRC-circuit (fig. 2). Initially current is flowing through a breaker in parallel with the fuse element. Near current maximum the breaker opens and the current commutates into the fuse element. The arc initiates at a notch in the centre of the strip and arcing occurs during some milliseconds at a nearly constant current (variation less than 5%). Current is again commutated by firing a parallel thyristor and the decrease of arc current and arc voltage is registered simultaneously by a computer system. The time the current needs for commutation is varied by the series inductance L_c. Its value is chosen such that the commutation time (t_{com} in fig. 2) is significantly longer than the arc time constant which may range from several microseconds up to tens of microseconds [5]. Too long commutation times are prohibited by the demand that the arc channel dimensions shall not change during current decay. (The assumption is made that the lumen dimensions are identical with the arc channel dimensions, at least for not too low currents).
Fig. 3 shows an oscillogram of fuse current and arc voltage in the commutation phase. The voltage-current characteristic obtained is plotted on a logarithmic scale. The curve is very similar to the quasi-static characteristic measured by Maecker [6] for wall-stabilized arcs. For low currents the arc voltage is independant of current [7]. In case of $I > 200$ A the characteristic closely follows a relation $U_{arc} \sim I^{0{,}4}$ as predicted by eq. 2. In a series of 15 experiments the current prior to commutation was varied in the range 800 - 2200 A, and the value of β in $V \sim I^{\beta}$ was determined. An average value of $\beta = 0{,}41$ was found [4] which agrees well with the theoretical result. It was proven that β did not depend on the commutation time provided its value was not less than approx. 60 µsec. For lower values deviations from the static characteristic were observed.

THE ARC CHANNEL EXPANSION.

Due to the transfer of arc energy to the surrounding sand melting and evaporation of silica will occur. By the melting process an increase in space occurs as the molten quarz will occupy only a part of the original sand volume. Due to the arc pressure the molten silica will (partly) be pressed into the voids of the solid sand leading to a further increase of

the lumen area. Expansion of the arc is thus possible and will lead to a decrease of the arc voltage.
Using a one-dimensional approach the increase of the thickness D (fig. 1) was calculated on the basis of an energy balance [4]. Under the assumption that the arc energy is transferred exclusively in the $\pm$ y direction and is used for the heating and melting of silica it was found that (for a constant current):

$$D = \sqrt{(D_o')^2 + B\,t} \qquad (3)$$

Here D_o' is the initial thickness of the arc channel at the onset of arcing and B a parameter whose value depends on the current and the properties of the silica and the arc discharge. (B has the dimension of the diffusion coefficient). The parabolic dependency of the thickness on time was investigated by experiment.

Copper strips (5 x 0,1 mm^2; 5 x 0,2 mm^2) were arced at constant current in the range of 300-2600 A. Arcing was initiated at a notch in the centre of the strip. Each fulgurite was cut at several places and from each cross-section the lumen dimensions were measured by microscope. The width D (fig. 1) showed a small increase (less than 20%) in comparison with the increase in thickness (up to ten times) and justified therefore a one-dimensional approach.
In order to check eq. 3 D^2 was plotted as a function of the distance x from the fulgurite ends (see fig. 4). Because the burn-back rate V_f in each experiment is known the x-axis can be transformed into a time axis by $t = xV_f^{-1}$. The underlying supposition of this transformation is that the local channel growth at a specific cross-section is entirely decided by the energy flow in that cross-section (no axial dependency). Probe experiments showed that this supposition is justified [4]. As a result the variation D with position is transformed to a *local* variation of D with time. 17 Fulgurites were investigated in this manner. Although the data points showed a certain scatter and deviations occurred for longer arcing times a fair lineair relation between D^2 and t was found for all currents investigated. On the average no differences were found between the channel growth on cathode- or anode side. The value of B in eq. 3 could be established and proved to be:

$$B = 1{,}23.10^{-8}\ I^{1,4}\ (m^2 sec^{-1}) \qquad (4)$$

It was not possible to establish the initial value D_o' by experiment. Generally it will have an average value larger than the width of the fuse element due to the voids present between the sand grains and the fuse element [4].

THE BURN-BACK RATE.

Erosion of the fuse element by the arc footpoints leads to an increase in arc length and a rise in the arc voltage. Generally the rate of arc length increase is a factor ten higher than the rate of increase of the arc cross-section. As a consequence (cf eq. 2) the increase of the arc voltage by burn-back is significantly higher than the decrease of the arc voltage by channel expansion.
Experimental and theoretical results on the burn-back rate of silver and copper elements have been reported elsewhere [8]. We have found that in

case of moderately high current densities and not too long arcing times the burn-back rate V_f is given by $V_f = c\,J$ ($msec^{-1}$) (5)

Here J is the current density in the fuse element and c is a material constant which has a value of $1{,}06.10^{-9}$ (m^3C^{-1}) for copper elements and $1{,}03.10^{-9}$ ($m^3\,{}^{-1}$) for silver. For high current densities and for long arcing times preheating of the fuse element occurs and this increases the burn-back rate value [8].
In recent experiments silver elements were deposited on quarz glass as a carrier and enclosed in compacted sand. The burn-back rate was measured for different values of the thickness of the element. For a value larger than 50 µm results were the same as found for elements entirely enclosed in sand. However for a thickness of 15 µm the burn-back rate decreased by a factor two i.e. the value was c was $c = 0{,}5.10^{-9}$ (m^3C^{-1}). Analysis showed that the decrease of the burn-back rate was not due to the presence of the quarz carrier but most likely is caused by a restricted energy transfer from the anode/cathode fall regions to the very thin fuse element.
It seems therefore that eq. 5 is only valid provided its thickness is larger than 50 µm; for lower values the constant c depends on the size of the element.

THE ARC VOLTAGE.

Combination of the data on arc plasma, arc channel expansion and arc elongation gives the possibility to calculate the arc voltage. A series of experiments were done [4] in which the arc voltage of Cu fuse elements ($5 \times 0{,}1\ mm^2$; $5 \times 0{,}2\ mm^2$) were registrered as a function of time. The elements had a single notch. Current was kept constant during arcing. During the entire observation time burn-back of the element occurred. The current density in the experiment was varied between $0{,}7.10^9$ - $3{,}8.10^9$ Am^{-2}.
Using the equations mentioned in this report one can calculate the arc voltage as a function of time in case of constant current.
The result is:

$$U_{th} = 0.068\ [Z \ln \Lambda]^{0,4}\ I^{0,4}\ D_o'\ V_f\, b^{-0,4}\, B^{-1} [\sqrt{1 + B(D_o')^2 t} - 1]$$

In order to compare theoretical and experimental values we used the function $R = U_{th}.U_{exp}^{-1}$. A value of $Z \ln \Lambda = 3{,}56$ was taken as derived from the work of Chikata *et al* [9].
Fig. 5 shows some results. For current densities less than $2.10^9 Am^{-2}$ the results are quite satisfactory as they lay close to an average value R. For higher current densities deviations occur. Analysis showed that they are mainly due to preheating of the fuse element which leads to higher burn-back rates. If this effect, which was not included in the calculations, is taken into account, the agreement will be improved.
The average value of R for 17 measurements was $\bar{R} = 0{,}62$ (instead of 1). This difference is probably due to a too low value of $Z \ln \Lambda$. In case of $Z \ln \Lambda = 11{,}5$ an optimum agreement is found. This value is also more in accordance with Maecker's experiments on wall stabilized arcs. Another unsure parameter is the initial thickness of the arc D_o'. The value was estimated [4] from the space available between the sand grains and may have been taken too low.

CONCLUSIONS.

We have found expressions for the burn-back rate of fuse elements, the arc expansion in the fulgurite and the dependency of the electric field strength on current. Combination of these effects make it possible to calculate the arc voltage.

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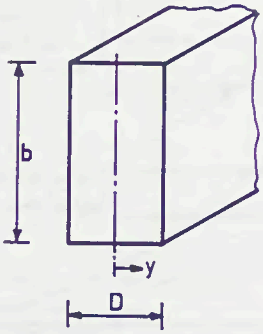

Fig. 1 Dimensions of the rectangular arc.

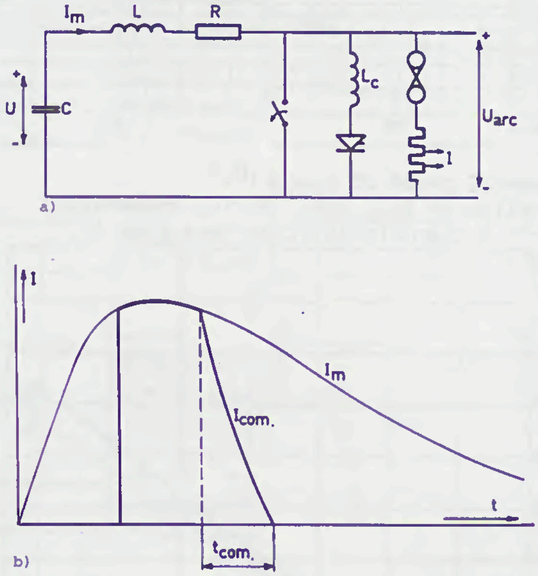

Fig. 2 a) Experimental circuit R = 4,4 ; L = 45 mH,
C = 6,8 nF; U = 0 - 15 kV; L_{c} = 10 - 200 µH.

b) Current flow: I_m through the main circuit
I_{com} through the fuse.

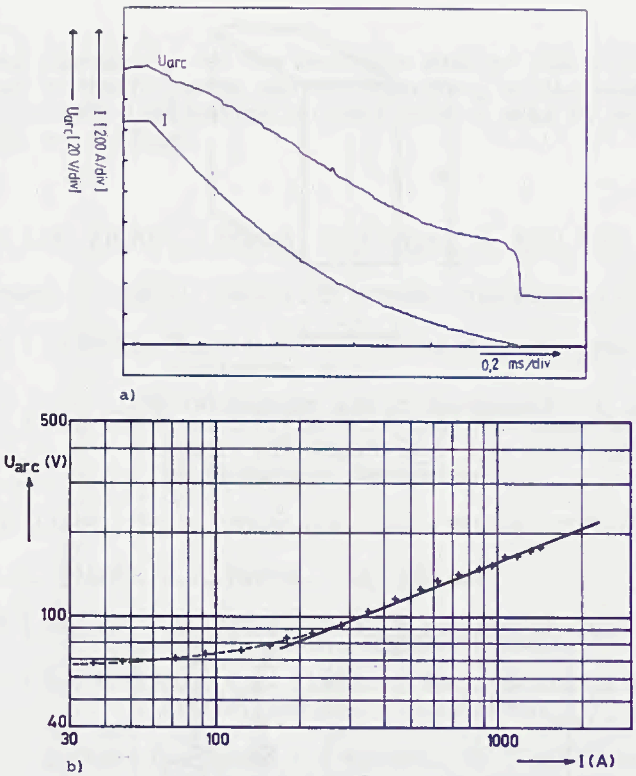

Fig. 3 Experimental proof of $U_{arc} \sim I^{0,4}$
a) variation of U_{arc} and I during commutation
b) U_{arc} - I characteristic derived from a).

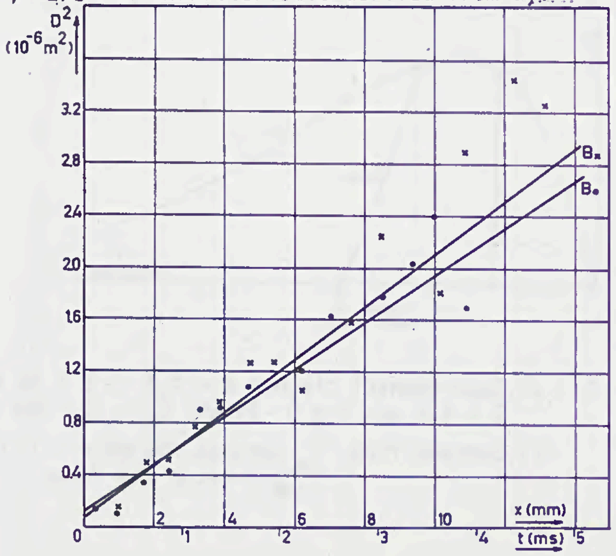

Fig. 4 Increase in channel thickness for copper 5 x 0,2 mm^2
I = 2420 A (.) anode side; (x) cathode side.

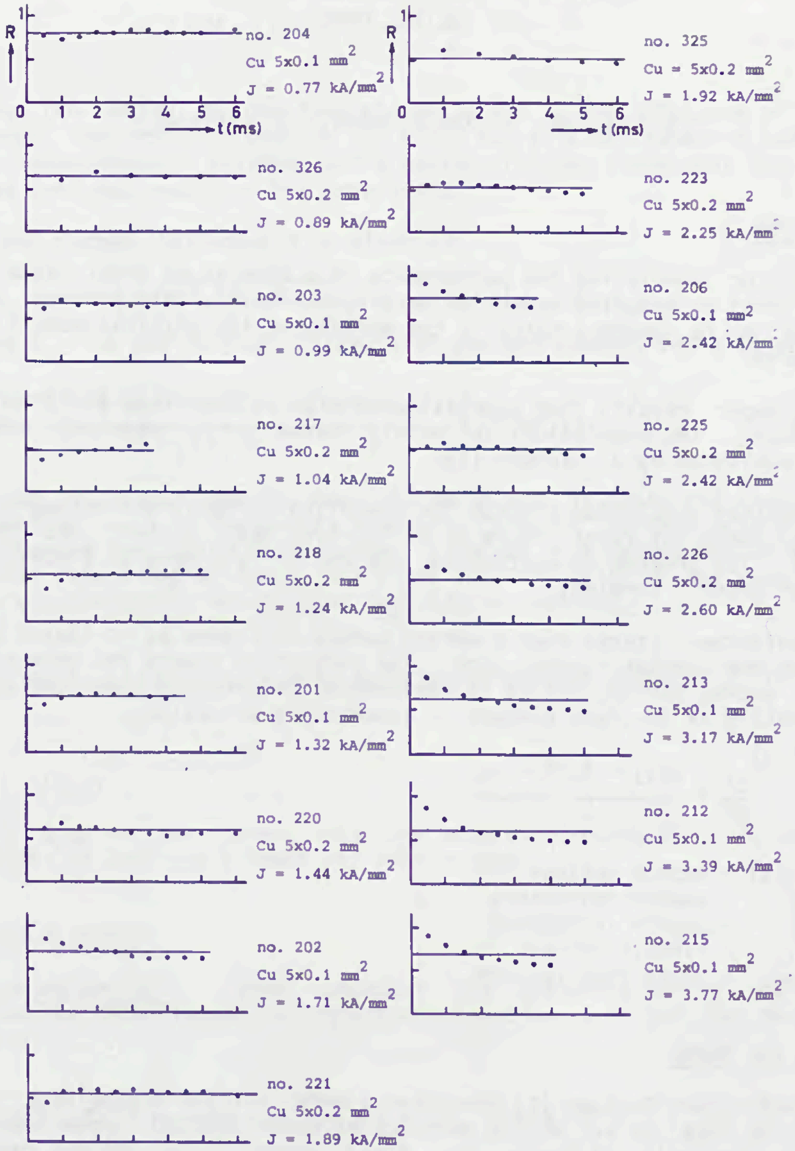

Fig. 5 Comparison of measured and calculated values of the arc voltages in different trials.
$R = U_{th}.U_{exp}^{-1}$