FUSE ARC VOLTAGES, FROM STRIATION UNTIL GRADUAL BURNBACK

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Abstract: For fuses the character of of the arc voltage generation can be distinguished in the ultrafast voltage peaks as observed for uniform wires and the more continuous arc voltage generation during gradual burnback. This article intends to present one general model which combines both arcing descriptions into one general model, based on many experimental observations. The work is mainly to extend Daalder's model for sand filled fuses to substrate fuses. It proved to be able to describe measured performances of test samples and commercial high voltage fuses.

I. Introduction

Fuses, especially with sand filling, have been widely used as protective devices in electric power networks. In case of a fault, fuses operate to interrupt the circuit, by introducing a circuit element with a voltage fall above the source. However, for a critical range of currents the heat dissipation inside fuses may cause fracture of the fuse body. To establish certain criteria for developing fuses, it is therefore of importance to understand the arcing behavior of fuses. During the past 30 years, several empirical or semi-empirical models have been proposed for the arcing process, concerning arc initiation, burnback and column expansion, and the related voltage rise. For system studies, where it may be required to model several fuses simultaneously in 3-phase systems, preferably a simplified model like Wilkins' model [1] seems most appropiate. For fuse designers however, a more complicated model, describing real physical processes, might be preferred. The objective of this work is to contribute to the physical arc modelling: the choice has been made for Daalder's model [2] extended to substrate type fuses, including experimental results with test samples as well as commercial fuses.

II. Combined modeling

II.1 General description of arcing mechanisms

In principle three situations can be distinguished, dependent upon the fuse configuration and the level of the current:

1. For uniform wires or strips, as used in miniature fuses, a number of small arcs with fixed distances are initiated across the whole length of the conductor. Within an extremely short time these arcs merge to one arc, if there is sufficient energy available. This arcing process is known as striation[6].

2a. For fuse strips with notches, in the high current range, initial arcing takes place in the notches similar to the uniform wire behavior. Afterwards the wider strips gradually burn back. During this period the arc elongation has a positive effect on the voltage increase, while the expansion of arc column has a negative effect. Probably also the pressure rise in the arc causes a voltage increase, while the pushing away of molten sand surroundings enable a pressure relief with on its turn a fall of voltage. The solid strip part is heated during this whole process, which can accelerate the burnback. However if the melting energy is reached an exponentially rise of the burnback rate occurs, again with similarity to the striation process [7].

2b. Many fuse designs have abilities to stimulate fast arc initiation in over load range, for instance, fuse strips with M spots. In the overload current range the arcing of these fuses is initiated at the M spots. Afterwards a gradual burnback takes place. The voltage rises because of arc lengthening, which is more or less compensated by arc broadening. Alternative concepts use isolated low temperature melting conductors in series.

II.2 Expression for the arc voltage

In general, arc voltage consists of the electrode voltage fall and column voltage. After fuse wires or strips are melted, one or more arcs are initiated. Each resulting arc voltage U is described with a general equation

$$U = U_{ac} + \int_0^{l_{arc}} E \, dl$$

where E is electric field, which can vary along the arc column. U_{ac} is the anode - cathode voltage, and l_{arc} is arc length. In case of more arcs in series, the total arc voltage can be obtained by considering individual contributions.

II.3 Initial arc voltage

In the case of striation, which is supposed to be relevant for short arcs in notches and sometimes for the wider cross sections, a sudden peak arcing voltage is reached within a very short time. The peak value of the arc voltage for the individual arcs, as well as the total voltage can be described by the equations as presented by Hibner [3]. At the arc initiation, striation takes place, the peak arcing voltage can be assumed to be contributed by several short arcs The initial peak arcing voltage for a large range of initial current values i_0 and cross sections S has been found to be

$$U_o = \rho_o l \sqrt{\frac{i_o}{S}}$$

where l is the initial arc length and Hibner constant ρ_0=0.5 V $A^{-0.5}$.

II.4 The electrode voltage fall

The electrode voltage fall U_{ac} is sometimes described by the equation of Dolegowski [4], although the actual existence of the electrode voltage fall for fuses is under discussion. For current density $j < 8$ kA.mm^{-2}, the electrode voltage fall U_{ac} of anode and cathode is presented as:

$$U_{ac} = 20 \pm 5 + k\, i^{0.39}, \text{ with } k = 1.5.$$

II.5 Electric field E

Assuming the thickness D of the arc channel is much small than its width b, the energy balance equation is solved by polynomial approximations analogous to a method used by Wheeler [5]. The result of electric field E is

$$E = q(Z \ln \Lambda)^{0.4} \frac{I^{0.4}}{b^{0.4} D}$$

where Z is the average charge, Λ is the Coulomb cut off and $\ln\Lambda$ varies slowly with Z, T and the electron density n_e, q is a constant (0.034). For copper fuse elements (5*0.2 mm^2), $Z \ln\Lambda$ = 11.5 was found.

II.6 Cross sectional area of arc column

If an arc column is assumed with the thickness D of the arc channel much smaller than its width b, the channel expansion can be described by

$$\frac{dD}{dt} = \gamma\left(1 - \frac{\rho_s}{\rho_l}\right)\frac{E\,i}{2bH}$$

with enthalpy increas H, degree of molten silica γ and ρ_s or ρ_l specific density in solid or liquid state. Introducing the relation between E and I, the thickness can be found as

$$D = \sqrt{D_0'^{\,2} + Bt}$$

where D'_0 is the initial thickness of the arc channel. The initial channel thickness D_0' was assumed to consist of the element thickness D_0 and the contribution d_e due to sand grains, it is written as

$$D_0' = D_0 + 2d_e$$

The increase for one side due to sand grains is

$$d_e = \left(1 - \frac{\pi}{3\sqrt{3}}\right) R$$

In principle, determination of initial thickness D_0' should be made on the basis of measurements of fulgurite expansion., In our opinion, D_0' should include element thickness, air space among sand grains and the increase due to arc pressure. Therefore, the value of initial thickness D_0' will be larger than that given by Daalder's formula here. Especially, this may effect the arc channel expansion for very thin elements.

The slope B for time t is defined as

$$B = q(Z \ln \Lambda)^{0.4} \frac{I^{1.4}}{b^{1.4}} \frac{\gamma}{H}\left(1 - \frac{\rho_s}{\rho_l}\right)$$

with ρ_s/ρ_l = 0.68 and $H/\gamma = 3.9 \cdot 10^9$ J.m^{-3}.

Again concerning the arc channel expansion, γ indicates the degree of the flow of molten silica. To maintain the arc, sand melts and silica vapor contributes to arc pressure, thus γ will be influenced by grain size of sand, the viscosity of molten silica and the pressure of arc. In case of $\gamma = 1$, no flow of molten silica occurs, the channel expansion is purely due to fusion of sand. For $\gamma > 1$, of course, the flow of molten silica takes place. Because the increase in pressure can accelerate the flow of molten silica, the effect of pressure on γ should be considered for further studies of arc channel expansion.

This value consists of the element thickness D_0 and the contribution due to sand grains. In our opinion, it gives actually the lower limit, because the space among grains still can be taken by arc in spite of the arc pressure. If the thickness increase due to the initial arc pressure is assumed to be $k*R$, then the minimum and the maximum initial thickness can be expressed as

$$D_0^{'} = D_0 + d_e \ ,$$

$$D_0^{'} = D_0 + d_e + k * R$$

Similar to the description of the initial arc thickness $D_0^{'}$, the initial arc width b_0' in its minimum and maximum can be expressed respectively as

$$b_0^{'} = b_0 + 2 * k * R,$$

$$b_0^{'} = b_0 + 4 * k * R$$

From a wide range of experiments, k can be found to be about 2. This means that if sand is properly compressed, an extra increase in order of grain size may be expected. During arcing process, the initial width keeps more or less the same as compared with the thickness increase. For fuses with compact sand, the initial arc width is the same, while the initial thickness should include the contribution of the other side.

In relation with the arc column expansion, the constant B can be defined in accordance with different with of the elements. For substrate fuses, the expression B can be rederived as

$$B = 2.27 * 10^{-12} \frac{I^{1.4}}{b^{1.4}}$$

II.7 Burn back velocity V

The single side burnback rate is determined by the element erosion which is mainly due to local electrode effects, it is expressed [2] as

$$V_{th} = \frac{U_{con} \, j}{H}$$

where j is the current density in the strip, U_{con} is the heat loss per Ampere from the arc to the strip, and H is the enthalpy increase for arc interface before a strip part is removed due to arc.

The enthalpy increase per unit volume H is defined as

$$H = C_s*\rho_s*(T_m-T_b) + L*\rho_s + C_l*\rho_s*(T_d-T_m)$$

with melting temperature T_m, initial temperature T_b, C_s or C_l for specific heat in solid or liquid state and L heat of fusion, while T_d = 1700 chosen for silver elements.

For small J^2t value during the arcing ($J < 8$ kA.mm^{-2}), $V = C*j$ is established with $C = 1.06$ copper elements and $C = 1.03$ silver elements. For substrate fuses with silver elements plated on the glass, the constant C was found to be 0.66. This can be realized by a lower value of U_{con} or a higher value of H, however, the exact situation in the process is not clear. For high current densities (>8 kAmm^{-2}), or long enough time periods, experiments show that V increases exponentially with J. The consideration of H should be interpreted numerically with small timesteps [7].

III. Modeling results and experimental verification

In this section, not published experimental results (with DC currents) of the Eindhoven laboratory will be compared with the values found from the complete arc modeling computer program. Substrate fuses were used in experiments as test objects. First two sets of test objects were used. The silver element was positioned on the quartz glass and surrounded by sand fillers with grain size of about 0.2 mm. The element thickness of the strip part is 10 µm. For the first set, the width of the band was b_b = 2 mm, while the notch had a width b_n = 0.3 mm and length 0.8 mm. For the second set, the width of the band was b_b = 4 mm, while the notch had a width b_n = 0.3 mm or 1 mm, both with length 20 mm.

Figure 1 shows a typical picture of the fulgerite after arcing. Clearly the one side arc expansion is observed.

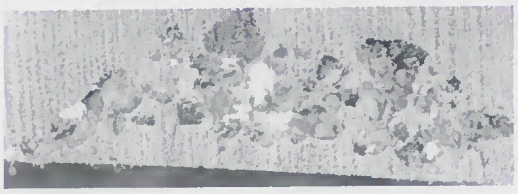

Figure 1. Fulgerite of an arc channel on substrate base.

Table 1 compares experimentally found values and calculated results for the initial arc voltage V_0 , peak arc voltage V_{top} and arc voltage at the end of current pulse V_e . In Table 2 the calculated values for the cross sectional area A_{cal} and end voltage V_{ecal} at the end of the current pulse are compared with experimental results.

Table 1 Arc voltage comparisons of measurements with calculations (l_n = 0.8 mm)

I_p	V_e	V_e (T)	V_0	V_0 (T)	V_{top}	V_{top} (T)
A	V	V	V	V	V	V
32	140		45		75	
31	117	91	39	42	-	60
31	96		39		71	
61	291		78		84	
60	366		45		81	
59	392	227	53	50	81	72
90	389		55		76	
91	431	376	58	55	85	82
92	474		70		78	
120	616	530	60	65	85	89
152	818	692	79	63	116	96
152	638		60		90	
185	-		110	65	140	101

Table 2 Comparisons of measured and calculated cross section area and end voltage

b_n [mm]	I [A]	t_b [ms]	A [mm^2]	A_{cal} [mm^2]	V_e [V]	V_{ecal} [V]
0.29	40	1.90	0.29±0.05	0.205	536	674
0.29	40	1.28	0.22±0.07	0.192	614	694
0.29	60	1.01	0.31±0.05	0.203	605	804
0.29	60	0.92	0.21±0.02	0.200	790	804
0.29	80	0.75	0.30±0.04	0.207	711	896
0.29	80	0.28	0.23±0.01	0.180	922	950
1	120	0.81	0.45±0.08	0.338	737	859
1	120	3.36	0.51±0.13	0.497	-	640
1	140	0.46	0.41±0.07	0.319	790	933
1	140	2.36	0.53±0.11	0.471	-	780

Finally, simulations of actual breaking tests for commercially 40A 12 kV high voltage fuses were performed: Figure 2 shows an example for prospective AC current of 41kA («+» and «o» indicates current and voltage measurements). Obviously a good agreement has been achieved.

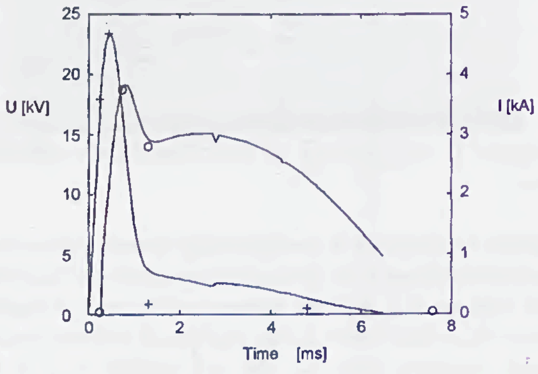

Figure 2 Comparison of simulation and experimental results of breaking tests for 40 A 12 kV h.v. fuses, I_{eff} = 41 kA, U_{eff} = 10400, ψ = 45° and p.f. = 0.2.

IV. Conclusions

For both fuses with compact sand and substrate fuses, an advanced method for simulating arcing process is proposed, which is based on Daalder's model [2]. Improvements are made on the determination of initial dimensions of arcing column and the influence of multiple fuse elements on the electric field. Agreements have been shown between measured fulgurite dimensions and calculated arc column length and cross sections. For substrate 12 kV 40 A high voltage full range fuses, simulations of arcing voltage and current are performed for breaking tests from an independent test station at different prospective currents. Theoretical results are found in good agreement with the experiment observations.

References

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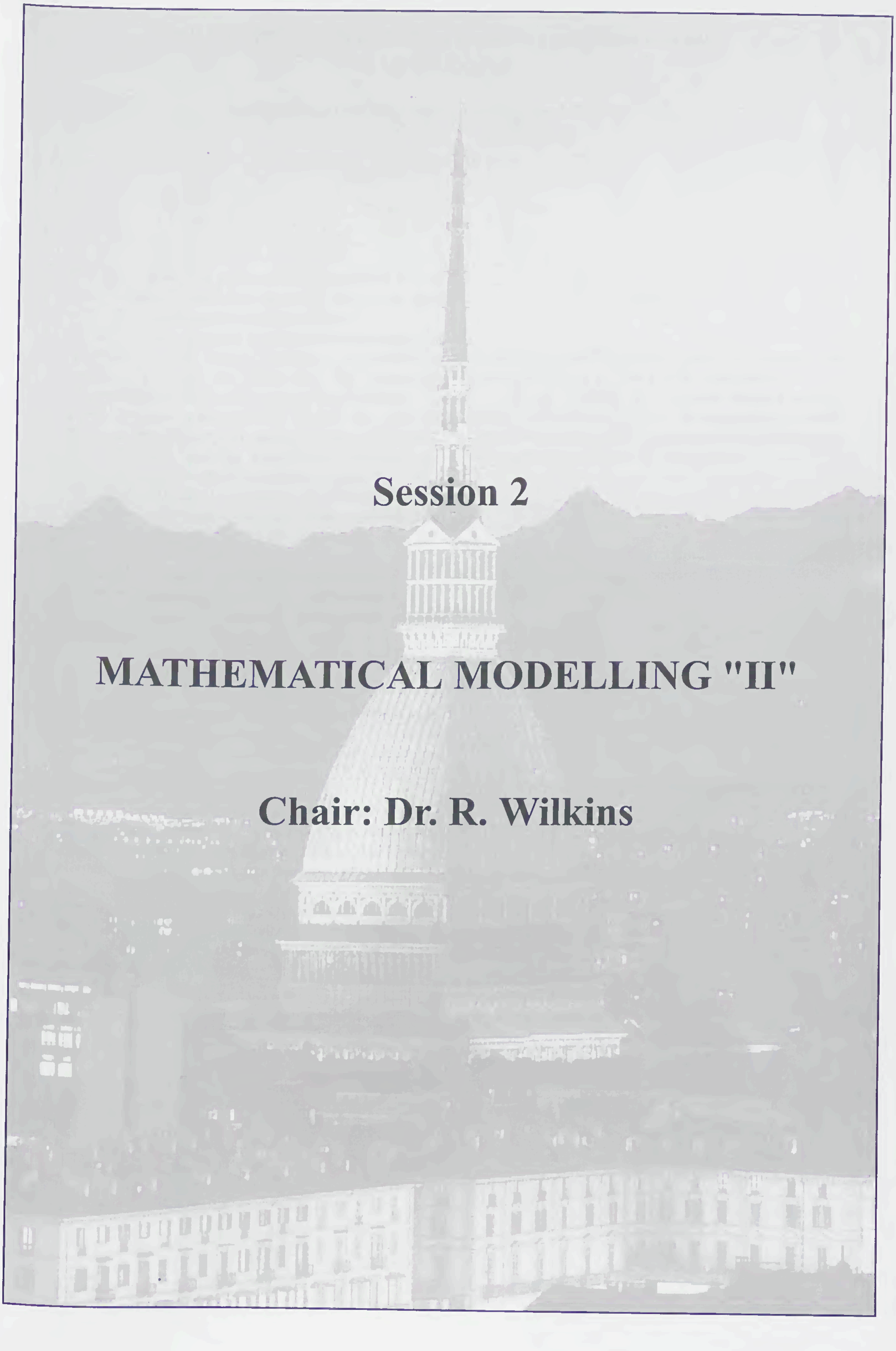

Session 2

MATHEMATICAL MODELLING "II"

Chair: Dr. R. Wilkins