

Comparison between model and experiment in studying the electric arc

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The paper presents a comparison between the results obtained using different modeling equations for the electric arc (Habedank, KEMA, Schavemaker and Schwarz) and the experimental measurements, in order to determine the best of them for predicting the behavior of a low voltage vacuum circuit breaker.

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1. Introduction

The switching tests, to which are subjected the interrupters, consume a large amount of power and materials. That's why efforts are made to obtain an antecalculation of the arc voltage, the post-arc current and the transient recovery voltage, the electric parameters definitory for the switching process. There are some equations (Mayr, Cassie and derived from) modeling the switching process, by taking into account the apparatus characteristics, such as dissipated power and the time constants.

Within the framework of this paper, the most suitable model of the switching phenomena in an a.c. low voltage vacuum circuit breaker is looked for, aiming to better predict the apparatus behaviour. From numerous and very attentive experimental investigations of the switching processes taking place at high currents interruption, statistically processed, the parameters of the electric arc model used in the modeling equations are determined. Finally, the arc voltage, the post-arc current and the transient recovery voltage, which represent the circuit breaker stresses in the switching process, are calculated. The obtained results are compared with the experimental ones in order to establish the best modeling equation for the studied low voltage vacuum circuit breaker, able to predict the behaviour of other similar circuit breakers or to optimise an existing apparatus.

2. Modeling equations for the electric arc dynamic regime

At the beginning of the last century, A.M. Cassie and O. Mayr have done the first tests (1930) concerning this subject. The equation belonging to Mayr is the most used up to now for investigation of the dynamic regime of the electric arc. *Mayr model* [1] is applied for the approximation of the electric arc behavior in the range of

current passing through zero and is described by the equation:

$$\frac{1}{G} \cdot \frac{dG}{dt} = \frac{1}{\tau_m} \left(\frac{u \cdot i}{P_0} - 1 \right) \quad (1)$$

where: u and i – instant values of the arc voltage and current respectively; G – dynamic conductance of the electric arc column supposed to have an exponential variation versus the stored energy, τ_m – time constant of the electric arc at current zero moment, P_0 – dissipated power at current passing through zero, considered to be constant.

Cassie model [1] represents a good approximation for the high current electric arc; he considered a linear variation of the column arc conductance with the stored energy and modeled the arc dynamic behavior with the following equation:

$$\frac{1}{G} \cdot \frac{dG}{dt} = \frac{1}{\tau_c} \left(\frac{u^2}{U_a^2} - 1 \right) \quad (2)$$

where are used the same symbols like in (1) with τ_c – time constant of the electric arc at the maximum current value and U_a – the electric arc voltage, considered to be constant.

The other known equations or systems of equations for the electric arc modeling (Habedank, KEMA, Schavemaker and Schwarz) are derived from Mayr and Cassie models and contain four or more parameters. The main problem of the electric arc simulation by means of any model is to determine the values of the parameters, which are not really constants, due to the high speed evolution of the physical phenomena in the extinguishing chambers of the interrupters. Although the parameters are considered constants and they are calculated using the oscillograms resulted from experiments. The determined parameters are valid just for a certain type of interrupter,

characterized by specific features of burning and cooling of the electric arc.

The four parameters of Mayr and Cassie models are also the parameters of the *Habedank model* [2] which considers the electric arc conductance ($G = i/u$) being a Cassie conductance ($G_c = i/u_c$) and a Mayr conductivity ($G_m = i/u_m$) in series. It is a system with three unknowns: G_c , G_m and G and contains the Cassie and Mayr model equations, modified, because: $u_c = u \cdot G/G_c$ and $u_m = u \cdot G/G_m$. The system is the following:

$$\frac{dG_c}{dt} = \frac{G_c}{\tau_c} \left[\frac{u^2}{U_a^2} \cdot \left(\frac{G}{G_c} \right)^2 - 1 \right] \quad (3)$$

$$\frac{dG_m}{dt} = \frac{G_m}{\tau_c} \left(\frac{u^2 G}{P_0} \cdot \frac{G}{G_m} - 1 \right) \quad (4)$$

$$\frac{1}{G} = \frac{1}{G_c} + \frac{1}{G_m} \quad (5)$$

Schwarz model [3], derived from Mayr model, considers an exponential variation with the electric arc conductance of τ ($\tau \cdot G^\alpha$) and P_0 ($P_0 \cdot G^\beta$), where τ and P_0 are the initial values, at the current zero moment; the constants α and β are obtained by iteration, until calculated and experimental results are well fitting. *Kema model* [3] is formed from three Mayr models, that is from 3 conductances (G_i) in series, each one calculated from a modified Mayr equation; each conductance has an exponential variation $G_i^{n_i}$, but with different values of the exponents $n_i \in (1,2)$. *Schavemaker model* [4] reunites the Cassie and Mayr models in the same equation.

3. Calculated and experimental results

Fig.1 and 2 represent typical oscillograms for the interrupting process in a low voltage vacuum circuit breaker, obtained in an experimental setup, able to provide asymmetric short-circuit currents up to 54 kA_{rms} (110 kA_{max}) at 805 or 1360 V_{rms} and to perform accurate and repeatable determinations.

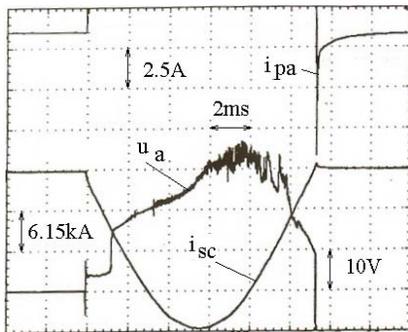


Fig.1. Typical oscillogram with i_{pa} - the post-arc current, i_{sc} - the short circuit current and u_a - the arc voltage.

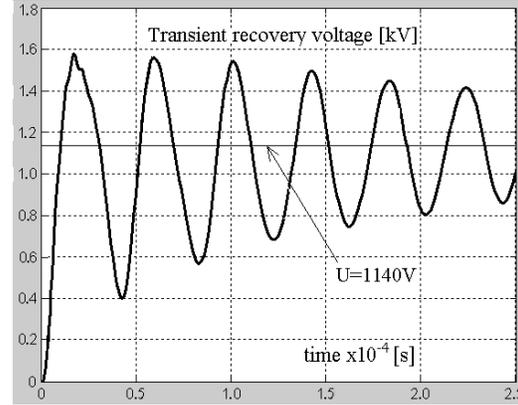


Fig. 2. The transient recovery voltage (trv) for the interruption from Fig.1.; $U=1140V$ is the maximum value of the voltage supply ($805V_{rms}$).

The short circuit interrupted current (i_{sc}) has a maximum value of 24 kA and has an asymmetrical behavior, due to the testing circuit parameters. The arc voltage (u_a) has an average value of $U_a = 20V$ and the post-arc current (i_{pa}) a maximum value of 7.8A. The transient recovery voltage has a frequency of $f_0 = 23.5kHz$ and an over oscillation factor $\gamma=1.4$.

For determining the constants P_0 and τ_m , necessary for the Mayr model, it was used the Asturian method [5], which starts from experimental results of measured current and voltage, in order to calculate numerically the arc conductance and its derivative, at equally distanced time intervals, Δt . The estimation of those values of P_0 and τ_m , which lead to the smallest difference between calculated and experimental conductance derivatives is made by the least squares method [6]. This way it is obtained a pair of values τ_m and P_0 which can be used for modeling the electric arc in the investigated device. Because two oscillograms are not identical, even the experimental conditions are conserved for the same switching device, several pairs τ_m and P_0 were determined. These ones can be obtained for the same device, but it is preferably for several devices from the same series. Average values of the pairs τ_m and P_0 should be used in the model, in order to provide more general results. In the Cassie arc model equation, U_a is the average value of the arc voltage, so only the time constant τ_c must be numerically calculated, in a similar way as described for P_0 and τ_m .

From the experimental data presented in Fig.1 and 2 the parameters obtained [6] for the *Mayr and Cassie models*, so that the modeled phenomena fit as well as possible the experiment are: $P_0 = 15.75kW$; $\tau_m = 3.177\mu s$; $U_a = 20V$; $\tau_c = 4\mu s$. The initial conditions, necessary to solve the differential equation are: $G(0) = 9700S$ and $u(0) = 0$.

In order to obtain the 4 interesting variables for the interrupting process (the interrupted short circuit current, the post-arc current, the arc voltage and the transient recovery voltage), are used the MATLAB Simulink and the Arc Model Blockset [3]. The arc models, with their specific parameters, are implemented in a circuit, calculated to provide a short circuit current and a transient

recovery voltage similar with those obtained experimentally. Using the *Mayr model*, the voltage arc is very close to zero; using the *Cassie model*, no circuit breaking occurs (Fig.3). That's why the other models, which combine Mayr and Cassie models, are further investigated.

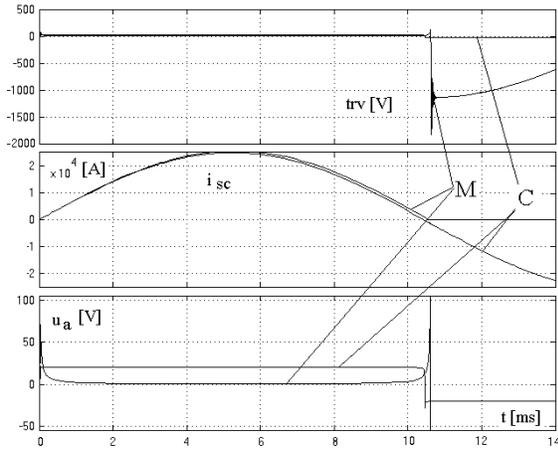


Fig.3. Comparison between Mayr (M) and Cassie (C) arc models.

The *Habedank model* has the advantage of using the 4 parameters already calculated for *Mayr and Cassie models*. These 4 parameters are mathematically calculated and the problem has a unique solution. For the other models: *KEMA, Schwarz and Schavemaker*, the parameters are determined by successive trials, and the solution is not unique. So, the *Habedank model* is the one with which the comparison of the other models is made.

The results are synthetic presented in the Fig. 4, 5 and 6. These figures are made by reuniting the modellization results for the same time scale: a half period or the current zero moment. There are also different scales for voltages and currents, on the same axe.

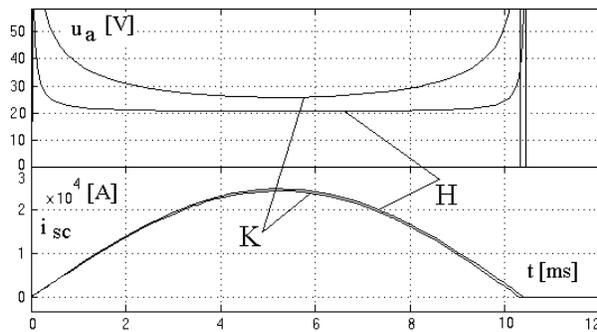


Fig. 4.a. Comparison between Habedank (H) and KEMA (K) arc models: the arc voltage and interrupted current

The *Habedank model* is better because the arc voltage has an almost constant value of 21V and the short circuit current is longer, closer to the experimental measurements (11ms). In the current zero moment, the *Habedank model* is also better, because, for almost similar recovery voltages ($f_0 = 24\text{kHz}$, $\gamma = 1.57$), the *KEMA model* does not calculate any post-arc current, while the *Habedank model* calculates a post arc current of 8A, similar with the experimental one.

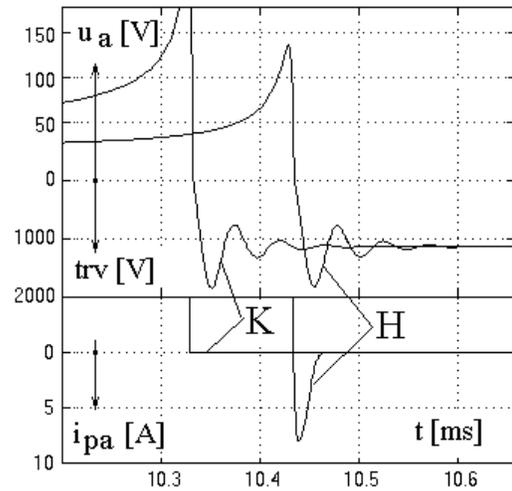


Fig.4.b. Comparison between Habedank (H) and KEMA (K) arc models in current zero moment: the arc voltage, the transient recovery voltage and post-arc current

The *KEMA arc model* parameters used to solve the equations system from [3] are: $T1 = 3.177\mu\text{s}$; $A1 = 0.8 \cdot 10^{-4} \text{ 1/W}$; $A2 = 10.5 \cdot 10^{-5} \text{ 1/W}$; $k1 = 10$; $k2 = 20$; $k3 = 80$ with the same initial conditions: $G(0) = 9700\text{S}$ and $u(0) = 0$.

The *Schwarz model* leads to calculated results also worst then *Habedank model*: an arc voltage variation far from the experimental one, with very big value before current zero moment (1150V), a transient recovery voltage with higher oscillation factor ($\gamma = 1.76$) and a very short post-arc current, three times shorter than the one calculated with *Habedank model*. Also the *Habedank model* calculates a post arc current shorter than the experimental one.

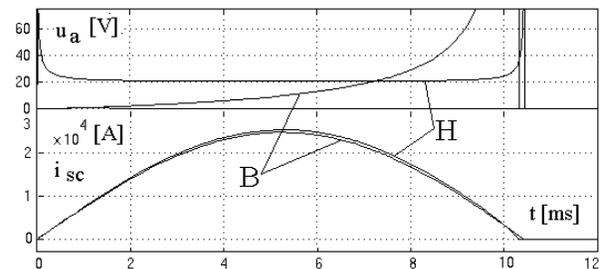


Fig.5.a. Comparison between Habedank (H) and Schwarz (B) arc models: the arc voltage and interrupted current

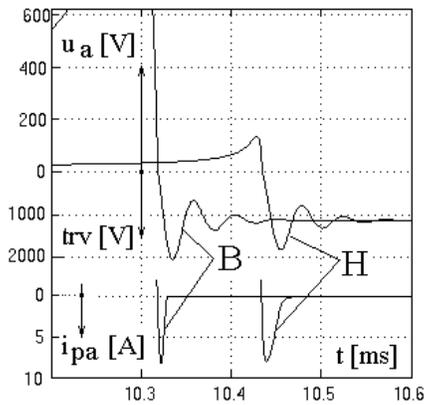


Fig.5.b. Comparison between Habedank (H) and Schwarz (B) arc models in current zero moment: the arc voltage, the transient recovery voltage and post-arc current.

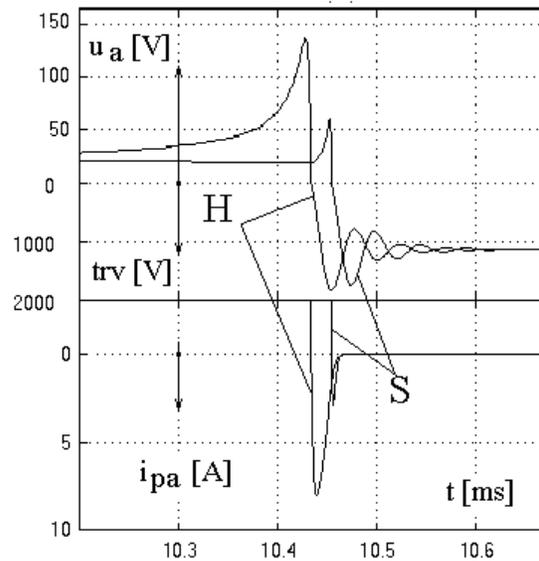


Fig.6.b. Comparison between Habedank (H) and Schavemaker (S) arc models in current zero moment: the arc voltage, the transient recovery voltage and post-arc current

The Schwarz model parameters used to solve the equation [3] are: $\tau=40\mu\text{s}$; $\alpha=0.5373$; $P_0=100\text{MW}$; $\beta=0.3$, with the same initial conditions $G(0)=9700\text{S}$ and $u(0)=0$. The parameters are determined by successive trials. The important parameters are τ and α , because they determine the current and voltage variation. For fixed value of τ and α , the other 2 parameters, P_0 and β , can vary in a rather large domain.

The Schavemaker arc model gives good results: the arc voltage remains almost constant, with little peak before current zero moment and the short circuit current is a little longer then the one calculated with Habedank model. The transient recovery voltage is almost the same, at both compared models, but the post arc current is very short and has a maximum value of only 2.75A calculated with the Schavemaker model.

The parameters used to solve the Schavemaker arc model equation [3] are: $\tau=1.227\mu\text{s}$; $U_a=20\text{V}$; $P_0=2750\text{W}$; $P_1=0.55$ with the same initial conditions $G(0)=9700\text{S}$ and $u(0)=0$.

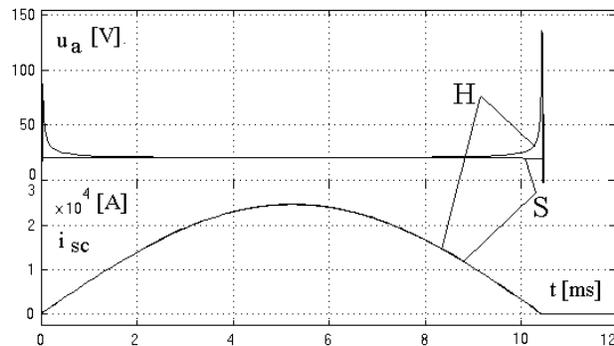


Fig.6.a. Comparison between Habedank (H) and Schavemaker (S) arc models: the arc voltage and interrupted current

4. Conclusions

The errors between the Habedank model and experiment are around 30% concerning the post arc current duration and transient recovery voltage amplitude, but only 5% concerning the amplitude of the post arc current and the frequency of the transient recovery voltage. The errors introduced by the method of τ_m , τ_c and P_0 calculation are in the same range (5%). The calculated curves have a faster variation, the post arc current and the oscillations of the transient recovery voltage have a shorter duration.

That's why a model which takes into account also the thermal effect of the interrupted current combining the Mayr and Cassie models, as Habedank and Schavemaker models, will lead to better results. The Habedank model presents the advantage of determining the 4 parameters by calculation starting from experimental oscillograms. The method of calculation leads to a unique solution. For Schavemaker model, only U_a is calculated as the average value of the measured arc voltage. The other three parameters must be obtained by successive trials and the solution is not unique.

So the Habedank model is considered to give the best results concerning the modellization of the studied vacuum circuit breaker behavior. It is important to obtain, further, a better interpretation of the parameters model and their relation with the vacuum circuit breaker design.

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