

## UNIVERSAL ARC RESISTANCE MODEL "ZAGREB" FOR EMTP

Sandra HUTTER  
HEP d.o.o., Elektra Zagreb – Croatia  
[sandra.hutter@hep.hr](mailto:sandra.hutter@hep.hr)

Ivo UGLEŠIĆ  
FER – Croatia  
[ivo.uglesic@fer.hr](mailto:ivo.uglesic@fer.hr)

### ABSTRACT

We developed the arc resistance model for use with EMTP. The electrical arc was simulated using a black box model based on the Cassie and Mayr arc equation. The model was tested on a benchmark circuit and the simulation results match well with the referenced models.

### INTRODUCTION

The need for an appropriate arc model arose repeatedly in numerous EMTP studies on problems related to overvoltage calculation. An arc model would be useful for various applications such as breaking of small inductive currents, calculation of VFTO in GIS or modeling of different types of SF6 and pneumatic circuit breakers applied in studies of switching overvoltages (e.g. interruption of short circuit currents).

### DEVELOPMENT OF THE ARC MODEL

Black box models use a mathematical description of the electrical behavior of the arc. These types of models do not give a full representation of the physical processes that goes on inside a circuit breaker [1].

Recorded voltage and current traces during the "thermal period" are used to obtain circuit breakers parameters that are later on substituted in differential equations. We used the most basic Cassie-Mayr equation, as well as its modifications from the Schwarz-Avdonin model. Assuming that the circuit breakers parameters are known, this model can also be used with other equations derived from the Cassie-Mayr equation.

### PHYSICAL PROCESS:

A short theoretical explanation of the physical process that occurs during AC arc extinction in the case of short line fault (SLF) is given below [2].

The main task of a circuit breaker is current interruption, which requires that the interelectrode gap changes from a conductive plasma into an insulating gas. At the instant of current zero, the input power is zero, because the restriking voltage is zero. However, after that zero time point a small post arc current is going to flow. Recovery voltage between circuit breaker contacts will increase rapidly.

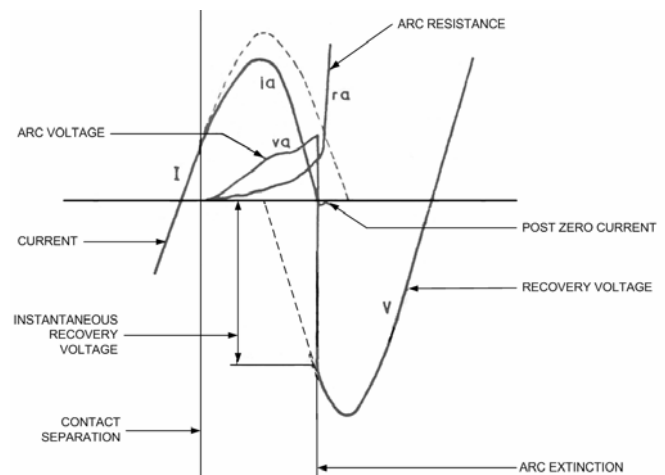


Fig. 1. A.C. arc extinction [2].

If the input power, during the short time following the instant of current zero ( $< 1$  ms) exceeds the arc power loss the arc is going to reignite.

### Cassie and Mayr arc equation

Different arc models use different functions to describe the relationship between the arc cooling power, the thermal time variable and conductance.

The description of these different approaches is given and explained in [1].

The electrical arc was simulated using its conductance-dependent parameters described by the Cassie and Mayr arc equation:

$$\frac{dg}{dt} = \frac{1}{\tau(g)} \left( \frac{i^2}{P(g)} - g \right) \quad (1)$$

where  $g$  represents the arc conductance,  $i$  - the arc current,  $P(g)$  - the arc cooling power and  $\tau(g)$  - the arc thermal time constant. Calculation of the arc conductance requires data on the cooling power and the thermal time constant.

Parameters  $P(g)$  and  $\tau(g)$  are conductance dependent. The cooling power  $P$  and the thermal time constant  $\tau$  depend on temperature, circuit breaker type and design, and they can be defined as a function of conductance  $f(g)$ .

$$P = P_o \cdot g^\beta \quad (2)$$

$$\tau = \tau_o \cdot g^\alpha \quad (3)$$

Cassie and Mayr arc equation could be solved if a sufficiently small time interval ( $\Delta t$ ) can be observed in which  $P$  and  $\tau$  are constant. The differential equation was solved numerically with the Euler method for differential equations of the first order. The solution is:

$$g(t + \Delta t) = g(t) + \left( \frac{i^2}{P(g)} - g(t) \right) \left[ 1 - e^{-\frac{\Delta t}{\tau(g)}} \right] \quad (4)$$

Depending on the difference between input (power) and cooling thermal energy (power loss), the arc temperature (and conductivity) is either going to increase or decrease.

**Benchmark circuit**

We used the test circuit described in [3]. The benchmark circuit is depicted in Fig. 2.

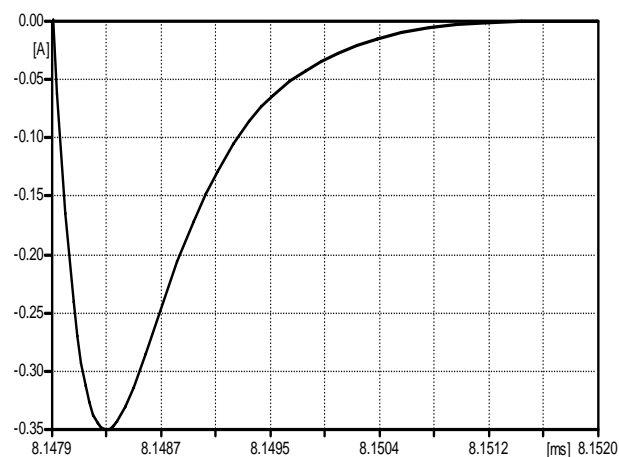
The first step in solving equation (4) is to find the solutions of the network equations (in EMTP) with the initial conductance value  $g_o = g(t_o)$ . The solution to these equations gives the value for the current  $i(t_o)$ . The initial values  $P(g_o)$  and  $\tau(g_o)$  are also calculated for the conductance initial value.

The following equations are used:

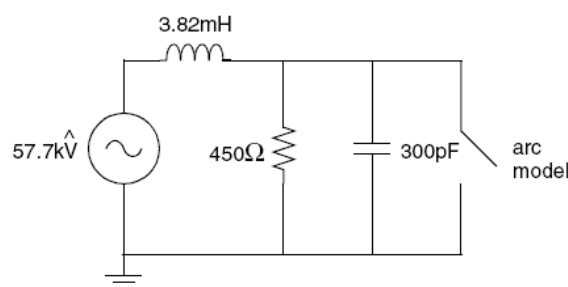
$$P = P_o \cdot g^\beta = 4 \text{ MW} \cdot g^{0.68} \quad (5)$$

$$\tau = \tau_o \cdot g^\alpha = 1.5 \mu\text{s} \cdot g^{0.17} \quad (6)$$

Initial resistance value was in this case 0.0001  $\Omega$ . With known values at the time step  $t_o$  the next time step is solved  $g(t_1) = g(t_o + \Delta t)$  in MODEL section of the EMTP. The output value from MODEL section is resistance and it is used as input value for nonlinear resistance component R(TACS) Type 91.



**Fig. 3a.** Post zero arc currents:  
- developed model ZAGREB  $I_{\max} = -0.35 \text{ A}$



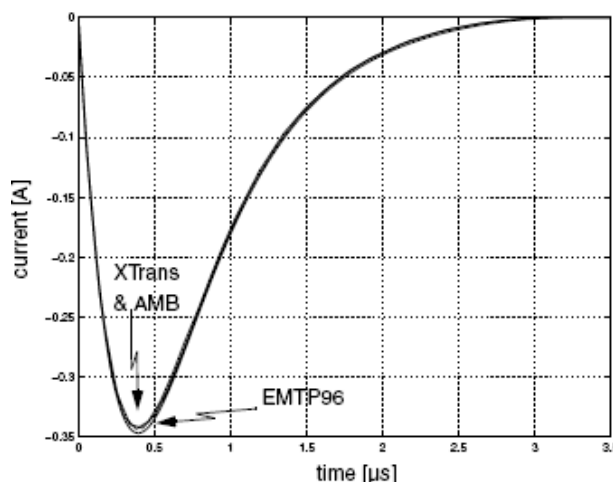
**Fig. 2.** Test circuit (60 Hz) and arc model parameters:  
 $P_o = 4 \text{ MW}$  and  $\beta = 0.68$ ;  $\tau = 1.5 \mu\text{s}$  and  $\alpha = 0.17$  [3].

We used a time step of 10 ns. Such small time step can be problematical in some applications and can prolong a computation time, however in EMTP a time step has to be fixed.

Calculated post zero arc currents and peak values of the arc voltage were compared to three different models developed at Delft University of Technology and are shown in Fig. 3-5. below.

Figures 3a., 4a., and 5a. show the graphs of the calculated values with the model ZAGREB (Appendix A) and the figures 3b., 4b., and 5b. (in the second column) show the graphs obtained with the three different models in the same test circuit described in [3], which are: EMTP96, XTrans and MATLAB Simulink/PSB/AMB based models.

Graphs of the post zero arc current and arc voltage give more information than the arc resistance graph and are more suitable for comparison. On Fig.3a. current zero is at the time point 8.1749 ms from the beginning of simulation, and a time interval of 4.1  $\mu\text{s}$  is shown. On Fig 4.a. and 4.b. are shown, respectively, time intervals of 648  $\mu\text{s}$  and 10  $\mu\text{s}$  before the time instant of current zero.



**Fig. 3b.** Post zero arc currents:  
- comparison with referent models

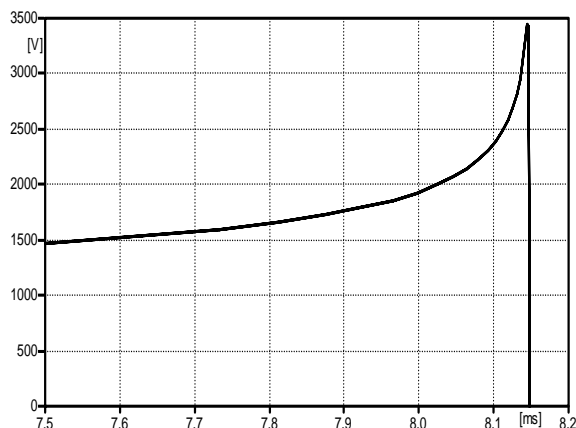


Fig. 4a. Arc voltage: developed model

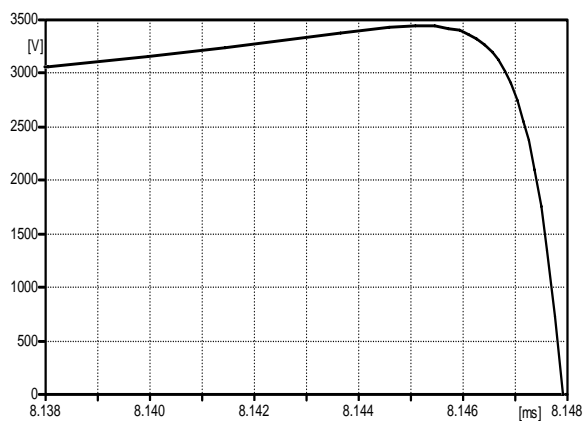


Fig. 5a. Arc voltage – detail:  
-developed model ZAGREB  $U_{max} = 3442$  V

**Air blast and SF6 circuit breakers**

In order to compare the behavior of the air blast and SF6 circuit breakers, parameters of the model "Zagreb" used in the benchmark circuit were replaced with the following values from the literature [4]:

$$P = P_o \cdot g^\beta = 16 \text{ MW} \cdot g^{0.5} \tag{7}$$

$$\tau = \tau_o \cdot g^\alpha = 6 \mu\text{s} \cdot g^{0.2} \tag{8}$$

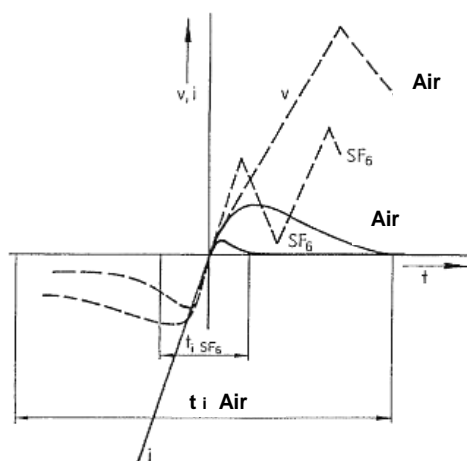


Fig. 6. Thermal period for short line fault interruption [1].

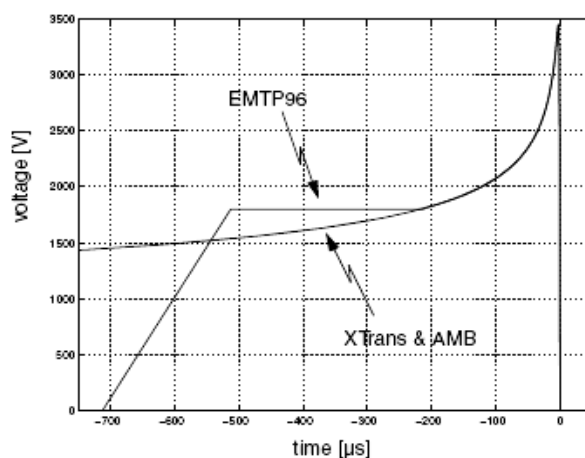


Fig. 4b. Arc voltage: comparison with referent models

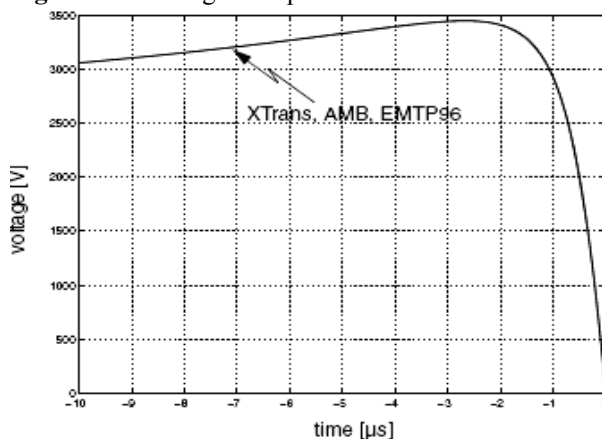


Fig. 5b. Arc voltage – detail: comparison with referent models

Different quantities (post arc current peak zero, voltage range after zero and thermal period duration) characterizing the thermal period of the switching process in the air blast and SF6 circuit breakers are compared in table 1. The given values are valid only for the given benchmark circuit.

The air blast circuit breaker has in general a longer thermal period (Fig. 6), for this benchmark circuit and chosen circuit breaker parameters the thermal period and the peak value of the arc voltage were respectively 2 and 2.7 fold higher.

**Table 1.** Obtained values of post-arc current peak zero, voltage range after zero and thermal period duration for air blast and SF6 circuit breakers

	Air blast	SF <sub>6</sub>	Ratio
Thermal period duration	6 μs	3 μs	2
Postarc current peak zero	1.885 A	0.35 A	5.4
Voltage range after zero	9314 kV	3442 V	2.7

**Application**

This model was successfully applied in the switching overvoltage analysis conducted for a 400/110 kV substation.

Analysis showed that consecutive switching of two or more SF6 or pneumatic circuit breakers will not cause high overvoltages, due to the fact that the electrical arc will be extinguished at the moment of the current zero passing.

Similar model with different parameters was also applied in calculation of VFTO in GIS during disconnector switching.

**CONCLUSION**

Black box arc resistance models for the SF6 and air blast circuit breakers were developed for use with EMTP.

Arc resistance is calculated for each time step in MODELS section, from equation (4), which is a numerical solution of the differential Cassie and Mayr arc equation. This solution is valid if sufficiently small time intervals can be observed.

Circuit breakers parameters: cooling power and the thermal time constants, were obtained from the literature.

Depending on the circuit breakers parameters, different types of circuit breakers will have different thermal period duration. In general, a rate of rise of the electrical arc resistance is higher for the SF6 circuit breakers, which means that the dielectrical strength between the circuit breaker contacts recovers faster.

**REFERENCES**

[1] CIGRE WG 13.01, 1993, "Applications of Black Box Modelling to Circuit Breakers", *Electra* no.149, 41-71.

[2] C.H Flurscheim, et Al, 1982, *Power circuit breaker theory and design*, IEE, Peter Peregrinus Ltd, London, UK, 191.

[3] P. H. Schavemaker, L.Van Der Sluis, 2002, "The Arc Model Blockset", *Proceedings of the Second IASTED International Conference, POWER AND ENERGY SYSTEMS (EuroPES)*, 644-648.

[4] V. Phaniraj, A.G. Phadke, 1988, "Modeling of Circuit Breakers in the Electromagnetic Transients Program", *IEEE Trans. On Power Systems*, vol. 3, no.2, 799-805.

**APPENDIX A**

## MODEL ZAGREB

comment-----

| Schwartz arc model |

-----endcomment

INPUT U1, U2

OUTPUT RB

VAR I, RB2, RB, G, G2, TAU

INIT

RB:=0.0001

ENDINIT

EXEC

I:=(U1-U2)/RB

IF (ABS(I)>1.E-12) THEN

G:=(1./RB)

TAU:=(1.5E-6\*(G\*\*0.17))

G2:=((I\*\*2.)/(4000000.\*(G\*\*0.68))-G)\*(1.-  
-1./EXP(timestep/TAU))

RB2:=(1./ABS(G+G2))

RB:=RB2

ENDIF

ENDEXEC

ENDMODEL