

## Electric Arc model for High Voltage Circuit Breakers Based on MATLAB/SIMULINK

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**Abstract**—A circuit breaker is a switching device that the American National Standards Institute (ANSI) defines as: "A mechanical switching device, capable of making, carrying, and breaking currents, under normal circuit conditions and also making, carrying for a specified time and breaking current under specified abnormal circuit conditions such as those of short circuit." High Voltage Circuit Breaker's working base is the electric arc that appears between their contacts when establishing or interrupting the electric current in the circuit. This electric arc is a complex phenomenon where lots of physic interactions take place in a very short time. Over the years, as our knowledge of the interrupting process progressed, many techniques have been developed to test the circuit breakers and simulated arc model. There are three models (Physical Model Black Box Model and Parameter Model) that describe the behavior of the arc. Therefore, the optimization of the operation of high voltage circuit breakers makes necessary a deep understanding of the phenomena involved in the appearance of the electric arc. This knowledge can be achieved by means of modelization and simulation tools. This option allows us to obtain the evolution of physical magnitudes which would be difficult to measure in laboratory tests. The aim of this paper is to describe the phenomena of the electric arc in high voltage circuit breakers, as well as the specification of the mathematical, physical and software needs for its modelization and simulation.

**Keywords** - Electric arc, high voltage circuit breakers, Physical Model, Black Box Model, Parameter Model

### I. INTRODUCTION

Circuit-breakers are very important electric power transmission equipment related to quality of service, because they can isolate faults that otherwise could cause total power system breakdowns. When circuit breaker contacts separate to initiate the interruption process, an

electrical arc of extremely high temperature is always produced and becomes the conducting medium in which current interruption will occur. With modern high-voltage breakers, the arc is blown with gas in the same way as a match is blown out with your breath, but with 100 million times the blowing power.

In simple terms, circuit-breakers consist of a plug that is in connection with a contact when the breaker is closed. The current then flows right through the breaker. To interrupt the current, the plug and the contact is separated with rather high speed, resulting in an electric arc in the contact gap between the plug and the contact. This is illustrated in Figure:1 Since short-circuit currents in most high-voltage power systems frequently reach 50 to 100 kilo amperes, the consequent arc temperature goes beyond 10,000 degrees (C), which is far above the melting point of any known material.

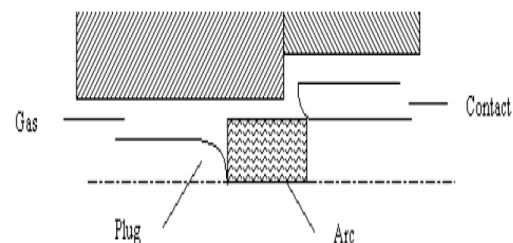


Figure: 1 Simplification of the contact gap

In this paper the characteristics of the electric arc are described with the aim of characterizing the interruption process in high voltage devices. In addition, an overview of the most important models and simulation methods using MATLAB are exposed. [1-2]

### II. ELECTRIC ARC PHENOMENON IN HIGH VOLTAGE CIRCUIT BREAKER

The electric arc in a circuit breaker plays the key role in the interruption process and is therefore often addressed as *switching arc*. The electric arc is a plasma channel between the breaker contacts formed after a gas discharge in the extinguishing medium. When current flows through a circuit breaker and the contacts of the

breaker part, driven by the mechanism, the magnetic energy stored in the inductances of the power system forces the current to flow. Just before contact separation, the breaker contacts touch each other at a very small surface area and the resulting high current density makes the contact material to melt. The melting contact material virtually explodes and this leads to a gas discharge in the surrounding medium either air, oil, or SF<sub>6</sub>. Physically, the arc is an incandescent gas column, with an approximate straight trajectory between electrodes (anode and cathode) and temperatures over 6000 and 10000 °C. Metallic contact surfaces are also incandescent and a reduction in the cross section of the arc is observed near them. This way, three regions can be defined: a central zone or arc column and the anode and the cathode regions (Figure 2). [3]

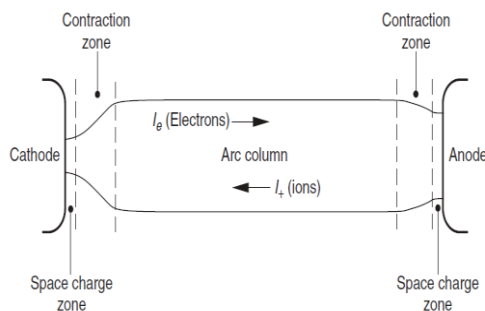


Figure: 2 The arc channel can be divided into an arc column, a cathode, and an anode region

From the arc channel, the potential gradient and the temperature distribution can be measured. Figure 3 shows a typical potential distribution along the arc channel between the breaker contacts.

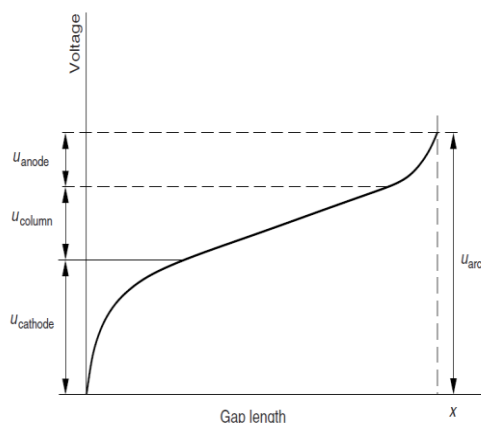


Figure: 3 Typical potential distribution along an arc channel

The peak temperature in the arc column can range from 7000–25000 K, depending on the arcing medium and configuration of the arcing chamber.

The role of the cathode, surrounded by the cathode region, is to emit the current-carrying electrons into the arc column. A cathode made from *refractory material* with a high boiling point, (e.g. carbon, tungsten, and molybdenum) starts already with the emission of electrons when heated to a temperature below the evaporation temperature this is called *thermionic emission*. Current densities that can be obtained with this type of cathode are in the order of 10000 A/cm<sup>2</sup>. The cooling of the heated cathode spot is relatively slow compared with the rate of change of the transient recovery voltage, which appears across the breaker contacts after the arc has extinguished and the current has been interrupted. A cathode made from *non refractory material* with a low boiling point, such as copper and mercury, experience significant material evaporation. These materials emit electrons at temperatures too low for thermionic emission and the emission of electrons is due to *field emission*. Because of the very small size of the cathode spot, cooling of the heated spot is almost simultaneous with the current decreasing to zero. The current density in the cathode region is much higher than the current density in the arc column itself. This results in a magnetic field gradient that accelerates the gas flow away from the cathode. This is called the *Maecker effect*.

The role of the anode can be either *passive* or *active*. In its passive mode, the anode serves as a collector of electrons leaving the arc column. In its active mode the anode evaporates, and when this metal vapor is ionized in the anode region, it supplies positive ions to the arc column. Active anodes play a role with vacuum arcs: for high current densities, anode spots are formed and ions contribute to the plasma. This is an undesirable effect because these anode spots do not stop emitting ions at the current zero crossing. Their heat capacity enables the anode spots to evaporate anode material even when the power input is zero and thus can cause the vacuum arc not to extinguish. Directly after contact separation, when the arc ignites, evaporation of contact material is the main source of charged particles. When the contact distance increases, the evaporation of contact material remains the main source of charged particles for the vacuum arcs. For high-pressure arcs burning in air, oil, or SF<sub>6</sub>, the effect of evaporation of contact material becomes minimal with increasing contact separation, and the plasma depends mainly on the surrounding medium. [1-3, 5]

### III. MODELING OF ELECTRIC ARC

Arc modeling has always been one of the main topics in circuit breaker research. Arc models can be classified in three categories:

- Black box models (also often called P-τ models) (BB)
- Physical models (PM)
- Parameter models
- Models based on graphics and diagrams (GD)

whose main application fields are shown in Table 1 [4]

**Table 1. Application field of different switching models**

Problem type	Application		
	Develop- ment	Test	Operation
Physical processes understanding	PM		
Mechanics dimensioning	PM	GD	
Dielectric recovery description	PM, GD	GD	GD
Influence of the arc on the current	PM, GD, BB	GD, BB	BB
HVDC breakers	PM, GD, BB	GD, BB	GD, BB
Small inductive currents	PM, GD, BB	GD, BB	GD, BB
SLF (Short Line Fault)	PM, GD, BB	GD, BB	GD, BB
Design and verification of test circuits	GD	BB	

#### A. Physical models (PM)

- The circuit breaker design engineers work mostly with physical arc models when designing a new prototype. Physical arc models are based on the equations of fluid dynamics and obey the laws of thermodynamics in combination with Maxwell's equations. They consist of a large number of differential equations.
- The arc-plasma is a chemical reaction and, in addition to the conservation of mass equation, describes the rate equations of the different chemical reactions. In the case of a local thermodynamic equilibrium, the rate

equations become the equilibrium mass action laws and that, in the simplified case of the reaction of a monatomic gas, becomes the Saha equation, describing the degree of ionization in the gas.

- The Navier–Stokes equations represent the fluid dynamics of the quenching gas, composed by three transport equations coupled to each other: (1) mass balance (2) momentum balance (3) and energy balance. These equations can be expressed as follows:

Conservation of mass (continuity equation):

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \mathbf{u}) = 0 \quad (1)$$

Conservation of momentum (Navier–Stokes equation):

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \text{grad})\mathbf{u} = -\text{grad}(p) \quad (2)$$

Conservation of energy:

$$\rho \frac{\partial h}{\partial t} + \mathbf{u} \cdot \text{grad}(\rho h) - \sigma E^2 = \text{div}(\rho \mathbf{u}) + \text{div}[K \cdot \text{grad}(T)] - R[T, \rho] \quad (3)$$

Where

$p$  = pressure     $\sigma$  = electric conductivity  
 $\rho$  = gas density     $K$  = thermal conductivity  
 $\mathbf{u}$  = gas flow velocity     $T$  = gas temperature  
 $h$  = enthalpy of gas     $R$  = radiation loss

$E$  = electric field strength     $r$  = arc radius

Maxwell equations describe the interaction between electrical and magnetic field intensity,  $\vec{E}$  and  $\vec{H}$ .

$$\nabla \times \vec{E} = - \frac{\partial \vec{B}}{\partial t}; \nabla \times \vec{H} = \mathbf{j} \quad (4)$$

$$\nabla \cdot \vec{E} = \rho_q; \nabla \cdot \vec{B} = 0 \quad (5)$$

Thus, electric arc physical models consider the conservation laws for mass; momentum and energy for arc macroscopic elements, but extra source terms are added. On one hand Lorentz-force density term ( $\mathbf{j} \times \mathbf{B}$ ) is added in the momentum balance and on the other hand the ohmic heating term ( $\mathbf{j} \cdot \mathbf{E}$ ) in the energy balance. Those extra terms couple flow dynamics with electromagnetic process, described by Maxwell's equation (4, 5) [6-7]. Finally, an important characteristic of physical models is that they require the knowledge of plasma properties such as mass density, specific heat, viscosity, etc. These properties are strongly dependent on temperature and pressure values and, in the presence of vaporized metal or plastic, they depend also on the characteristics of the mixture.

### B. Black Box Models

In *Black box models*, the arc is described by a simple mathematical equation and gives the relation between the arc conductance and measurable parameters such as arc voltage and arc current. These black box models are not suited to design circuit breaker interrupters but are very useful to simulate arc-circuit interaction in network studies. Black box models are based on physical considerations but are, in fact, mathematical models; the behavior of the arc rather than the physical processes is of importance. Usually, black box models consist of one or two differential equations.

The classical black box models are the *Cassie model* and the *Mayr model*. Both the Cassie and Mayr equation are a solution of the *general arc equation*. Many of these models are based on the equations proposed by Cassie and Mayr, which represent the variation in the conductance of the arc by a differential equation obtained from physical considerations and implementation of simplifications. On this way, Mayr assumed that the arc has fixed cross-sectional area losing energy only by radial thermal conduction. In contrast, Cassie assumed that the arc has a fixed temperature being cooled by forced convection [8, 2]. The *Cassie model* is well suited for studying the behavior of the arc conductance in the high-current time interval when the plasma temperature is 8000 K or more. The *Mayr model* is suited for modeling of the arc in the vicinity of current zero when the temperature of the plasma is below 8000 K.[3] Thus, "black box" models are in general represented by one differential equation relating the arc conductance with magnitudes such as voltage and arc current.

$$\frac{1}{g} * \frac{dg}{dt} = \frac{1}{T(i,G)} * \frac{ui}{P(i,G)} - 1 \quad (6)$$

Where:

G : Arc conductance

u : Arc voltage

i : Arc current

P, T: Parameters of the model

The fundamental purpose of "black box" models is to obtain a mathematical model that represents the circuit breaker test and can be applied in predicting the behavior of the circuit breaker under different conditions. These models can only be applied if the particular process that takes place is governed by the conductance. In other cases, such as in the dielectric region of breakdown processes, these models are not directly applicable. [9, 2]

### C. Models based on graphics and diagrams

Finally, analytic expressions and graphics can be used, which represent a correlation between

parameters of the circuit and different magnitudes associated with the interruption process and the circuit breaker performance. These expressions and graphics can be obtained from tests or from the application of both physical and "black box" models. [4]

### IV. SIMULATION SOFTWARE TOOLS

Different software tools can be applied to simulate the behavior of the electric arc, according to the previous classification of arc models. Regarding "black box" models, software for simulation of power systems transients, such as ATP/EMTP and MATLAB/Simulink can be used [3]. These tools allow the analysis of power systems in the time-domain by solving the differential equations that represent the behavior of the various components.

For physical models, software of modeling the coupling between fluid dynamics and electric and magnetic phenomena must be used. In those models, the fluid dynamics part of the problem represented by Navier-Stokes equations is solved by means of a CFD (computational fluid dynamics) solver, whereas for electromagnetic issues Maxwell equations must be solved by a FE (finite element) solver [6]. A typical approach is the use of ANSYS, in combination with a computational fluid dynamics package, CFD, such as FLUENT or CFX. Finally, as models based on graphics and diagrams are derived from the results obtained from simulations of the previous two types of models ("black box" and physical models), software tools to implement them do not really exist.

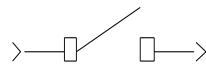
#### A. Examples

The aim of this section is to show some examples of different simulations, for "black box" models.

Regarding "black box" models, a significant example is the Arc Model Blockset [4]. The Arc Model Blockset is a library that currently contains seven arc models to be used in combination with the Matlab Power System Blockset. In this application, the arc is represented as a non-linear resistance, mathematically defined by a differential equation whose purpose is to the study of arc circuit interaction. In particular, the arc models incorporated in the Arc Model Blockset are: Cassie, Habedank, KEMA, Mayr, Modified Mayr, Schavemaker and Schwarz.

The arc models have been modeled as voltage controlled current sources. and the differential equation representing the electric arc is incorporated by means of the Simulink DEE (Differential Equation Editor). For example, Figure 4 shows the Mayr arc model included in the Arc

Model Blockset, and Figure 5 shows the dialog box for the introduction of model data.



Mayr arc model

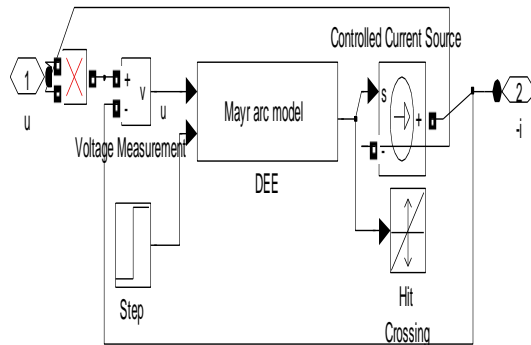


Figure 4 Mayr arc model [10]

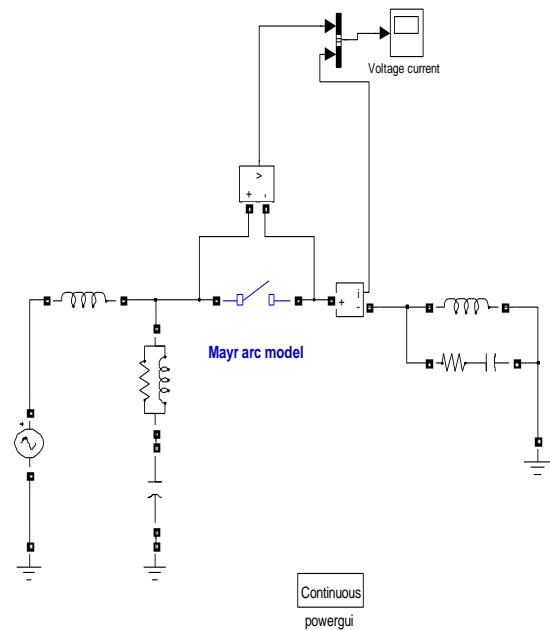


Figure 6 Figure: 2 Arc Model Test Circuit [10]

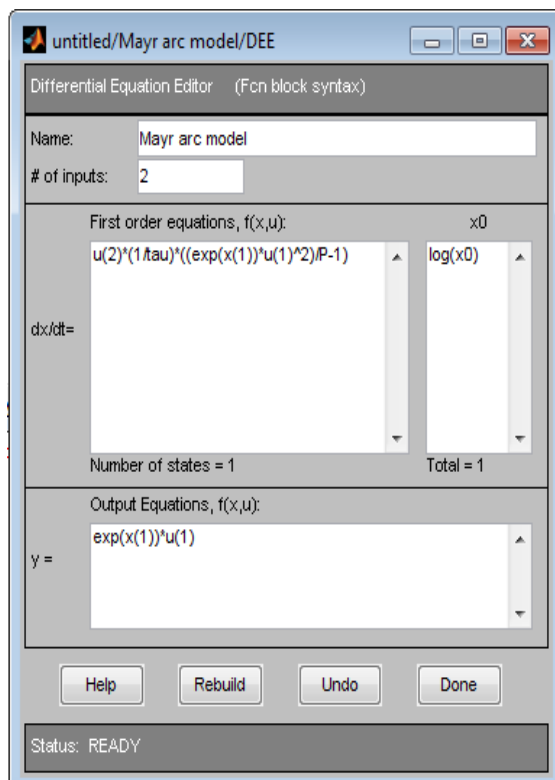


Figure 5 Arc model dialog box [10]

Figure 7 shows an example of the results obtained in the simulation of a circuit with the Mayr arc model.

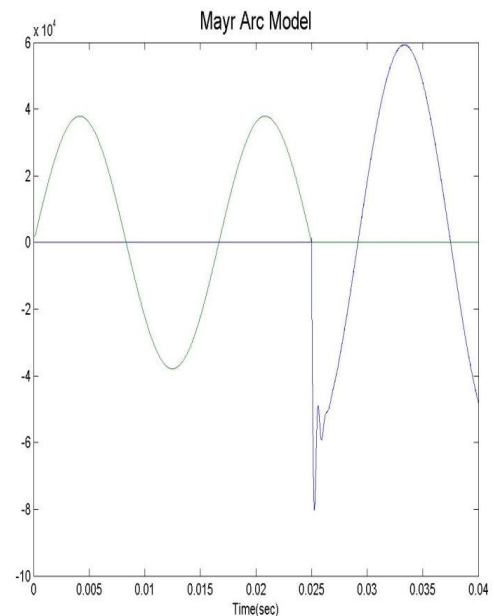
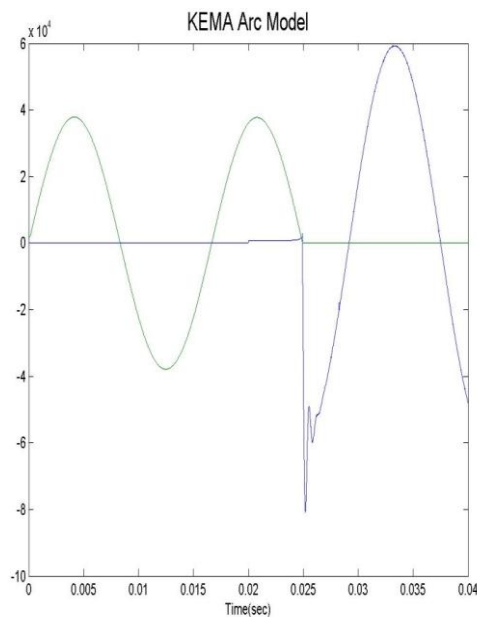


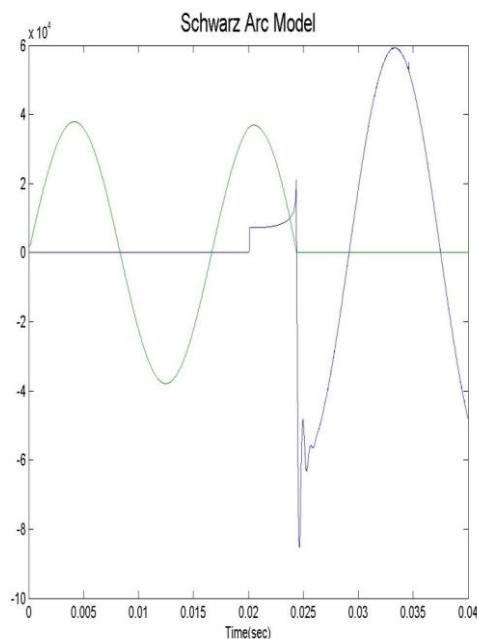
Figure 7 Computed voltage and current of Mayr's arc model [10]

These arc models can be implemented in a test circuit in a straight forward way. [10]





**Figure: 8 Computed voltage and current of KEMA arc model [11]**



**Figure: 9 Computed voltage and current of Schwarz arc model.**

In Figure 7, 8, it can be observed the detailed behavior of the voltage and current around the current zero crossing when the circuit breaker contacts starts to separate at  $t=0.02s$ . As it is shown, the rapid increase in the transient recovery voltage leads to the reduction of the arc current, until it gets the zero value and the arc finally disappears.

## V. Conclusion

The electric arc is an important phenomenon which determines the operation of high voltage circuit breaker. The use of modeling and simulation tools can help to improve these devices, reducing the need of prototype development and testing and so, the cost associated to this optimization process. Three main groups of arc models can be defined: physical models, black box models and models based on graphics and diagrams. The type of model to be applied may differ depending on the purpose of the simulation.

Black-box modeling is adequate to study the arc-circuit interaction, whereas in the case of the design of new circuit breakers or to increase the understanding of the interruption process, the most appropriate, despite their complexity, are physical models.

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