Analysis and Modilization of Electric Arc Model for High Voltage Circuit Breaker Based on Matlab/Simulink

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ABSTRACT
Circuit breakers play an important role in electrical power system networks. They must clear faults and isolate faulted sections rapidly, clearly and reliably. They are also used for normal load switching. A circuit breaker is a switching device that is capable of making, carrying for a specified time and breaking current under specified abnormal circuit conditions such as those of short circuit. High voltage circuit breakers 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. Many techniques have been developed to test the circuit breakers and simulated arc model. There are three models Black Box Model, Physical Model and Parameter Model that describe the behavior of arc. This paper evaluates the black-box arc model for circuit breakers with the purpose of finding criteria for the breaking ability. Cassie’s and Mayr’s electric arc the two models for analytical determining of electric arc parameters, which were introduced in this paper. This model Cassie’s and Mayr’s obtained improved better results. Therefore, the optimization of the operation of 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 paper describe the phenomena of the electric arc in HVCBs, as well as the specification of the mathematical, physical and software needs for its modelization and simulation.

Keywords
Circuit-breaker, Cassie’s and Mayr’s Black Box Model, Matlab/Simulink

1. INTRODUCTION
Circuit breaker is a switching device which can be operated manually and automatically for controlling and protection of electrical power system respectively. As the modern power system deals with huge currents, the special attention should be given during designing of circuit breaker for safe interruption of arc produced during the operation of circuit breaker. It is huge important role in electric power system equipment related to quality of service, because they can isolate faults that otherwise could cause total power system breakdowns. It can open or close a circuit in a small fraction of time, being its purpose the establishment or interruption of the circulation of current through the circuit under usual or unusual working conditions.

When circuit breaker moveable contacts start to separate the interruption process of the current in a circuit breaker is always carried out by an electric arc of maximum high temperature is produced. As a consequence, the contact area between contacts decreases and current density gets larger, until the energy associated with this process causes the metal of the contacts to begin to vaporize and an arc appears. In spite of the existence of a physical separation of the switching contacts, the established arc makes possible that current continues flowing. Thus, the current interruption involves the extinction of the electric arc, which is achieved when the interrupting medium between contacts becomes again an isolating medium [1-3].

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. Its shows in below fig. 1.

![Fig.No.1. Simple contact gap of CB](image)

The arc period is defined as the time from contact separation to interruption. During the arc period, very high conductivity is desired in the breaker. That is equal to a low power
development. When the current reaches zero, the breaker must change from being a good conductor to a good insulator in very short time. If this transition is fast enough, the arc is extinguished and the current will be interrupted and only a small current will flow in the breaker. An arc model must be used for calculation of the arc fault current. There are a lot of arc models for describing the arc. Arc models can be classified in three groups: physical models, black box models and models based on graphics and diagrams. Black box models describe only the relation between input and output signals. Black box models define the interaction between the arc and the electrical circuit during the fault. In black box models, the arc is described by one differential equation or several differential equations relating the arc conductance which describes the energy balance of the arc column. Black box models are modifications of the models proposed by Cassie and Mayr [4,5,6], which provide a qualitative description of the phenomena in the low and high current regions respectively.

This paper described the characteristics of the electric arc with the aim of characterizing the interruption process in high voltage devices. In addition to the most important models such as Cassie arc model/Mayr arc model and simulation methods using MATLAB/SIMULINK.

2. BLACK BOX MODELS

In black box models define the interaction between the arc and the electrical circuit during the current interruption process. In these models the most important issue is the behavior of the arc and not how the interruption process develops. 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 [7]. 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]. Thus, "black box" models are in general represented by one differential equation relating the arc conductance with magnitudes such as voltage and arc current [7,9].

\[ 1/G \frac{dG}{dt} = 1/T(i,G) *ui/(P(i,G))-1 \]  

(1)

Where:

G: Arc conductance

u: Arc voltage

i: Arc current

P, T: Parameters of the model

P and T parameters are calculated so as to obtain a good correlation between calculated results and those obtained by testing. The different models differ in the type of functional dependence of model parameters and how they are determined. Most of these models have no physical justification. The fundamental purpose of "black box" model 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 [4, 14]. In other cases, such as in the dielectric region of breakdown processes, these models are not directly applicable.

3. ELECTRIC ARC PHENOMENON

The electric arc is a complex phenomenon. A high number of physical phenomena interact during its formation, maintenance and interruption, in a very short time. In HVCBs, where the interruption medium is air, the electric arc is formed once the air has been ionized and converted into plasma, becoming this way conductive. Formation of the electric arc depends mainly on the separation of the circuit breaker contacts, the applied current and the ionization of the insulating medium. When the separation of the contacts starts, the electric arc appears and maintains if the temperature in the circuit breaker chamber is high enough to ionize the isolating medium, if the current is enough to melt and volatilize the metal and if the distance between the electrodes is high enough to hold the arc. The value of the current is important at the beginning of the circuit breaker contacts’ separation. If the current is low, the rise in temperature is not enough to provoke the melting and volatilization of the metal and only a spark is originated. However, beyond a certain limit, the temperature reached exceeds the melting and volatilization limit of the metal, determining that the spark becomes conductive and an electric arc appears. During the opening process of the electrical contacts, the insulating medium (air, vacuum or SF6) becomes conductive, allowing the circulation of electric current through an electric arc.

The electric arc is a plasma channel between the breakers contacts formed after a gas discharge in the extinguishing medium. The ionization degree depends on several factors, such as temperature, pressure and gas ionization potential. Plasma is another state of aggregation for material, like solid, liquid and gas. The electric arc is formed by a plasma column consisting of ions and electrons from the inter-contact medium and metal vapoors from the electrodes. Physically, the arc appears as an incandescent gas column with an approximately rectilinear trajectory between electrodes, whose core reaches temperatures between 6000 and 10000K. In Fig. 2 there are three region a central zone or arc column and the anode and the cathode regions.

![Fig.No.2. Arc structure with three region arc column, a cathode, and an anode region.](image)
These three regions have different characteristics. Thus, the voltage drop behaves also in a different way on them:

- The cathode region is full of metal vapours from cathode, with a lot of positive ions and a small number of electrons. Thus, this region is characterized by the existence of high electric field (108-109 V/m) [15] and temperature values, as well as by a higher current density than in the arc column, due to the smaller section. Therefore, cathode provides electrons from the material, which are accelerated by the high electric field existing in the cathode region, reaching enough energy to ionize other neutral particles. Depending on the material, refractory and non-refractory cathodes can be distinguished. In the case of refractory materials with high boiling point e.g. zirconium, molybdenum, tungsten and carbon, electron emission is produced by heating the material below the evaporation temperature (thermionic emission). The current densities obtained with this type of cathodes are around 104A/cm2. The use of refractory materials in combination with good conductors, such as silver or copper, shows reduced erosion characteristic when the arc happens. In non-refractory materials cathodes with low boiling points, such as copper, experiment a significant evaporation of the material. Electron emission in these materials occurs by the effect of the high electric field in the proximity of the electrode surface (field emission). In this case, the range of typical values for current density is around 106-108A/cm2.

- In arc column region mode, the current flow is mainly due to the displacement of electrons, resembling to the metallic conduction phenomena. This zone contains an excess of positive ions which neutralize the charge of electrons and allows high currents under small voltage drops. Ions are directed towards the opposite electrode. These voltage drops correspond to the appearance of intense fields capable of giving sufficient energy to the ions to keep the electrodes incandescent and cause the release of new ions. The voltage drop along the arc column is characterized by a uniform longitudinal voltage gradient. The voltage gradient in the arc column depends on the arc current and the energy exchange with the environment. The increase in the arc current leads generally to an increase in the diameter so that the section of the arc tends to be automatically adjusted.

- In anode mode region, as a result of the rejection of positive ions and the attraction of electrons, there is a negative space charge that causes a sharp voltage drop, called anodic drop. Anode may be passive or active, depending on whether it acts as collector of electrons coming from cathode or provides ions to the arc column due to the evaporation of contact material. In general, the current density is significantly lower than the one in the cathode area and, similarly, a constriction occurs in this region of the arc.

For high-pressure arcs burning in air, oil, or SF6, the effect of evaporation of contact material becomes minimal with increasing contact separation, and the plasma depends mainly on the surrounding medium [9-14].

4. interruption of the electric arc

Operation of circuit breakers is generally based on the modification of the arc plasma conductivity, mainly by means of temperature control. Thus, interruption of the circulating current is based on arc cooling. In case of AC, the current passes through zero every half cycle, so the aim is to modify quickly the arc conductivity in the vicinity of the zero current. In contrast, DC current does not change its polarity, so it must be forced to zero.

4.1 Dc Interruption

When the contacts start to separate, the current does not disappear instantaneously but it keeps flowing through the arc established between contacts. As it has been said, DC current interruption has the disadvantage that there is no natural zero current, so it has to be forced to zero.

4.2. Ac Interruption

The interruption of AC currents is facilitated by their zero crossing, twice per cycle, being only necessary to prevent the reignition of the arc after the zero crossing of the current. If the circuit breaker is able to separate the contacts at the moment of zero current and does it with such a high speed that voltage between contacts cannot bridge the gap between them, the circuit is interrupted.

There are different interruption technologies based on the interruption medium. The main interruption techniques currently used are Interruption in air (LV), in vacuum (MV) and in SF6 (MV and HV).

5. Arc Interruption Theories

The physical complexity in behavior of electric arc during the interrupting process has always provided the incentive for researchers to develop suitable models to describe this process. Over the years many researchers have advanced a variety of theories. Some of the very important theories are:
Cassie arc model was presented by Cassie in 1939 [16]. Cassie assumed that the arc has a fixed temperature being cooled by forced convection. This implies that the cross-section area of the arc is proportional to the current and that the voltage over the arc is constant. Cassie arc model is suitable for arcs with high currents. The power dissipation was assumed to be blast arc and was represented by following differential equation (2)

\[ \frac{R}{V}(1/R) = \frac{1}{\theta} \left( \frac{V}{V_0} \right)^2 - 1 \]  

Where \( R \) is the arc resistance, \( V \) is arc voltage at any instant, \( V_0 \) is arc voltage in steady state, and \( \theta \) is the arc time constant i.e. the ration of energy stored per unit volume to the energy loss rate per unit volume.

Mayr arc model was introduced in 1943 [6, 17]. Mayr assumed that power losses are caused by thermal conduction and the arc conductance is dependent on tem-perature. The cross-section area of the arc is assumed constant. Mayr arc model is fit for currents near zero. Schwarz developed a modified Mayr arc model in 1971. The time constant and the cooling power in the model are dependent on the arc conductance [38]. This model was described by differential equation (3).

\[ \frac{R}{V}(1/R) = \frac{1}{\theta} \left( \frac{V}{V_0} \right)^2 - 1 \]

Where \( R \) is the arc resistance, \( V \) is arc voltage at any instant and \( V_0 \) is the energy loss from periphery of the arc at steady state.

The arc models have been modeled as voltage controlled sources and the differential equation representing the electric arc is incorporated by means of the simulink Differential Equation Editor. The arc models can be implemented in a circuit in a straight forward way.

5.1. Cassie arc model

\[ \frac{1}{g} \frac{dg}{dt} = \frac{d}{dt} \left( \frac{1}{\tau} \left( \frac{u^2}{U_c^2} - 1 \right) \right) \]  

Where \( g \) is the conductance of the arc, \( u \) is the voltage across the arc, \( \tau \) is the arc time constant, \( U_c \) is the constant arc voltage. Cassie’s arc model fig. 5 can be implemented with test circuit.

5.2. Mayr’s arc model

\[ \frac{1}{g} \frac{dg}{dt} = \frac{d}{dt} \left( \frac{1}{\tau} \left( \frac{ui}{p} - 1 \right) \right) \]

Where \( g \) is the arc conductance, \( u \) is the arc voltage, \( i \) is the arc current, \( \tau \) is the arc time constant, \( P \) is the cooling power. The fig. 6 shows the Mayr’s arc model.

5.3. Combination of Cassie-Mayr Arc Model

Two identical circuits are displayed: one with a Cassie and one with a Mayr arc model. The circuit is a simple representation of a circuit breaker interrupting short-line fault.
6. RESULTS

Fig.No.8 Voltage and Current waveform of Mayr’s arc model

Fig.No.9. Voltage and Current waveform of Cassie arc model

7. CONCLUSION

Cassie-Mayr arc model has been studied and implemented as a “black-box” model in MATLAB/SIMULINK. The electric arc is an important phenomenon which determines the operation of high voltage circuit breakers. The use of modeling and simulation tools can help to improve these devices, reducing the need of prototype development and testing. The simulation produced current and voltage waveform are very useful for studying complex current interrupting process in the circuit breakers without considering the underlying complex physical phenomenon.

REFERENCES