BLACK BOX ARC MODELING OF HIGH VOLTAGE CIRCUIT BREAKER USING MATLAB/SIMULINK

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ABSTRACT

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. This paper evaluates the black-box arc model for circuit-breakers with the purpose of finding criteria for the breaking ability. A black-box model is a model that requires no knowledge from the user of the underlying physical processes. In this paper, knowledge of the physical processes is required when evaluating and developing the arc models. This paper is meant to give a detailed study of black box model with the purpose to evaluate, combine, improve and apply to already existing circuit-breakers. Cassie-Mayr arc models was evaluated. Cassie’s model gives good results for large currents, while Mayr’s model is better for currents near zero. Therefore, a combination of the Cassie and Mayr model will be used to obtain better result.

Keywords: Black-box arc model, cassie-mayr, circuit-breaker, Matlab/Simulink

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. [1]

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.[2]

![Figure: 1 Simplification of the contact gap](image)

Because of these extreme temperatures, investigation and knowledge of current interruption through arc diagnostics is very difficult and limited. Hence, circuit breaker design is still done for a major part on full-sized prototypes by a cut-and-try method and has remained more of an art than a science. It is now possible to measure and predict by modeling the interrupting limits of modern breakers. [1]

In this paper the characteristics of the electric arc are described with the aim of characterizing the interruption process in high voltage circuit breakers. In addition, an overview of the most important model such as Cassie-Mayr arc model and simulation method using MATLAB/SIMULINK is exposed.

II. BLACK-BOX MODELS

“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. In 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. [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.
The rate of collapse of associated magnetic field, very high voltage would be induced which would severely stress the insulation of the system. On the other hand, the arc provides a low resistance path for the current after contact separation, thereby preventing current chopping and associated abnormal switching over voltages in system. In case of alternating current (ac), arc is momentarily extinguished at every current zero. To make the interruption complete and successful, re-ignition of the arc between the contacts has to be prevented after a current zero. [4]

It is thus evident that arc plays an important role in current interruption and therefore must not be regarded as undesirable phenomenon. It must also be realized that, in absence of arc the current flow would be interrupted instantaneously, and due to the rate of collapse of associated magnetic field, very high voltage would be induced which would severely stress the insulation of the system. On the other hand, the arc provides gradual, but quick transition from current carrying to current breaking states of the contacts. It thus permits the disconnection to take place at zero current without inducing the potentials of dangerous values.[3]

IV. ARC INTERRUPTION THEORIES [5]

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:

- Slepian’s Theory
- Prince’s Theory
- Cassie’s Theory
- Mayr’s Theory
- Browne’s Theory

\[
\frac{1}{g} \frac{dg}{dt} = \frac{1}{T(t,G)} \frac{ul}{P(t,G)} - 1
\]  

(1)

Where:

- \( G \): Arc conductance
- \( u \): Arc voltage
- \( i \): Arc current
- \( P, T \): Parameters of the model
A. CASSIE MAYR’S ARC THEORY

In 1939 Cassie proposed a model of arc in which the arc was assumed to have cylindrical column with uniform temperature and current density, so that its area varies to accommodate the change in current. The power dissipation was assumed to be proportional to the column cross section. This model was intended to represent an air blast arc and was represented by following differential equation:

$$\frac{Rd}{dt} \left(\frac{1}{R}\right) = \frac{1}{\theta} \left\{ \frac{v}{v_0}^2 - 1 \right\}$$

Where $R$ is the arc resistance, $v$, is arc voltage at any instant, $v_0$, is arc voltage in steady state, and $\theta$ the arc time constant i.e. the ration of energy stored per unit volume to the energy loss rate per unit volume. Cassie assumed that only convection causes the power losses, which means that the temperature in the arc is constant. This implies that the cross-section area of the arc is proportional to the current and that the voltage over the arc is constant. [9]

A few years later, in 1943, Mayr proposed a somewhat improved model, in which arc was assumed to be of fixed diameter but of varying temperature and conductivity, the power loss occurred from the surface of the arc only. This model was described by differential equation:

$$\frac{Rd}{dt} \left(\frac{1}{R}\right) = \frac{1}{\theta} \left\{ \frac{v_i}{w_o}^2 - 1 \right\}$$

Where $i$ is the arc current at any instant and $w_o$ is the energy loss from periphery of the arc at steady state. Mayr assumed power losses are caused by thermal conduction at small currents. This means that the conductance is strongly temperature dependent but fairly independent of the cross-section area of the arc. The area is therefore assumed constant. It has been found that Cassie’s model best describes the period before current zero where as Mayr’s model represent better the post arc regime. [9]

V. TEST CIRCUIT

The arc models can be implemented in a circuit in a straight forward way. [5]
VI. CASSIE-MAYR'S ARC MODEL [10]

A. CASSIE ARC MODEL

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

(4)

*Where* \( g \) is the conductance of the arc, \( u \) is the voltage across the arc, \( i \) is the current through the arc, \( \tau \) is the arc time constant, \( U_c \) is the constant arc voltage. Cassie’s arc model can be implemented with test circuit shown above. The figure 3 shows the Cassie’s arc model [5]

B. MAYR’S ARC MODEL
\[
\frac{1}{g} \frac{dg}{dt} = \frac{dilng}{dt} = \frac{1}{\tau} \left( \frac{ul}{P} - 1 \right)
\]

(5)

Where \( g \) is the arc conductance, \( u \) is the arc voltage, \( i \) is the arc current, \( \tau \) the arc time constant, \( P \) is the cooling power. The figure 4 shows the Mayr’s arc model

![Figure: 4 Implementation of the Mayr Arc Model](image)

The initial conductance of the arc \( g(0) \) can be altered. Furthermore, the time at which the contact separation of the circuit breaker takes place can be specified. Until that time the arc model behaves as a conductance with the value \( g(0) \). [5]

**C. COMBINED CASSIE-MAYR’S 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 a short-line fault. At the source side of the circuit breaker a circuit is present for reproducing a (2 parameter IEC) transient recovery voltage, while the RLC circuit at the line side represents a short transmission line that is short circuited.

![Figure: 5 Combined Cassie-Mayr Arc Model](image)

**VII. RESULT**

**A. CASE - I**

When the circuit breaker contact separation starts at \( t = 0 \) s, the following arc voltage and arc current are computed (overall and detail around the current zero crossing). [10], [5]
CASSIE’S ARC MODEL

Figure 6: Voltage Current Comparisons for the Cassie Model. (At T=0 S)

MAYR’S ARC MODEL

Figure 7: Voltage Current Comparisons for the Mayr’s Model. (At T=0 S)

CASSIE -MAYR’S ARC MODEL

Figure 8: Voltage Comparisons for the Cassie and Mayr Arc Models. . (At T=0 S)
B. CASE – II

When the contact separation starts at \( t = 9 \) ms, the following arc voltage and arc current are computed. [5], [10]

CASSIE’S ARC MODEL

Figure 9: Current Comparisons for the Cassie and Mayr Arc Model.

Figure 10: Voltage Current Comparisons for the Cassie Model. (At \( T=9 \) ms)

MAYR’S ARC MODEL
Figure 11: Voltage Current Comparisons for the Mayr’s Model. (At T=9 ms)

CASSIE-MAYR’S ARC MODEL

Figure 12 Voltage Comparisons for the Cassie and Mayr Arc Models. (At T=9 ms)

Figure 13: Current Comparisons for the Cassie and Mayr Arc Models. (At T=9 ms)

VIII. CONCLUSION

Matlab/Simulink is a very powerful tool for developing arc models. Through this work a Cassie-Mayr arc model has been studied and implemented as a “black-box” model in MATLAB/SIMULINK. The simulation produced current and voltage oscillograms are very useful for studying complex current interruption process in the circuit breakers without considering the underlying complex physical phenomenon.
REFERENCES