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Black Box Modeling of HVCB: A Comparative Approach

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Abstract

Electric arcs in high-voltage circuit breakers (HVCBs) are intricate phenomena, governed by a multitude of physical interactions, that play a crucial role in their operation. While essential for interrupting or diverting current flow during faults or system operations, their uncontrolled formation can lead to non-linear behavior within the HVCB. To understand and optimize HVCB performance, modeling and analyzing the electrical properties of these arcs becomes critical. This study investigates the application of black box models, such as Cassie, Mayer, and Schavemaker, as a practical approach to mathematically represent the electrical characteristics of arcs in HVCBs. These models offer an alternative to exploring the full complexity of the underlying physical processes.

Significantly, this research introduces the application of the Schavemaker model within the ATPdraw software for the first time. Utilizing a customized MODELS block, the study investigates the efficacy of these black box models in representing arcs during HVCB analysis. By comparing current and voltage indicators across various operational modes, the study aims to outline the fundamental aspects of electric arcs in HVCBs, define the essential mathematical, physical, and software requirements for their modeling and simulation and provide valuable insights into these complex phenomena, complementing the challenges associated with traditional laboratory testing. This approach offers a valuable contribution to the understanding and optimization of HVCBs, paving the way for improved performance and safer power system operation.

Keywords: Circuit breaker, Black box model, ATPdraw, Arc voltage, Post arc current

1. Introduction

High-voltage circuit breakers, in particular, hold a critical role in safeguarding power systems. These essential components must fulfill several key criteria to operate effectively. They should serve as efficient conductors when closed, provide effective insulation when opened, not cause over voltages during operation, and demonstrate rapid switching capabilities. The various types of high-voltage circuit breakers, such as hydraulic press, air press (steam air), and SF6 gas, are central to ensure the reliability and stability of power systems (Lazzari et al., 2023).

However, when high-voltage circuit breakers approach the point of opening, they can generate high-temperature electrical arcs. In contemporary high-voltage breakers, the arc is extinguished using gas in a manner akin to extinguishing a match with a breath, albeit with a force that is 100 million times more powerful. 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 are separated with rather high speed, resulting in an electric arc in the contact gap between the plug and the contact. This is illustrated in Fig. 1.
Understanding and managing the characteristics of these arcs, particularly their voltage profiles, are essential components of ensuring the safety and performance of high-voltage circuit breakers. In this context, this study delves into the performance and behavior of high-voltage circuit breakers, shedding light on the critical factors that contribute to their effective operation in modern electrical systems.

Circuit breakers serve as critical control elements within power systems, acting as sophisticated switches that utilize relays for operation. Their ideal function is to swiftly interrupt the flow of electricity and effectively isolate two interconnected networks. However, under practical conditions, the physical separation of the breaker’s contacts doesn’t immediately extinguish the current. Instead, an electric arc forms between the contacts, posing a challenge to complete interruption.

This arc arises due to the intense heat and pressure created when the contacts separate under load. The surrounding medium (air, oil, or SF6) breaks down and forms a high-temperature plasma channel, composed of free electrons and ions, that allows current to flow despite the physical separation. Characterized by distinct regions and a variable voltage distribution, the arc’s behavior depends on factors like electrode material, medium type, and chamber configuration. The cathode plays a crucial role in emitting electrons, while the anode can be passive or actively contribute ions to the plasma.

The successful extinguishment of this arc relies on the strength of the dielectric medium surrounding the breaker, enabling it to withstand the transient recovery voltage (TRV) generated across the open contacts. This complex interplay between arc dynamics and TRV necessitates employing circuit breaker models to analyze and optimize their performance under various operating scenarios (Nakartishi, 1991a). Despite the intricacy involved in interrupting an arc, several techniques have been devised to simulate and model arc behavior (Gustavsson, 1992a). Models and simulations make it possible to analyze the time-based progression of certain physical quantities that are challenging to measure in laboratory tests. Consequently, it is possible to evaluate the impact of these parameters on the arc interruption process and the arc phenomenon itself. Understanding these intricacies is essential for optimizing circuit breaker performance and arc quenching techniques.

The advancement of circuit breakers is heavily influenced by research into arc modeling. These models are classified into three distinct categories based on their characteristics, as outlined in Table 1 (Cigre Working Group, 1998):

- Physical models (PM).
- Models due to graphics and diagrams (GD).
- Black box models also referred as (P-τ) models or parameter models (BB).

### 1.1. Physical models (PM)

These models offer detailed representations of the physical processes involved in arc formation and behavior, requiring extensive computational resources and expertise to capture the complex interplay of physical phenomena occurring during current interruption (Schavemaker and van der Sluis, 2002). These models, built upon electromagnetic and
thermodynamic laws, offer a detailed mathematical representation of the electric arc's behavior considering some key factors such as (Mahajan et al., 2013a; Karett and Lindmayer, 1998):

- **Chemical activity of plasma**: Equations account for various chemical reactions within the plasma, ensuring accurate determination of local thermodynamic equilibrium.
- **Electrical conductivity**: The interaction between the plasma and the magnetic field (generated by the arc or external sources) is factored in, affecting the plasma's velocity.
- **Heat and radiation**: The rate equations consider heat generated by the Joule effect and electromagnetic radiation emitted by the arc.
- **Fluid dynamics of the quenching gas**: The Navier–Stokes equations model the movement of the gas during interruption, coupled with the electromagnetic behavior described by Maxwell's equations.
- **Plasma properties**: The model accounts for the dependence of the plasma's density, viscosity, and specific heat on temperature, pressure, and the vaporized materials (metals or plastics) present.

The inherent sensitivity of plasma properties to temperature and pressure variations presents a significant challenge in physical arc modeling. This complexity necessitates considerable computational resources, making such models sophisticated yet computationally expensive. However, their ability to unravel the intricate details of arc behavior ultimately leads to safer and more effective circuit breaker designs, ensuring enhanced power system protection (Thomas and Browne, 1984; Myint and Lwin, 2014; Van der Sluis, 2001; Lindmayer et al., 2005).

### 1.2. Graphical and diagrammatic models (GD)

These models utilize simplified visual representations of the arc, offering ease of use. They can be used to establish a connection between circuit parameters and the effectiveness of the circuit breaker's interrupting process (Myint and Lwin, 2014). These relationships can be derived from physical and black box models, or even from direct testing but they are limited accuracy in complex scenarios and only valid within the parameter range established through experimentation (Blahous, 1982). However, their application remains valuable in designing circuit breakers, assessing the severity of circuit tests, and comparing test performance with real-world network conditions (Cigre Working Group, 1998; Van der Sluis, 2001).

### 1.3. Black box models (BB)

Black box models, also known as parametric models ($\pi$-models), play a crucial role in circuit breaker analysis by providing a pragmatic balance between accuracy and computational efficiency. These models represent the arc's electrical behavior through mathematical equations, obviating the need for in-depth knowledge of the underlying physical intricacies. This characteristic renders them highly suitable for practical applications in circuit breaker analysis (Van der Sluis, 2001; Torres et al., 2011).

While black box models do not delve into the complexities of the arc disruption process, they leverage established physical principles to establish a connection between arc conduction and measurable quantities like voltage and energy through difference equations. These models primarily focus on understanding arc behavior during the interruption phase, offering valuable insights for network studies and simulating arc–circuit interactions with a reasonable degree of accuracy (Cigre Working Group, 1993; Cigre Working Group, 1998).

It is essential to acknowledge the limitations of these models. Due to their simplified nature, black box models are not directly applicable to the design of circuit breaker interrupters themselves. However, they provide invaluable support in network studies and performance evaluations by efficiently representing the arc's role within the larger system. Typically, these models involve one or two differential equations, offering a computationally efficient approach to understanding circuit breaker behavior within established applicability limits (Mahajan et al., 2013a; Pedro, 2017).

| Table 2. Comparison between physical and black box models. |
|-----------------|-----------------|-----------------|
| **Arc model**   | **Physical model** | **Black box model** |
| Advantage        | More precise    | Simple |
|                  | Describe the physical process inside the CB. | Low computational effort. |
|                  | Describe the steady-state behavior of the arc. | Describe the dynamic behavior of the arc. |
| Disadvantage     | Complex calculations. | Based on the measurements and observed data. |
|                  | Parameters during natural current zero crossing changed. | Can't simulate the physical process inside the CB. |
In essence, black box models bridge the gap between theoretical understanding and practical application in circuit breaker analysis, offering valuable insights with an emphasis on functionality and practical implementation compared to physical models. A comparison between both physical and black box models is presented in Table 2.

They offer a more practical approach through mathematical conductance calculations, simulating the arc’s dynamic behavior within the network. However, their accuracy relies heavily on precise, often challenging-to-determine arc parameter descriptions. Additionally, transferring these parameters to different arc conditions is complex, often requiring separate determinations for each configuration (Walter and Franck, 2014). Furthermore, questions remain about the ability of a single equation with conductance as the sole state variable to fully capture the arc’s behavior (Seeger et al., 2006). While physical models offer detailed physical relationships and power calculations, they are often limited in their ability to capture dynamic behavior due to mathematical complexities (Bishop, 1954).

The researchers acknowledge these concerns but attribute them primarily to the challenges of precise parameter determination and validation for specific arcs. They emphasize the practicality of these models, arguing that even intricate black-box models can be valuable as long as their parameters can be set through experimentation (Walter and Franck, 2014). Table 3 highlights the prevalence of conductance-based black-box models compared to those built on physical relationships and power calculations.

This study aims to further explore and compare these models by simulating them using ATP Draw. This software will be used to analyze the behavior of three prominent models: Cassie, Mayer, and Schavemaker.

Previous studies have employed various simulation tools for these models, as shown in the table. References (Mahajan et al., 2013a; Pedro, 2017; Yuan et al., 2013; Tian and Huawei, 2018; Saitwal and Khampariya, 2018 and Saad, 2020) employed MATLAB to simulate the Cassie model, while references (Leung et al., 2005; Mahajan et al., 2013a; Chmielewski et al., 2019) utilized EMTP (Electromagnetic Transients Program). Mayer model simulations were primarily conducted using MATLAB in references (Pedro, 2017; Mahajan et al., 2013a; Tian and Huawei, 2018; Saitwal and Khampariya, 2018; Saad, 2020 and Tie and Haoyun, 2018), with SIMULINK used in some cases (Mahajan et al., 2013a; Pedro, 2017; Tian and Huawei, 2018; Saitwal and Khampariya, 2018; Chmielewski et al., 2019).

Finally, the Schavemaker model was only covered using MATLAB and SIMULINK simulations in references (Pedro, 2017; Yuan et al., 2013; Hosseini et al., 2013).

By employing ATP Draw, this study aims to provide a comparative analysis of these three models, offering insights into their behavior and potential advantages and disadvantages under unified simulation conditions. This approach will allow for a more comprehensive evaluation and understanding of their respective functionalities.

2. Circuit breaker mathematical modelling

2.1. The critical role of circuit breakers in power systems

Circuit breakers serve as essential control elements within power systems, functioning as sophisticated switches controlled by relays to ensure efficient isolation between interconnected networks. Ideally, these devices should operate instantaneously, achieving complete current interruption without delay. However, the physical separation of the breaker’s contacts in real-world scenarios inevitably leads to the formation of an arc between them.

The success of the interruption process relies on two critical factors:

- **Dielectric Strength of the Medium:** The medium surrounding the contacts (air, oil, or SF6 gas) must possess sufficient dielectric strength to withstand the transient recovery voltage (TRV) that arises at the natural current zero crossing. This ensures that the medium does not break down and allows unintended current flow.
- **Arc Extinguishment:** The arc itself needs to be effectively extinguished to prevent continued current flow after the initial separation of the contacts. This is typically achieved through various mechanisms depending on the type of circuit breaker and the surrounding medium.

These critical factors, as discussed in (Cigre Working Group, 1993; Nakartishi, 1991b), are intertwined and essential for ensuring successful circuit breaker operation and safeguarding the stability and reliability of power systems.

2.2. Circuit breaker model based on ideal switch

The circuit breaker is often represented in power system simulations as an ideal switch that activates at the instant that the current is zero, instantly separating the two networks (Lazzari et al., 2023).
Table 3. Comparison between physical and black box models.

<table>
<thead>
<tr>
<th>Arc Model</th>
<th>Model Used</th>
<th>Year</th>
<th>Ref.</th>
<th>Simulation Methodology</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2005</td>
<td>Leung et al. (2005)</td>
<td>SIMULINK</td>
<td>√</td>
<td>Demonstrates high precision in characterizing the uninterrupted arc phase within a region of constant arc voltage.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2013</td>
<td>Mahajan et al. (2013b)</td>
<td>EMTP</td>
<td>√</td>
<td>Simple to implement.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2013</td>
<td>Yuan et al. (2013)</td>
<td>PSCAD</td>
<td>√</td>
<td>Inadequate depiction of the zone where arc current reaches zero.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2017</td>
<td>Pedro (2017)</td>
<td>EMTDC</td>
<td>√</td>
<td>Not suitable for analyzing the arc's behavior during the low current period.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2018</td>
<td>Tian and Huawei (2018)</td>
<td>ATP</td>
<td>√</td>
<td>Utilizes a fixed parameter that does not accurately describe practical arc behavior.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2018</td>
<td>Saitwal and Khampariya (2018)</td>
<td>ATP</td>
<td>√</td>
<td>Modeling the interruption of arcs is not feasible.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2019</td>
<td>Chmielewski et al. (2019)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2020</td>
<td>Saad (2020)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2005</td>
<td>Guardado et al. (2005a)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2005</td>
<td>Leung et al. (2005)</td>
<td>MATLAB SIMULINK EMTP PSCAD EMTDC ATP</td>
<td>√</td>
<td>Suitable for high resistance and low current arc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2013</td>
<td>Mahajan et al. (2013b)</td>
<td>SIMULINK</td>
<td>√</td>
<td>More accurate in the near current zero crossing region for arc extinguishing stage.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2017</td>
<td>Pedro (2017)</td>
<td>EMTP</td>
<td>√</td>
<td>Easy to implement.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2018</td>
<td>Tian and Huawei (2018)</td>
<td>ATP</td>
<td>√</td>
<td>Allow the arc to interrupt.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2018</td>
<td>Tie and Haoyun (2018)</td>
<td>ATP</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2018</td>
<td>Saitwal and Khampariya (2018)</td>
<td>ATP</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2019</td>
<td>Chmielewski et al. (2019)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2020</td>
<td>Saad (2020)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schavemaker</td>
<td>Guardado et al. (2005a)</td>
<td>2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2013</td>
<td>Yuan et al. (2013)</td>
<td>MATLAB SIMULINK EMTP PSCAD EMTDC ATP</td>
<td>√</td>
<td>Suitable for the high and low current regions.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2013</td>
<td>Hosseini et al. (2013)</td>
<td>SIMULINK</td>
<td>√</td>
<td>Consider the time constant and a cooling power as a function of power input.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2017</td>
<td>Pedro (2017)</td>
<td>EMTP</td>
<td>√</td>
<td>The high current region is not accurate as the low current region.</td>
</tr>
</tbody>
</table>

(continued on next page)
The green highlight in the waveform in Fig. 2 indicates that the breaker operates at 10 ms.

The separation of circuit breaker contacts does not always take place precisely at the point of current zero and in an immediate manner during real circuit breaker operation. This occurs as a result of the addition of a particular period known as the “arching time.” The period of time between the beginning of an arc and its final extinction over all poles (ABB, 2003). The successful quenching of the arc depends on various factors, including the travel of the contacts, the properties of the dielectric medium between the contacts, the characteristics of the arcing window, and the rate at which the contacts move (Patel et al., 2019).

Even if the arc is quenched at the moment of current zero, a small current with a magnitude typically in the range of a few amperes may continue to flow between the contacts of the circuit breaker. The residual current that persists after the arc between the contacts has extinguished is called post-arc current.

2.3. Visualizing the modeling process

Flowcharts serve as a valuable tool for visualizing the intricacies of CB modeling, facilitating clear and concise communication by deconstructing complex processes into manageable phases, they offer a structured roadmap for successful model development and application. Fig. 3 presents a flowchart outlining the CB modeling process.

Given the crucial role of mathematical models in accurately representing CB behavior during arcing and post-arc phases within power system simulations, black-box models form the primary approach for CB representation. These models effectively capture the thermal period of the interruption process, with its duration influenced by both the inherent characteristics of the interruption and the extinguishing media employed. Their frequent adoption stems from their efficiency in calculations involving short line faults and interruption of small inductive currents.

These black box models adhere to the principles of energy balance theory and the Majority of electric arc models are based on the first order differential equation which has the generalized form (Mahajan et al., 2013b; Guardado et al., 2005b):

$$\frac{1}{g} \frac{dg}{dt} = \frac{1}{T(|i|, g)} \times \frac{u \times i}{P(|i|, g)}$$

Equation (1) describes the general mathematical form representing the electric arc, where g is arc
conductance, \( u \) arc voltage, \( i \) arc current and \( P \) and \( T \) are the constant parameters of black box models.

Black-box models have been traditionally used to model electric arcs instead of physical models because they are simple and only consider the electrical behavior of the arc, such as current and voltage. However, these models ignore the underlying physical processes of the arc and focus on the arc dynamics. In the following section, several mathematical models will be discussed, among which the Cassie and Mayr models serve as the basis for various other mathematical representations and Shavemaker model which is one of their modifications.

2.4. Cassie model

One of the earliest valuable differential equations that elucidated the dynamic characteristics of an electric arc was introduced in 1939 by A.M. Cassie (Cassie, 1939; Garzon, 2002; Gustavsson, 1992b). Cassie derived his equation to calculate the conductivity of the arc, under the following assumptions:

- Temperature within the arc remains constant, without variation in both spatial and temporal dimensions.
- The arc column is cylindrical in shape, with a cross-sectional area \( A(t) \) that changes over time depending on the arc composition.
- The power dissipation of the arc is primarily influenced by convection.

\[
\frac{1}{g} \frac{dg}{dt} = \frac{1}{\tau_c} \left( \left( \frac{u^2}{U_C^2} \right) - 1 \right)
\]

Equation (2) describes the Cassie model, where \( U_C \) constant arc voltage, and \( \tau_c \) Cassie time constant.

2.5. Mayr model

Mayr adopted a significantly distinct perspective from that of Cassie. In 1943, Mayr theory was introduced regarding arc behavior (Garzon, 2002;
According to Mayr theory, the following key points are considered:

The arc is characterized by a cylindrical column shape, with a cross-sectional area that remain the same over time.

The temperature (T) within the arc column is uniform but varies with time, and it is contingent upon the energy stored (Q).

Cooling of the arc occurs solely through the process of thermal conduction.

\[
\frac{1}{g} \frac{dg}{dt} = \frac{1}{\tau_m} \left( \frac{u \times i}{P_0} - 1 \right)
\]

Equation (3) gives where \( i \) is arc current, \( P_0 \) is the arc cooling power, and \( \tau_m \) is Mayr time constant.

2.6. Schavemaker model

Schavemaker arc model is a modified version of the Mayr arc model, utilizing constant time parameter \( \tau \) based on current zero measurements and cooling power as a function of the electrical power input. This model comprises a single differential equation for both high and low current regions (Schavemaker and Sluis, 2000; Pasumpon et al., 2016).

\[
\frac{d \ln g}{dt} = \frac{1}{\tau} \left( \frac{P_{\text{supp}}}{\max(U_{\text{arc}},|i|,P_0 + P_1 u \times i)} - 1 \right)
\]

Equation (4) gives where \( P_1 \) is the cooling constant; \( P_1 \) is set to zero after the current zero crossing, \( P_{\text{supp}} \) is the electrical power supplied = \( u \times i \), \( U_{\text{arc}} \) is the constant arc voltage in the high current area.

Within the region characterized by high electrical currents, Equation (4) simplifies to the subsequent differential equation:

\[
\frac{1}{g} \frac{dg}{dt} = \frac{1}{u_{\text{arc}} |i|} - 1 \]

This equation exhibits a distinct resemblance to the Cassie arc model. At the point of current zero, Equation (4) simplifies to the subsequent differential equation.

\[
\frac{1}{g} \frac{dg}{dt} = \frac{1}{\tau} \left( \frac{u \times i}{P_0} - 1 \right)
\]

Which is a perfect match for the Mayr arc model.

3. Techniques and results of simulation

The complex behavior of the electric arc in circuit breakers has been successfully replicated within ATPdraw, a graphical preprocessor for the Electromagnetic Transients Program (EMTP). This was achieved by utilizing the “MODELS language,” a powerful tool within ATPdraw for defining user-specific models (Dubé, 1996).

To represent the arc’s non-linearity, an ATP user-defined model block was employed. This block encapsulates the governing differential equations and utilizes numerical methods for their solution. In this simulation, the forward Euler method was chosen for its efficiency and simplicity.

The model’s input is the current at the circuit breaker contact. The output, representing the
Dynamic arc resistance, is integrated into the circuit via a Type 91 TACS block within ATPdraw. This approach enables accurate simulation of the arc's influence on circuit behavior.

3.1. Parameters of simulation circuit

In Fig. 4, the circuit used for conducting the T100s test in accordance with IEC 62271-100 is illustrated with left side terminal fault. All the parameters of this circuit have been obtained from the specifications outlined in the standard, and their respective values are provided in Table 2 (IEC, 2012).

The term “T100s” denotes a test configuration for circuit breakers in which one terminal of the circuit breaker is shorted to ground, resulting in the flow of a current equal to 100 percent of the rated short-circuit current through the circuit breaker contacts.

In Fig. 4, the circuit breaker is represented by an ampere meter, an arc model, and a nonlinear resistance. In this circuit, the Mayr model is employed as the arc model, and the parameters for the Mayr model is listed in Table 5.

It's important to note that the parameters for the Mayr model have been derived through an approximation of the behavior of arc voltage and current throughout the arcing period. Specifically, at 1 ms, the contacts of circuit breaker are mechanically set apart to initiate the test.

Table 4. Circuit simulation inputs (Patel et al., 2019).

<table>
<thead>
<tr>
<th>Us</th>
<th>Ls</th>
<th>Cd</th>
<th>C1</th>
<th>R1</th>
<th>C2</th>
<th>R2</th>
<th>L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>183.886</td>
<td>11.7 mH</td>
<td>0.0222</td>
<td>0.9475</td>
<td>90.031</td>
<td>0.663</td>
<td>28.81</td>
<td>21.8 mH</td>
</tr>
<tr>
<td>KV</td>
<td>μF</td>
<td>μF</td>
<td>Ω</td>
<td>μF</td>
<td>Ω</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Mayr model parameters (Patel et al., 2019).

<table>
<thead>
<tr>
<th>P (W)</th>
<th>τm (sec)</th>
<th>t_open (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$400 \times 10^3$</td>
<td>$1 \times 10^{-6}$</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Fig. 6. Constant arc region zoomed in.

Fig. 7. Post arc current zoomed in.
3.2. Simulation results

Figure 5 shows the verification of the Mayr model code using MODELS language in ATP draw. A comparison between the published arc output (Patel et al., 2019) and simulation arc output shows good accuracy with the developed model. The simulation’s output, as illustrated in Fig. 5 is not distinct enough with regard to the operation of an ideal switch but if the output is zoomed in as shown in Fig. 6 the constant arc voltage region portion and current zero crossing as illustrated in Fig. 7 it manifests a clear discrimination.

3.3. Variation of cooling power effect

For the circuit shown in Fig. 4 taken into consideration the same set of parameters for the simulation physical circuit mentioned in Table 4. The Mayr parameters for the three different cases are listed in Table 6, and the impact of variation in cooling power is presented in Fig. 8.

3.4. Impact of alteration in current rate of change with respect to time (di/dt) at current zero

Predicting the rate of current zero change during current interruption is achieved by altering the source inductance as shown in Table 7 while keeping all other circuit parameters in Fig. 4 the same for the Mayr model.

The current output waveform depicted in Fig. 9 provides a clear illustration demonstrates that when the rate of di/dt at current zero is low, the flow of current is interrupted. Conversely, when di/dt is high, the current is not interrupted, and it persists, flowing through the open contact.

4. Arc models comparison

This section performs a comparative analysis of the results obtained from three mathematical models. These models have been created using the ATPdraw model library. More specifically, Fig. 11 shows the outputs generated by the Cassie, Mayr, and Schavemaker models, concentrating on cases of unsuccessful interruption. You can find comprehensive details regarding the parameters for all these developed models in Table 8.

Model parameters are obtained from Ref (Patel et al., 2019), Circuit Parameters are taken from Ref (Orama-Exclusa and Rodriguez-Medina, 2003) as reference and $R_g$ is set to be 100 Ω. Figure 10 shows a mathematical model of the arc that can be used to study the arc’s behavior under different models.
(generalized mathematical model). Separation of the circuit breaker mechanical contacts occurs at 5 ms as demonstrated in Fig. 12 and arc does not extinguish at any zero crossing. Figure 13 shows a zoomed-in view of the arc voltage for all three models, which can be used to understand the behavior of the mathematical model near the region of constant arc voltage.

To observe the arc voltage behavior of the three models in the vicinity of the current zero region, a magnified version of Fig. 13 is provided. This figure allows for a comparison of arc voltage among the four mathematical models.

Figures 13 and 14 and Table 9 show that Cassie model breaks faster, and the arc voltage extinguishing peak is the same of Mayr model. According to Table 9, the time to zero Schavemaker model is higher and according to Fig. 14, it is clear that the Mayr model breaks faster than Schavemaker model. (See Fig. 14)

![Fig. 9. Current waveform of circuit breaker with di/dt variation.](image)

![Fig. 10. Comparison circuit.](image)

![Fig. 11. Voltage comparison of arc models.](image)

Table 8. Arc model's parameters.

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter 1</th>
<th>Parameter 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mayr model</td>
<td>$P_0 = 1880300$</td>
<td>$U_c = 581.59$</td>
</tr>
<tr>
<td></td>
<td>$\tau_m = 7.01 \times 10^{-6}$</td>
<td>$\tau_c = 0.00011$</td>
</tr>
<tr>
<td>Schavemaker model</td>
<td>$P_0 = 1880300$</td>
<td>$U_{arc} = 581.59$</td>
</tr>
<tr>
<td></td>
<td>$\tau = 1.1 \times 10^{-5}$</td>
<td>$P_1 = 124.7$</td>
</tr>
</tbody>
</table>
5. Conclusion

Electric arcs are central to the operation of high-voltage circuit breakers (HVCBs), significantly influencing their performance. This study investigated the potential of modeling and simulation tools...
to improve HVCB design, offering a valuable alternative to costly and time-consuming physical prototyping and testing. By leveraging simulation tools to understand HVCB behavior, engineers can optimize designs and create more effective and reliable power system protection systems.

The research employed a complex differential model of arc dynamics to simulate the opening of an HVCB under a terminal fault condition. This simulation utilized a specialized MODELS language tool within ATPdraw software, providing comprehensive control over the breaker’s representation, solution, and initialization, eliminating the need for transition conditions. Fundamental simulations were conducted using Cassie, Mayr, and Schavemaker black-box models, offering insights into circuit breaker behavior during interruption phenomena. A comparative analysis of these models further enhanced understanding.

Significantly, this study marks the first-ever presentation of the Schavemaker model within the ATPdraw software environment. This advancement opens doors for further exploration and refinement of this model using the capabilities of ATPdraw.

The primary objective of the study was to demonstrate the effectiveness of black-box modeling in assessing crucial parameters like the impact of cooling power on post-arc current and successful interruption outcomes. Furthermore, the research acknowledged the availability of various alternative models capable of predicting circuit breaker behavior, highlighting the rich landscape of modeling approaches available for this crucial domain.

In conclusion, this research paves the way for utilizing modeling and simulation techniques to optimize HVCB design and performance, particularly with the introduction of the Schavemaker model in ATPdraw. By leveraging these tools, engineers can gain valuable insights into arc behavior under terminal fault conditions and develop safer and more reliable power system protection systems, ultimately contributing to a more robust and efficient electrical grid infrastructure.

Ethical statement

This research adhered to ethical research principles and all data used in this study originated from publicly available sources or was generated through simulations using established software.

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Author contribution statement


Conflicts of interest

All authors declare no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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