Electric Arc Modeling in Circuit Breakers for Electromagnetic Transients Analysis

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Abstract

Circuit breakers play a very important role in Eletrical Power Systems. They are responsible for switching operations, connecting and disconnecting network elements, as well as interrupting currents harmful to the system. However, the circuit breaker doesn't respond instantaneously and exhibits also a non-linear behavior, resulting from the appearance of an electric arc in the dielectric. For this reason the modeling of the electric arc takes great importance in its representation. To approach this subject, the Black Box models are implemented for two distinct faults: terminal fault and short-line fault, in order to study their arc parameters, as well as their ability to represent the characteristics of the electric arc.

Keywords: Circuit breaker, Eletric Arc, Black Box Models, Terminal Fault, Short-line Fault, Interruption, Re-ignition

1. Introduction

Circuit breakers are the equipment responsible for switching operations in the power system and very important in the interruption of harmful currents to the system. Normally it is considered, for simplicity of representation, that the change of states of the circuit-breaker takes place instantaneously. In reality, the circuit-breaker does not respond instantaneously and also presents a non-linear behavior, during the switching operations, resulting from the appearance of an electric arc on it's dieletric. For that reason, is fundamental to understand the influence of the electric arc in the interruption process.

The literature of the specialty presents several models to represent the behavior of the electric arc in the circuit-breaker. The physical models are the most complex ones, and are based on the fluid dynamics equations to translate the behavior of the arc as a plasma. The simplest ones, Black Box models (also known by P-τ models) translate the nonlinear variation of arc conductance as a function of the arc voltage and current. While the first type of models is used by manufacturers in the development of equipment, the second is used in studies of electromagnetic transients since they translate the interaction between the electric arc and the circuit under analysis.

2. The Switching Arc

The switching arc present in the circuit breaker, during a switching operation, assumes a fundamental role in the process. The electric arc is a plasma channel that is established between the circuit breaker contacts after a discharge in the extinguishing gas. When a current flows through a circuit breaker and the contacts begin to move away, the magnetic energy stored in the inductances of the power system prevents the current from being interrupted, forcing it to continue [16]. Immediately before contacts separation, the contact area is very low and the high current density melts the circuit breaker contacts. The contacts material that has melted "explodes" and causes a discharge in extinguishing medium [16]. As the kinetic energy of the molecules increases, matter changes from the solid to the liquid state and from the latter to the gaseous state. A further increase in temperature, equivalent to the increase of energy state, cause molecules dissociation into separate atoms. If the level of energy continues to increase, orbital electrons of the atoms dissociate into free electrons, leaving positive ions. This state of matter is called plasma. Because of the free electrons and the heavier positive ions in the high-temperature plasma channel, the plasma channel is highly conducting and the current continues to flow after contact separation. The plasma conductivity is function of temperature and increases rapidly with its magnitude [16].

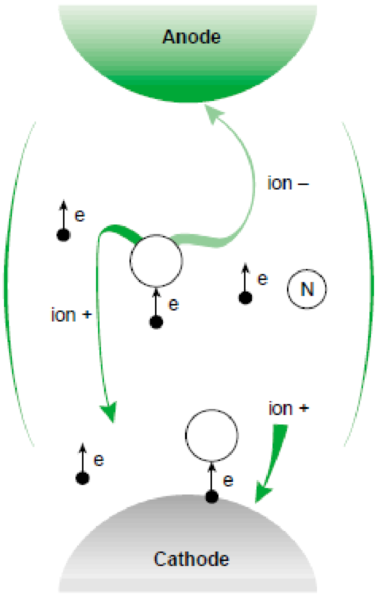


Figure 1: Electrical arcing in a gaseous medium [15]

The thermal ionization, as a result of the high temperatures in the electric arc, is caused by energy transfer between electrons and photons that have high kinetic energy, and positive ions and neutral atoms with reduced kinetic energy (see Figure 2.1). At the same time, there is also a recombination process when electrons and positively charged ions recombine to a neutral atom. When the ionization rate is equal to the recombination rate, the thermal equilibrium is reached. Normally, it is assumed that the electric arc is in thermal equilibrium during the entire transient phenomenon, since the time constants of the ionization and recombination processes are negligible when compared with arc variations [16].

The electric arc consists of three regions:

- Column region
- Cathode region
- Anode region

In the arc column, the current flow is maintained by electrons, and there is a balance between the electron charges and the positive ion charges. The peak temperature in the arc column can range from 7000 to 25 000 K, depending on the arcing medium and the configuration of the arcing chamber [16]. The voltage established between the circuit breaker terminals due to the arc and contacts resistance is called arc voltage [15].

2.1. Arc Extinction Regimes

The current interruption process in a circuit breaker assumes a complexity arising from the simultaneous interaction of various phenomena (electrical and magnetic).

In the electric arc extinction process two physical regimes (requirements) are involved [3]:

- **Thermal regime**: The arc channel has to be cooled down to a sufficiently low temperature in which it ceases to be electrically conducting.
- **Dielectric regime**: After the arc extinction, the insulating medium must withstand the rapidly increasing voltage that appears across circuit breaker terminals. This voltage is called the recovery voltage and its transient component, transient recovery voltage (TRV) which is motivated by the continuity of electric and magnetic energy.

If any of the requirements is not achieved, the current will continue to flow until, after half a cycle, it reaches zero again. The verification of the necessary conditions for current extinction is repeated in each passage for zero.

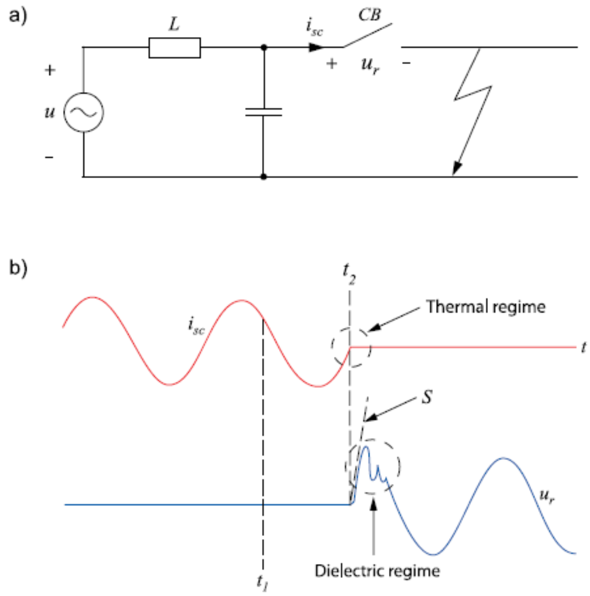
In figure 2 a) is presented the equivalent circuit for the terminal fault. In figure 2 b) is represented the short-circuit current and the recovery voltage, for the fault in question, where is shown the thermal and dielectric regime [3].

The instant of time t_1 represents the moment of contact separation, t_2 the moment of arc extinction and S the rate of rise of recovery voltage.

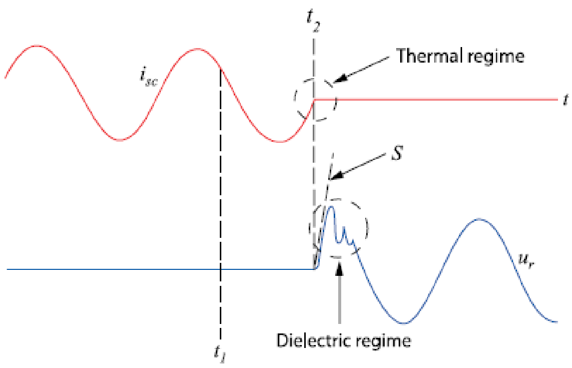
2.1.1 Thermal Regime

After the opening of the circuit breaker, an electric arc arises sustained by the dissipated energy under joule effect which subsists while the temperature of the medium is very high [15]. The electric arc interruption is carried out when current magnitude is near zero in case that the ionized channel rapidly recovers its dielectric characteristics. As the current approaches zero, arc conductance decreases with it. When the current theoretically reaches the zero magnitude, the arc conductance decreases as a function of the deionization time constant of the medium. This time constant is inherent to the inertia of the medium in recovering its dielectric characteristics. In this instant of time, the conductance assumes a small value diferent than zero, which, depending on the applied arc voltage, can produce a current of some amperes called post-arc current (see figure 3). The current interruption depends on an energy balance. If the arc input power exceeds the circuit breaker cooling power the medium recovers a conductive state, caused by thermal failure, and the current continues to flow. Otherwise, a successful thermal interruption is obtained [15].

Figure 3 illustrates the inertia in the electrical conductivity of the arc. The thermal interruption



(a) Simplified equivalent circuit for terminal fault



(b) Curves of short-circuit current i_{sc} and recovery voltage u_r

Figure 2: Arc extinction regimes - terminal fault [3]

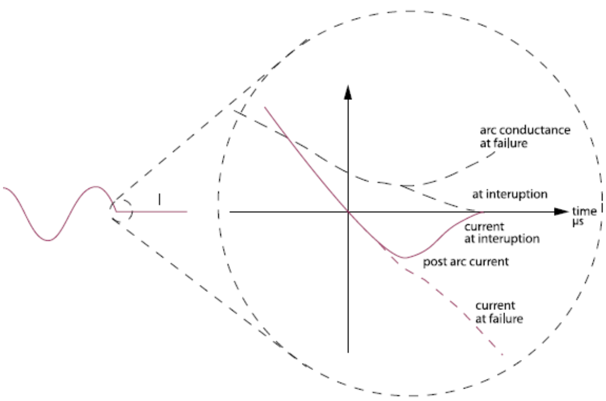


Figure 3: Current shape at interruption (the time scale is in the microsecond range) [3]

regime corresponds to the period of time starting some microseconds before current zero, until extinguishing of the post arc current, a few microseconds after current zero [3, 10].

2.1.2 Dielectric Regime

The dielectric regime begins with the extinction of the post-arc current and the manifestation of the transient recovery voltage (TRV) that appears on the circuit breaker terminals. At this time, the extinguishing/isolating medium is no longer electrically conducting, but it still has a much higher temperature than the ambient. This reduces the voltage withstand capacity of the contact gap. The dielectric interruption success will depend on the rate of recovery of the dielectric strength and the rate of rise of the TRV (see figure 4).

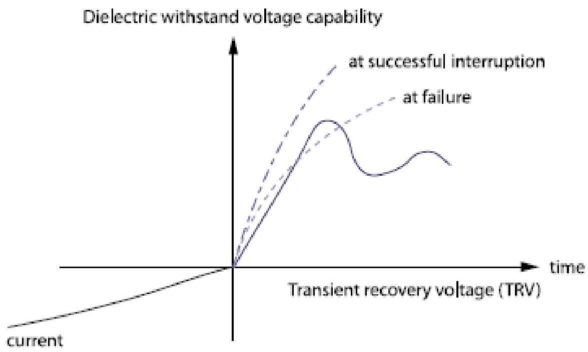


Figure 4: Dielectric regime [3]

As we can see at figure 4, whether the recovery rate of dielectric strength (contact disruption voltage - dashed curve) is higher than TRV rising rate (TRV voltage - continuous curve) a successful dielectric interruption is obtained. Otherwise, an unsuccessful interruption results and the current will start over by dielectric failure [3]. The resumption of current between the contacts of a mechanical switching device during a breaking operation with an interval of zero current of less than a quarter cycle of power frequency is entitled re-ignition [1]. Otherwise it is called restrike [2].

3. Electric Arc Models

Existing arc models can be classified into two categories [16, 6]:

- Physical models
- Parameter Models

In parameter models another category called Black Box Models is defined. The black box models are parameter models that use functions and simpler tables to determine the parameters of the models. [16, 6].

3.1. **Physical Models**

Engineers responsible for designing circuit breakers work largely with physical arc models when they plan to create a new prototype. Physical models are the most complex ones, since electric arc description are based on fluid dynamics equations and laws of thermodynamics, in combination with Maxwell's equations [16, 6]. These models are based on the conservation equations of mass, momentum and energy. Obtaining the solution through these equations requires simplifications in order to reduce complexity.

3.2. **Black Box Models**

Black box models (also called P - τ models) describe the electric arc through differential equations. They are considered mathematical models based on physical considerations that establishes the relationship between arc conductance and arc quantities like voltage and current [6, 7].

Although these models are not suitable for designing circuit breakers, they are very important to simulate the arc-circuit interaction, where they present a very reasonable level of precision [6]. For this simulation purpose is fundamental the behavior of the electric arc quantities, rather than the inherent physical processes characterization. The formulation of these models comes from physical simplifications, and it is therefore important to realize their applicability limit [6, 7].

Cassie and Mayr's arc models are known as the classic black box models. The other models degenerate from the classic models. Cassie assumed that the arc temperature, current density, and electric field are constant. Thermal convection is the main energy removal phenomenon and the arc cross-section varies with current and time [6, 4, 5, 12].

Taking into account these premises, result the Cassie's arc model equation [5]:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau}\left(\frac{u^2}{U_c^2} - 1\right) \tag{1}$$

where

$g =$ the arc conductance $[S]$
$u =$ the arc voltage $[V]$
$\tau =$ the arc time constant $[s]$
$U_c =$ the constant arc voltage $[V]$

This model is particularly suitable for studies involving high intensity currents due to the premises assumed [6].

Unlike Cassie, Mayr's model assumed that the arc cross section is constant and loses energy exclusively by thermal conduction. The arc conductance is a function of the internal energy of the arc [6, 4, 12]. Given these premises, result the Mayr's arc model equation [6, 4, 12]:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau}\left(\frac{ui}{P} - 1\right) \tag{2}$$

where

$g =$ the arc conductance $[S]$
$u =$ the arc voltage $[V]$
$i =$ the arc current $[A]$
$\tau =$ the arc time constant $[s]$
$P =$ the cooling power $[W]$

Due to the assumed considerations, this model is suitable for the thermal regime (low current intensities) [6].

The Habedank's arc model is the junction of the two previous models, and is defined by the following differential equations [9]:

$$\frac{1}{g_c}\frac{dg}{dt} = \frac{1}{\tau_c}\left(\frac{u^2}{U_c^2} - 1\right) \tag{3}$$

$$\frac{1}{g_m}\frac{dg}{dt} = \frac{1}{\tau_m}\left(\frac{ui}{P_0} - 1\right) \tag{4}$$

$$\frac{1}{g} = \frac{1}{g_c} + \frac{1}{g_m} \tag{5}$$

where

$g_c =$ the arc conductance described by Cassie's model $[S]$
$g_m =$ the arc conductance described by Mayr's model $[S]$
$g =$ the total arc conductance $[S]$

The arc conductance g results from the sum of the inverse conductance of both models, g_c and g_m. Habedank's arc model resulted from the aggregation of two complementary models, allowing a more rigorous representation of the various currents intensities .

Schavemaker's arc model is a modified Mayr's arc model with a time constant τ and a cooling power as a function of the electrical power input.

The Schavemaker's arc model equation is known by [13]:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau}\left(\frac{ui}{max\left(U_a\left|i\right|, P_0 + P_1 ui\right)} - 1\right) \tag{6}$$

where P_1 and P_0 are both cooling constants.

Schwarz's arc model is also a modified Mayr's arc model which the time constant and the cooling power are dependent on the arc conductance. The Schwarz's arc model equation is known by [6, 4, 11]:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau g^a}\left(\frac{ui}{Pg^b} - 1\right) \tag{7}$$

where a is the parameter that influences the condutance dependency of τ and b the parameter that influences the condutance dependency of P.

Finally, KEMA's arc model consists of three modified Mayr's arc models described by equations (8) to (13) [14].

$$\frac{\mathrm{d}g_1}{\mathrm{d}t} = \frac{1}{\tau_1 \Pi_1} g_1^{\lambda_1} u_{a1}^2 - \frac{1}{\tau_1} g_1 \quad (8)$$

$$\frac{\mathrm{d}g_2}{\mathrm{d}t} = \frac{1}{\tau_2 \Pi_2} g_2^{\lambda_2} u_{a2}^2 - \frac{1}{\tau_2} g_2 \quad (9)$$

$$\frac{\mathrm{d}g_3}{\mathrm{d}t} = \frac{1}{\tau_3 \Pi_3} g_3^{\lambda_3} u_{a3}^2 - \frac{1}{\tau_3} g_3 \quad (10)$$

$$\frac{1}{g(t)} = \frac{1}{g_1(t)} + \frac{1}{g_2(t)} + \frac{1}{g_3(t)} \quad (11)$$

$$u = u_{a1} + u_{a2} + u_{a3}; \quad (12)$$

where

$$\tau_2 = \frac{\tau_1}{k_1} \quad \tau_3 = \frac{\tau_2}{k_2} \quad \Pi_3 = \frac{\Pi_2}{k_3} \quad (13)$$

$g =$ the total arc conductance $[S]$

$u_n =$ the voltage across the n-th arc $[V]$

$u =$ the total voltage across the arc $[V]$

$\tau_n =$ the time constant of the n-th arc $[s]$

$\Pi_n =$ the (cooling) constant of the the n-th arc $A^{(\lambda-1)}V^{(3-\lambda)}$

$k_n =$ the free parameters

$\lambda_n =$ Cassie-Mayr control of the n-th arc

If $\lambda = 1$, results in a Cassie's arc model equation. If $\lambda = 2$, results in a Mayr's arc model equation. The k_n parameters depend on the breaker type while τ_1, Π_1, Π_2 depends on the current state of the circuit breaker [8, 11].

Although it is a model deduced from physical considerations, it is considered a mathematical model, where the physical description is no longer perceptible. In this way, its application is mostly practical and requires experimental tests.

4. Numerical Implementation of Arc Models

In this work, we proceed with the implementation, in Matlab, of the different arc models previously presented for the purpose of studying their characteristics. With this objective it was decided to implement the arc models for two distinct cases of fault:

1. Terminal fault

2. Short-line fault

In order to developed the Matlab program were considered equivalent circuits that caracterize the terminal fault (see figure 5) and short-line fault (see figure 6).

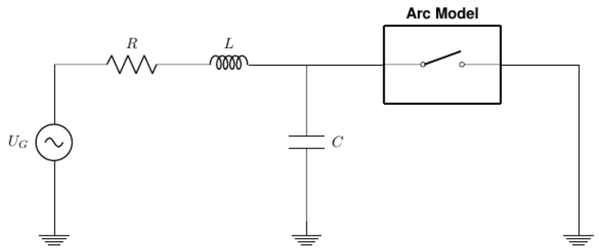


Figure 5: Equivalent circuit - Terminal fault

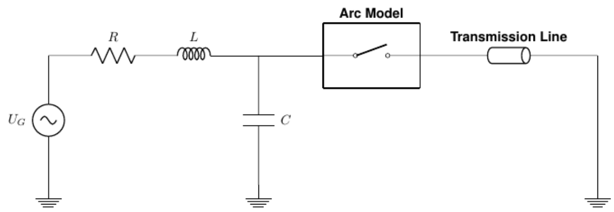


Figure 6: Equivalent circuit - Short-line fault

The circuit breaker is represented in the circuits of the figures 5 and 6 by the arc models presented above.

The implementation of the referred circuits and arc models in a Matlab program requires the use of numerical methods.

The elements of the circuits(R, L and C) were replaced by Norton equivalents.

The ordinary differential equations (ODE's), which govern the electric arc behavior, were implemented in three numerical methods, the Euler method, the Trapezoidal method, and the 2nd order Runge-Kutta method.

In order to validate the correct implementation of the models, it is possible to compare them with the Arc Model Blockset developed by the University of Delft in the year 2001 [11]. It is an extension of Matlab Simulink/Power System Blockset that can be used to make arc-circuit interaction studies during the breaker interrupting process. It allows to simulate through Matlab Simulink certain electric arc models that are a priori defined (see figure 7).

The purpose is to compare the simulations performed in Simulink with those of the implemented Matlab program.

In order to choose the numerical method to be used in the results, was simulated the comparison of the three integration methods with the Arc Block Set[1] solution (see figure 8).

[1] Simulated with a trapezoidal method which has built-in regressive differentiation formula (2-state method).

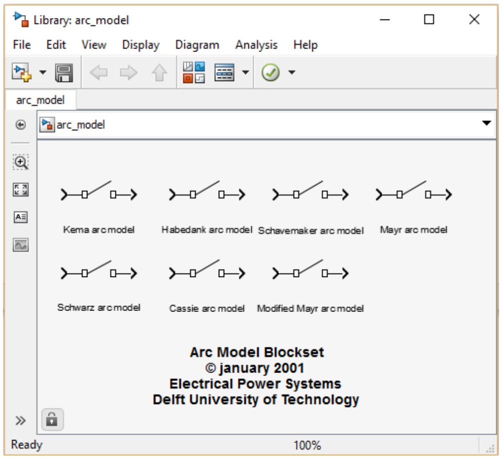
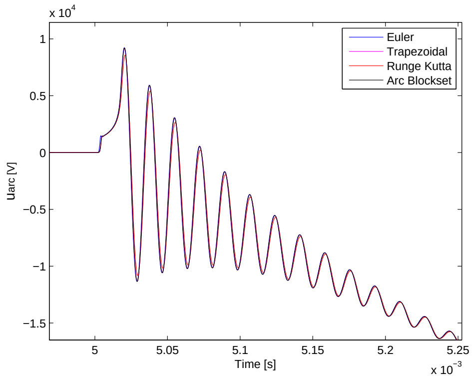
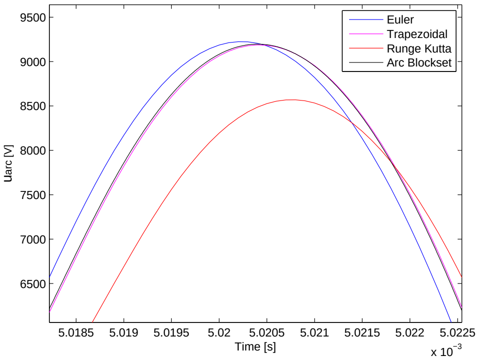


Figure 7: *Arc Model Blockset* [11]



(a) Mayr's arc voltage

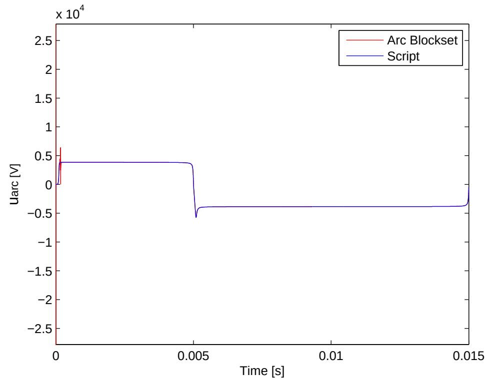


(b) Detail of arc voltage for $t \in [5.018, 5.0225]$ ms

Figure 8: Comparison of numerical methods for an interruption of Mayr's arc model

It can be concluded from the graph of figure 8 b) that the trapezoidal method has the closest result to the Arc Blockset method and, therefore, was the method chosen to perform the simulations.

Figure 9 illustrates one of the simulations carried out with the purpose of validating Cassie's arc model implementation for the terminal fault.



(a) Arc voltage

Figure 9: Arc voltage - Cassie's arc model

As can be seen from figure 9, the results of the Arc Blockset and Matlab script are identical, and therefore, Cassie's arc model was correctly implemented for the terminal fault.

5. Results

In this chapter we proceed with the analysis of the Schavemaker's arc model simulations for the terminal fault as well as the Mayr's arc model simulations for short-line fault. Simulations were performed for variations of the different models parameters, being verified the consequences in the electric arc behavior.

5.1. Terminal Fault

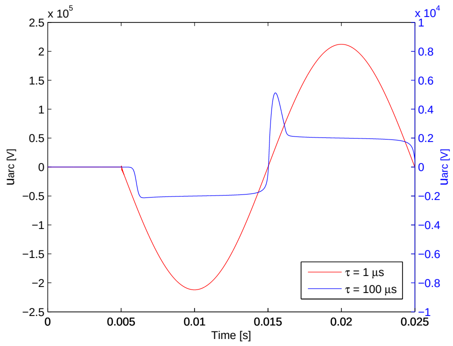
Figure 10, is obtained for $\tau = 100\ \mu s$ and $\tau = 1\ \mu s$, allow us to conclude that the decrease in arc time constant, associated with a decrease in the deionization time of the medium, allows to change the re-ignition paradigm to interruption.

The post-arc current occurs because the medium does not acquire its dielectric properties instantaneously (see figure 11 b)). The transient recovery voltage (TRV) is the voltage across the circuit breaker terminals and results from the energy stored in the coils and capacitors at the time of current interruption (see figure 10 b)).

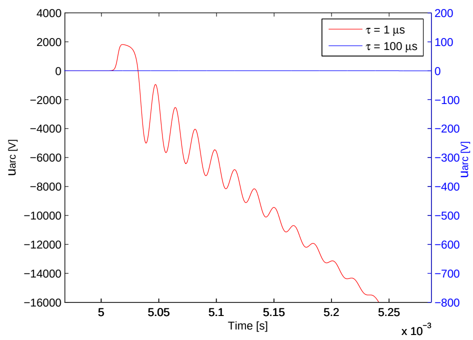
Figure 12 a) results from a simulation for an increment of 3 kV in the arc voltage constant parameter. Arc voltage tends to the predefined level ($U_a = 5\ kV$) and there is an accentuation of the voltage rise at the second zero of the current.

In relation to the cooling power P_0, two simulations were performed in the figure 12 b). The increase in the cooling power favors a greater medium deionization in the vicinity of the zero of current. If this effect does not occur in order to interrupt the current, a high voltage arises, resulting from the increase of the medium dielectric strength (greater resistance on the circuit breaker terminals).

Finally, the dimensionless parameter P_1 proves

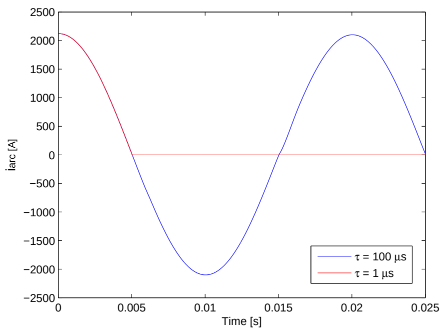


(a) Arc voltage

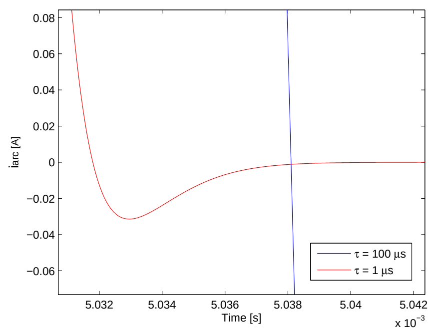


(b) Transient recovery voltage - details of a) for $t \in [4.95, 5.3]\ ms$

Figure 10: Arc voltage and current considering $P_0 = 1\ kW$, $P_1 = 0.8$ and $U_a = 2\ kV$



(a) Arc current



(b) Post-arc current

Figure 11: Arc voltage and current considering $P_0 = 1\ kW$, $P_1 = 0.8$ and $U_a = 2\ kV$

to be very sensitive, which is why an increment of only 0.1 was made (see figure 13). Through figure 13, it is possible to observe an accentuation of the voltage in the current passage by zero, as verified for the previous parameter.

5.2. Short-line Fault

Figure 14 illustrates the voltage, the current and the conductance of the Mayr's arc model for a variation of the arc time constant. It is verified, from figure 14 a), that there is a reignition for $\tau = 30\ \mu s$ and an interruption for $\tau = 0.30\ \mu s$.

In the first case, arc voltage assumes a relatively low value. Current continues to flow, as can be seen from figure 14 c), and the conductance increases and decreases as the current goes through zero, see figure 14 d).

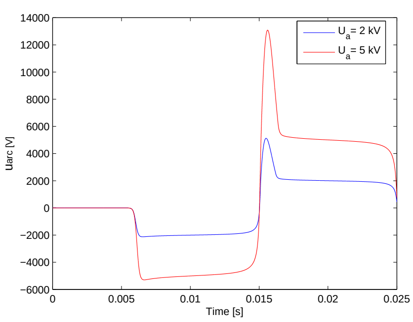
In the second case, the current is interrupted at the first current zero (see figure 14 c)). At the circuit breaker terminals the TVR appears (see figure 14 b)), which presents a triangular shape from the voltage waves propagation in the line when the current is interrupted. In figure 14 d), the conductance decreases, at the time of opening, from its initial value ($10^4\ S$) to zero very rapidly. The reason for changing the reignition situation to interruption is due to the fact that the conductance decreases more rapidly, at zero current, with the decrease of τ (higher deionization of the medium).

Figure 15 provides the arc voltage considering a variation of the cooling power, $P = 30.9\ kW$ and $P = 100\ kW$, with $\tau = 0.3\ \mu s$. As we can see, from figure 15 a) and b), current is interrupted for both cases. The consequence of this variation is an increment in the arc voltage amplitudes.

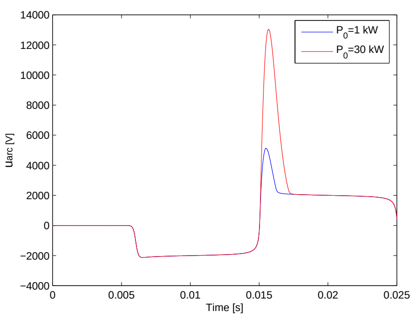
5.3. Model Comparison

In previous paragraphs, the parameters of the Schavemaker's and Mayr's arc models were studied, as well as their influence on the description of the electric arc. However, it is important to evaluate if for certain parameters/conditions of the circuit there are current interruption, and if this result is transversal to all implemented models.

Thus, it is intended to compare the various arc models in function of the possible current interruption, for the same simulation conditions, without taking into account the evolution of the arc magnitudes. For this purpose, simulations were performed for both faults with the parameters indicated in table 1. As shown by table 1, and although some of the models have specific parameters, an effort was made to standardize them, thus allowing their comparison. On the other hand, as the current interruption is a function of the chosen parameters,



(a) Arc voltage considering $P_1 = 0.8$ and $P_0 = 1\ kW$



(b) Arc voltage considering $U_a = 2\ kV$ and $P_1 = 0.8$

Figure 12: Arc voltage considering $\tau = 100\ \mu s$

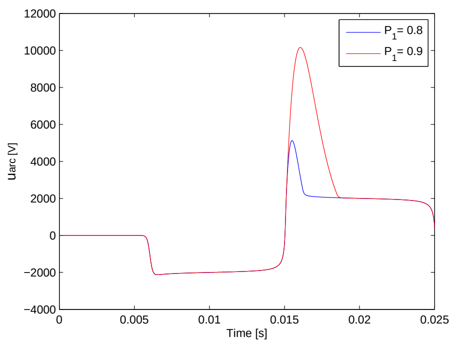
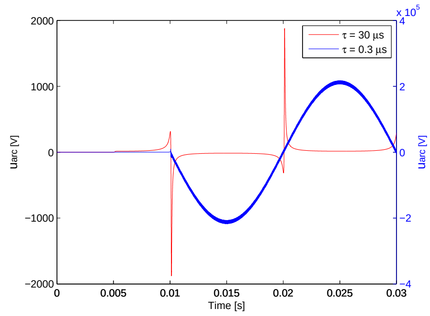
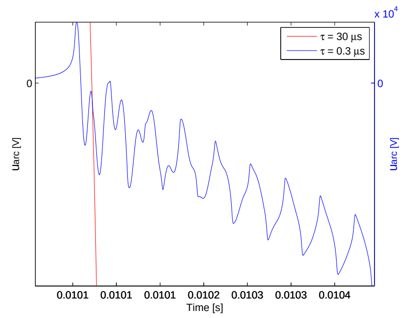


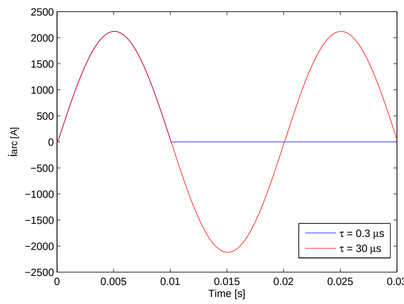
Figure 13: Arc voltage considering $\tau = 100\ \mu s$, $P_0 = 1\ kW$, $U_a = 2\ kV$



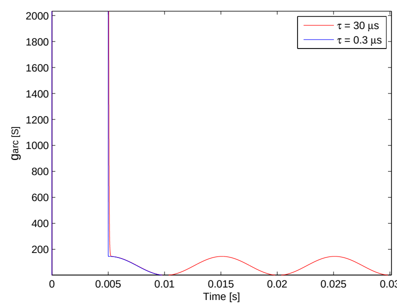
(a) Arc voltage considering $\tau = 30\ \mu s$ e $\tau = 0.3\ \mu s$



(b) Transient recovery voltage - detail of a) for $t\ \epsilon\ [0.0099, 0.0104]\ s$



(c) Arc current considering $\tau = 30\ \mu s$ e $\tau = 0.3\ \mu s$



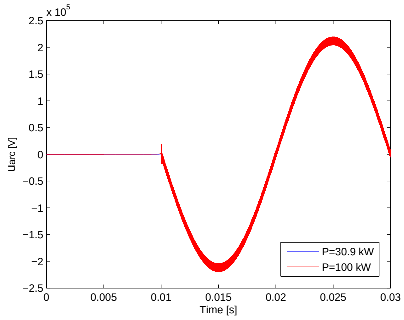
(d) Arc conductance considering $\tau = 30\ \mu s$ e $\tau = 0.3\ \mu s$

Figure 14: Arc magnitudes considering $P = 30, 9\ kW$

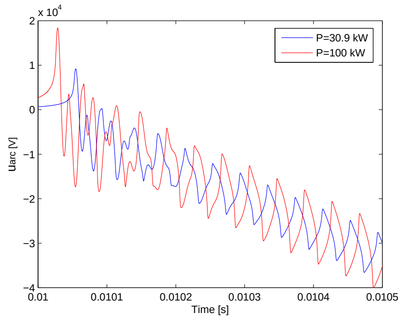
the result obtained will be different according to the chosen parameter selection. However, this fact does not invalidate the analysis in question since the purpose is to conclude that all arc models, under the same simulation conditions, present the same result independently of it. The interesting information of the performed simulations for the terminal fault is synthesized in table 2.

It is possible to conclude, from table 2 , that contrary to what would be expected for the same simulation conditions, not all models have the same result.

Cassie's arc model and Schwarz's arc model reveal a re-ignition, whereas the remaining arc models, Mayr's, Habedank's, Schavemaker's and



(a) Arc voltage considering $P = 30.9\ kW$ e $P = 100\ kW$



(b) Transient recovery voltage - detail of a) for $t\ \epsilon\ [0.01, 0.0105]\ s$

Figure 15: Arc magnitudes considering $\tau = 0.3\ \mu s$

Table 1: Parameters considered in the simulations for both faults

Arc Models	Parameters				
	$\tau[\mu s]$	$U[kV]$	$P[kW]$	a	b
Cassie	10	10	-	-	-
Mayr	10	-	30.9	-	-
Habedank	10	10	30.9	-	-
Schavemaker	10	10	-	-	-
Schwarz	10	-	30.9	1	1
KEMA	10	-	-	-	-

Table 2: Summary of interruptions/re-ignitions for the terminal fault

Arc models	Interruption / Re-ignition
Cassie	*Re-ignition*
Mayr	*Interruption* (2^{nd}*zero*)
Habedank	*Interruption* (2^{nd}*zero*)
Schavemaker	*Interruption*
Schwarz	*Re-ignition*
KEMA	*Interruption*

KEMA's reveal current interruption.

In spite of this, Mayr's and Habedank's arc models show that there was a restrike during the interruption process, since the current is only interrupted in the second passage by zero.

6. Conclusions

The objective of this work was to study the Black Box models in the electric arc modeling on a circuit breaker, when the short circuit current is interrupted.

With this objective, the different Black Box models were implemented for two different faults, a terminal fault and a short-line fault. From the simulations carried out, it was possible to conclude that each arc model has its own intrinsic characteristics, since for the same simulation situation, the arc magnitudes are represented differently. This fact is associated to the different differential equations that constitute the several arc models implemented.

However, the parameters present in most models, such as the arc voltage constant U_a, the arc time constant τ and the cooling power constant P, showed an influence on the arc characterization transverse to all models.

The constant arc voltage U_a defines the arc voltage level at a reignition and the higher its value, the higher the set level. The arc time constant τ influences the response time of voltage after the opening of the circuit-breaker, and allows to change the success or failure of the interruption. Thus, the lower its value is, the faster arc conductance decreases (more effective medium deionization), and greater the probability of current interruption. Cooling power constant P has an influence on the maximum amplitude of arc voltage and contributes in the same way to the current interruption. The energy removed from the arc is proportional to this constant, consequently, the higher its value is, more rapidly the medium recovers its dielectric characteristics. Therefore, the type of parameters influence is the same for all models and regardless of the fault type. It was also possible to conclude that they have a range of applicability depending on the fault type and model in question.

When compared to each other, for the same parameters and conditions, arc models dont exhibit all the same result in terms of current interruption. The fact that the models are made up of different differential equations is one of the reasons for the results uniformity lack. On the other hand, since in the limit all arc models would have to present the same result, it is possible to conclude that the parameters are not adjusted to the model and fault in question. In order to complement this analysis, it would have been opportune to extract the parameters of an experimental test, something that could not be achieved in this work.

In general, they are versatile and easy to implement models, with the ability to describe reignitions and interruptions with and without restrikes. However, they are limited to the interruption thermal regime and the physical processes perception is vanished by the mathematical formulation.

In the impossibility of doing it on this work, it would be interesting to apply the arc models, in future works, to experimental results in order to evaluate their prediction and representation of the current interruption process. Another opportune topic would be to study the ability of Black Box models to represent current chopping.

References

[1] IEC 60050 - International Electrotechnical Vocabulary - Details for IEV number 441-17-45: "re-ignition (of an AC mechanical switching device)". `http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=441-17-45` . Accessed: 2016-10-5.

[2] IEC 60050 - International Electrotechnical Vocabulary - Details for IEV number 441-17-46: "restrike (of an AC mechanical switching device)". `http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=441-17-46` . Accessed: 2016-10-5.

[3] A. Alfredsson. Live tank circuit breakers application guide. *ABB*.

[4] T. E. Browne. A Study of A-C Arc Behavior Near Current Zero by Means or Mathematical Models. *Transactions of the American Institute of Electrical Engineers*, 67(1):141–153, 1948.

[5] A. Cassie. Theorie nouvelle des arcs de rupture et de la rigidité des circuits. *Cigre, Report*, 102:588–608, 1939.

[6] W. Cigre. 13-01: Applications of black-box modelling to circuit breakers. *Electra*, 149:40–71, 1993.

[7] Cigré Working Group 13.01. State of the art of circuit-breaker modelling. *Cigré Brochure*, (135), 1998.

[8] N. Gustavsson. Evaluation and simulation of black-box arc models for high-voltage circuit-breakers. 2004.

[9] U. Habedank. On the mathematical-description of arc behavior in the vicinity of current zero. *etz Archiv*, 10(11):339–343, 1988.

[10] J. A. Martinez-Velasco. *Power system transients: parameter determination.* CRC press, 2009.

[11] P. Schavemaker. Arc model blockset for use with matlab simulink and power system blockset–users guide. *Delft University of Technology*, 2001.

[12] P. H. Schavemaker. *Digital testing of high-voltage SF6 circuit breakers.* PhD thesis, TU Delft, Delft University of Technology, 2002.

[13] P. H. Schavemaker and L. Van der Slui. An improved mayr-type arc model based on current-zero measurements [circuit breakers]. *IEEE Transactions on Power delivery*, 15(2):580–584, 2000.

[14] R. Smeets and V. Kertesz. Evaluation of high-voltage circuit breaker performance with a validated arc model. *IEE Proceedings-Generation, Transmission and Distribution*, 147(2):121–125, 2000.

[15] S. Theoleyre. Mv breaking techniques. *Cahiers Techniques (Schnedier Electric Technical Documents), Cahier*, 193, 1999.

[16] L. Van Der Sluis. *Transients in power systems.* John Wiley & Sons Ltd, 2001. ISBN:0-471-48639-6.