A NEW HYBRID CO_2 ARC MODEL FOR SHORT LINE FAULT

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

By

KHALID ELSIR ELSAMANI MOHAMED AHMED

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical and Electronic Engineering

NICOSIA, 2017

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name:

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ACKNOWLEDGMENT

First of all, I would like to extend my sincere and humble gratitude to Almighty Allah who endowed me potential and ability to make solid contribution to the already existing ocean of knowledge.

I am very grateful to many people and organizations for their generous support and encouragement that has made it possible for me to undertake this work. Special thanks is extended to my supervisor I wish to express my gratitude and sincere appreciation to my supervisor Prof. Dr. Sezai DINCER for his kind patronage, guidance, and concern not only during this project but always. I am really thankful to him for being there whenever I needed his advice, and I felt my quick progress from his advises.

In addition I wish to extend my thanks to the many other colleagues at all places which I worked before, both in North Cyprus and elsewhere, that have variously and generously shared their professional knowledge and experience, not to mention the invaluable moral support, over many years. It remains always a privilege to work with such skilled and dedicated people and in addition to have the good fortune to count many of them as close friends.

Finally, to my family, spread far and wide, I express my deep felt thanks and love to you for your unfailing love and support, not only during this thesis, but during the whole period of my educations and throughout of my life. Without their endless support and love for me, I would never achieve my current position. I wish my father and mother lives happily always. The same goes for the rest of my family who always had a word of appreciation and always stood beside me. Thank you

To my parents …

ABSTRACT

In this study, the SLF (Short Line Fault) interrupting performance of CO_2 circuit breakers has been evaluated through current zero measurements. The circuit breakers interruption capabilities are determined by arc model calculation. Cassie arc model alone cannot represent the whole range of the interruption process for short line fault so a proposed arc model has been constructed by combining one Cassie model and two Schwarz models with different arc parameters values connected consequently in series. The simulations of the proposed arc model agree with the measurements. Moreover the synthetic circuit of the proposed arc model is reconstructed in a form of the black box in order to predict and validate the arc parameters obtained by the proposed arc model.

Keywords: Circuit breakers, Gas insulation; MATLAB; Black box; Nonlinear systems; Parameter extraction; System identification

ÖZET

Bu çulişmad CO_2 gazli kesiçilerin kisa hat arıza kasme davranisleri sıfır akım geçiş ölşumleri kularınları arelız edilmiştirç Cassıe ark modeli tek başine kısa hat ariza davrşinin tamaminin güstermaz. Bu nedanle, önerilen ark modelinde Cassıe ark modeli ile iki farkli Schwarz modeli seri olarak tanımlaan ark parameterili bırlikta kulanimış ve kesme ışlevinin tüm bölğesi kapsanmıştir.

Onerilen ark modeli ile yapılan simülasonu sonoçlari olçüm sonoçlari ile uynm içindedirç ayrıça onerılen ark modeli ile elde edlien parameterlerin döğurlarması için ilgili kara kütü (Black-box) syntetik devleler ile teninlanare aanaliz edilinçtir.

Anahtar Kelimeler: Devre kesiciler, Gaz yalıtımı; MATLAB; Siyah kutu; Doğrusal Olmayan Sistemler; Parametre çıkarımı; Sistem kimliği

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LIST OF ABBREVIATIONS

GCB:	Gas Circuit Breakers
GIL:	Gas Insulated transmission Line
GIS:	Gas Insulated transmission Switchgear
HV:	High Voltag
AMB:	Arc Model Blockset
SC:	Short Circuit
TRV:	Transient Recovery Voltage.
CB:	Circuit Breaker.
TF:	Terminal Fault
AC:	Alternating Current.
ATP:	Alternative Transient Program
EMTP:	Electromagnetic Transient Program
TACS:	Transient Analysis of Control Systems
DEE:	Differential Equation Editor
SLF:	Short Line Fault
PSB:	Power System Blockset
ODE:	Ordinary Differential Equation
IEC:	The International Electrotechnical Commission
ANSI:	American National Standard Institute
ODP:	Ozone Depletion Potential
GWP:	Global Warming Potential
GCB:	Gas Circuit Breakers
IEEE:	Institute of Electrical and Electronic Engineer

CHAPTER 1
INTRODUCTION

In this chapter, the important usage of high voltage circuit breakers (CB) in power system will be described and defined. The researchers and developments used the simulation tools to study and evaluate the circuit breaker performance during Short Line Fault (SLF). Finally, a brief literature review will be given to some arc model used in power systems laboratories.

1.1 Introduction

According to the deregulation of electricity investments, availability, and stability of electrical power networks should be highly implemented in order to improve the competitiveness of electricity investments. In general, achieving such conditions is requiring the High Voltage (HV) networks to be working by slightly irregular conditions where these conditions have to be removed so fast. Therefore, HV CBs intended to disconnect abnormal conditions and the American National Standard Institute (ANSI) defined the CB as “a mechanical switching device, capable of making, carrying, and breaking currents under normal circuit conditions. Also capable of making and carrying for a specified time, and breaking currents under specified abnormal circuit conditions such as those of a short circuit” As it can be mentioned by ANSI definition the CB main purpose is to permits or interrupts the flow of currents in an electric circuit.

The phenomena of CB’s are important and as they’re some limitation for switchgear technologies in operation at different circuit conditions, developing the simulation tools used for studying, understanding, and evaluating CB’s is the purpose of this research work presented in this thesis.

The electric arc or arc discharge has always been present in the nature in its transient form, always feared because of its destructive power. In the CB’s the arc is the medium to maintain current continuity before the interruption. Therefore the process of extinguishing a current may be considered the process of extinguishing an arc.

1.2 Literature Review

As it has been mentioned earlier, the electric arc is the one of the basic components during currents interruption process in the electrical transmission and distribution systems. Moreover a lot of mathematical arc modeling and calculation methods are published and some of them are successfully applied in circuit breakers testing, development, and operation. Generally, in practical is impossible to provide a wide range description of different types of switching arcs by using just one arc model or sets of mathematical equations, therefore it's possible to have a comprehensive spectrum of different programs/tools as a basis for arc modeling. Moreover these tools applicability depend on their limitation in their use, otherwise the application of certain arc models or mathematical equations my result in unexpected errors.

The arc physics have several tools and can be classified into three main groups which are P-T or black box (BB) arc models, physical arc models, and other analytical and graphical tools for arc modeling. In this thesis we'll be concentrating on black-box arc models, these model is considering the arc as a two port which are the conductance changing in time according to the function of the circuit parameters, and on the other hand is the arc parameters. These arc models evaluate the transfer function by using a selected mathematical form, usually is a differential equation (DE) while fitting the rest of the free parameters into measured arc current i(t) and arc voltage v(t) data sets. Generally the main objective for black-box arc models is to use the v(t) and i(t) measurement of circuit breaker test together with a chosen arc model (mathematical model) of the particular arc of this experiment. Then this model can be used in order to predict the interrupting performance of circuit breaker in other circuit conditions.

In 1943, Mayr model was postulated (Mayr, 1943). Mayr model supposed that the losses of power are created by the thermal conduction and the arc conductance (g) is depending on temperature. In addition to that, Mayr assumed the arc volume region to be constant. Mayr model is generally used to represent the vicinity of currents zero (I_{zero}) measurement. Unlike Mayr, In 1939 Cassie model was introduced (Cassie, 1939). Cassie supposed that the arc is having a constant temperature which is cooled down by pushed thermal conduction. This reveals that the arc volume region is directly proportional to the voltage and that the current over the arc is fixed. Cassie model in general used to describe the arc in high current region. Both of Cassie and Mayr methods provide a valuable description of

the arc phenomena, the comparison with the measurement is reveals that the differential equations cannot be used in a large range of analysis. Therefore, in order to achieve better results there are several modifications of these two arc models has been done.
According to the rejection of the hypothesis in Mayr's model of a dynamic arc, Schwarz implemented a modified Mayr arc model in 1971 (Schwarz, 1971). Schwarz described the cooling powers and time constant in the arc model are based on the g. Moreover, there is several modifications have been done by using Cassie and Mayr arc model in their form. The first modification uses Mayr and Cassie arc model in their original forms are applied within a limited range of switching process considering the validity of these two models in different time interval.

1.3 Thesis Overview

The remaining part of this thesis consists of five chapters, which are organized as follows:
Chapter 2 will describe the important of gases in power system and the breakdown phenomena of different gases as well. Moreover, a bit of information will be given to illustrate these gases properties and their impact to the environmental atmospheric.
Chapter 3 is describing the existence of electric arc during the operation of high voltage circuit breakers and the tools which are used to simulate the arc while interrupting the current.
Chapter 4 presents the process of arc models configuration in MATLAB/SIMULINK and the parameters which are chosen to represent the circuit breaker. Moreover, a well-known arc models will be simulated.
Chapter 5 presents the proposed arc model which it will be used to study the SLF interruption performance of CO_2 circuit breakers through the current zero measurements. Also, the implementation of the proposed arc model to black box model will be described and compare it with the actual data sets. Finally, the r-square will be calculated between the simulation and measurement data sets.
Conclusion will present the result and future works for the HV circuit breaker arc modeling.

CHAPTER 2
AN INTRODUCTION TO GASES IN POWER SYSTEM

The important usage of gases in power system will be described and defined. Also, a brief review of the fundamental principles of gaseous ionization and breakdown is presented before examining the electrical performance and properties of different gases such as SF_6 and CO_2. Finally, the chapter will conclude by the impact of these gases to our environmental atmospheric.

2.1 The Application of Gases in Power System

Gaseous insulation plays a vital role in power system applications since they have been used to insulate power system equipments and substations. Moreover, these gases are widely used in Gas Circuit Breakers (GCB) in order to interrupt the arc and also to provide insulation between breaker contacts.

The most common applied to gas as insulation medium in HV power systems is air since it's free, available, and self restoring when the breakdown exist. From the last century, many studies have been done to check the electrical breakdown performance of air gaps. It has been found that some particular element affecting the gaseous insulation to the breakdown such as gas type, temperature, pressure, electrode material, voltage duration, voltage, polarity and frequency.

It has been found from a designer's perspective in order to improve the breakdown strength the optimum values for all variables given above should be assigned. In general the phenomena of gas, electrode configurations, atmosphere issues, and the characteristics of applied voltage are executed by means of applied experience.

The gases which are used in HV power networks and equipment's are provided just to make an electrical insulation and the structure of those gases are chosen base on three principles which are the high electric strength, higher liquefaction temperature, and lower cost (Christophorou and Olthoff, 2013).

There are several gases used in power system as an insulation medium which are air, nitrogen, and electronegative gases like sulfur hexafluoride. Hereunder, there are several properties required in order to provide arc interruptions:

(i) The chemical and thermal stability.

(ii) The dielectric strength should be high.

(iii)The thermal conductivity should be high.

(iv) Non inflammability.

(v) The ability to extinguish the arc.

(vi)The availability within acceptable cost.

The air is the cheapest and widely used as an interruption medium for circuit breaking. The advantage of the air over the electronegative gases, the air has a flexibility to be compressed to the maximum pressures at room temperature, in addition to that the air dielectric strength is higher than these gases. The CO_2 has almost similar dielectric strength as the air, but it can be classified as a better arc extinguishing medium within moderate currents (Jaeger et al., 1996; Nagel et al., 1996).

2.2 Electrical Breakdown in Gas Dielectrics

The breakdown in air (spark breakdown) can be described as the transformation from a non sustaining discharge to a self sustaining discharge. During the breakdown an extreme current will be initiated because of ionization where the ions and electrons are buildups from neutral molecules, and the transitions of ions to the cathode and electrons to the anode lead to an extreme current. The Townsend approach and Streamer approach are the existing forms of approaches describing the technique of the breakdown within several conditions, these conditions can be a pressure, temperature, structure of electrode external body, and arrangement of electrode field (Phontusa and Chotigo, 2008). Generally, the air is almost used worldwide for insulating several HV equipment since the capability of breakdown approximately 30kV/cm.

2.2.1 Townsend theory

Townsend approach describes the technique of the breakdown in gases within particular conditions and this approach which is described hereafter is expressed from (Kuffel and Kuffel, 2000; Naidu and Kamaraju, 2013). This approach described as when an electric field applied to electrons will accelerate the electrons to flow in the reverse direction of the filed towards the direction of the anode. Equation 2.1 describes when the field exerts work on the electron, where e: charge of the electron, x: length of the electron traveled through the field.

$$W = eEx \; = \; (½)mv^2 \tag{2.1}$$

The maximum speed e can reach but still there is some particular chance that electrons might conflict by molecules through the gas and during this process the thermal power is shifted to molecule. The process mentioned before is permitting to the ionization of molecule by releasing an e charge, this electron charge is going to accelerate affected by the field exposed on it and this might leads to generate again ionization collision. The first coefficient of Townsend approach is giving some chance that one e charge can generate ionization collision as per unit length where an e charge will be released. In addition to that as the pressure becomes higher the probability of collision becomes greater. The electron has a kinetic energy proportionally with field exposed on it, and the coefficient (α) for this reason is given as (E/p). The amount of conflictions is directly proportional to the applied pressure.

Second coefficient of Townsend approach (γ) is giving some chance that secondary electrons charges are released. These electrons charges can be immediately produced from the cathode which is fired by (+)ve ions towards the (-)ve electrode. This mechanism makes the ion to liberate electrons charges, the first one will neutralize the ion charge and the other e charge is released. This process used as a main secondary process in Townsend approach, and in addition to that it’s also a function of the gas pressure and the strength of the electric field as well. Moreover, the photo emission can similarly participate to secondary electrons and the liberated electrons are moved faster in the direction of (+)ve electrodes in an avalanche and might be possible to make a breakdown.

$$I = I_o\left(\left(e^{(\alpha-n)}\right) \div 1 - \left(\frac{\gamma\alpha}{\alpha - n}\left(e^{(\alpha-n)d} - 1\right)\right)\right) \tag{2.2}$$

In electronegative gases, the atoms have an ability to liberate electrons in order to top up their external frame and the chance for an electron to be connected into atom per unit length can be provided by the attachment coefficient (n) where this process is raveling the flow of electrons which is formed by the process described earlier. Equation 2.2, illustrating that the breakdown is occurred when the dominator reach to zero and this expressing the Townsend breakdown standard (Jørstad, 2012).

2.2.2 Voltage via current relation

There is a nonlinear relation between current and voltage before gas breakdown takes a place, the Figure 2.1 below illustrating the relationship. Region one contains some ions can be moved by applying electric field and this movements create induce current, then is going saturated within some amount of voltage and provide a fixed current as it can be seen in region two. Hereafter, in region three and four are produced by ion breakdown as illustrated earlier by Townsend approach.

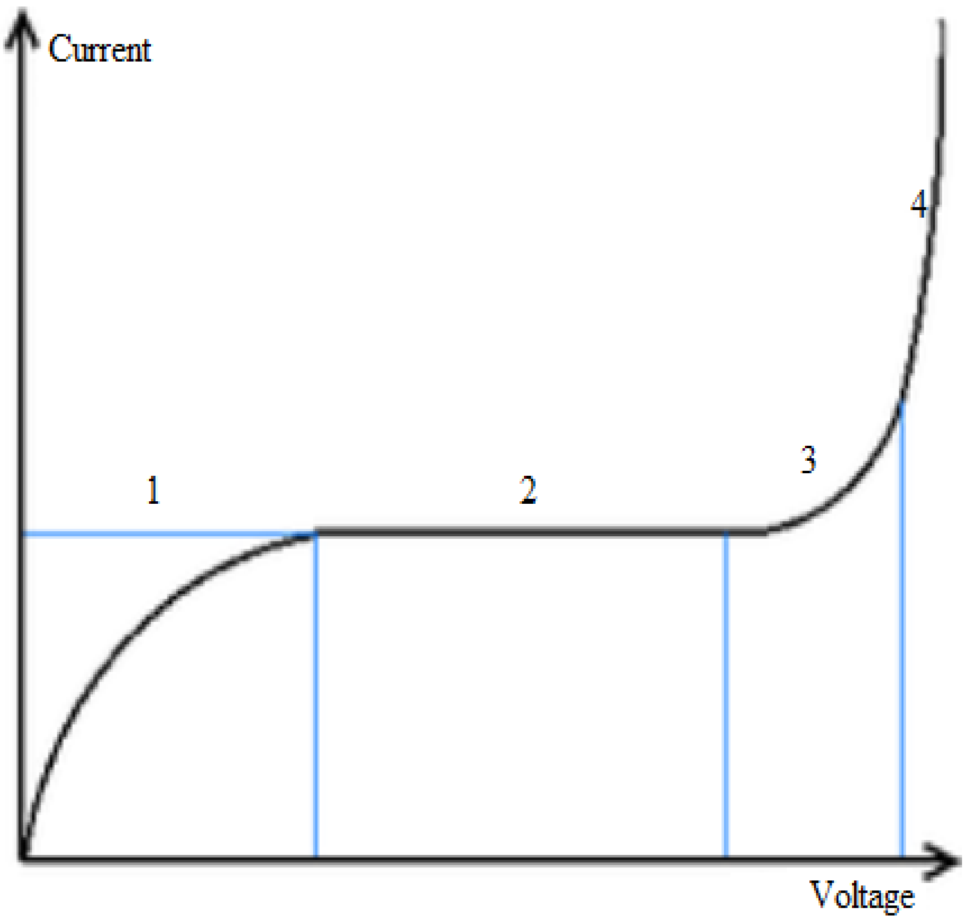


Figure 2.1: The relation of voltage via current

2.2.3 Streamer theory

Townsend approach when is used to breakdown at atmospheric pressure it has been realized to have certain drawbacks. In the first stage, as the expression given by Townsend approach, the current becoming greater because of the ionization processes only, but practically the breakdown voltages were discovered to be depending on gases pressure and the property of the electrodes and the gap as well. In the second stage, the mechanism calculates time lags of the order of ten to the power minus five seconds, but experimentally the breakdown is discovered to be created within short time of the order of ten to the power minus ten seconds. The Townsend approach didn't succeed to describe the discovered phenomena, and then the Streamer approach is proposed (Naidu and Kamaraju, 2013).

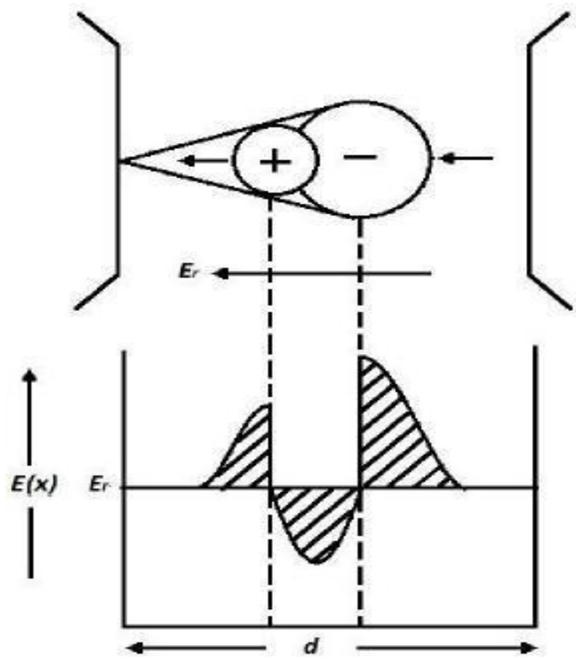


Figure 2.2: The distortion of the field due to existence of space charge (Naidu and Kamaraju, 2013)

The Figure given above is illustrating the field nearby the avalanche as it growths throughout the space and causing enhancement to the exposed electric field. In general, the gap charge at the front of the avalanche is considered to make spherical dimensions consisting of a (-)ve charge since the electron has a high ability to move. Through these conditions which mentioned above, the electric field will be improved at the top of the avalanche by the electric field lines from the positive electrodes terminating at its head. Moreover, at the lower part of the avalanche, the field between ions and electrons is reducing the applied field (E) and by moving further to lowest part, the field between negative electrodes and the positive ions becomes improved. The distortion of the field occurs and it gets visible when the charge carrier (n) reach hundred and six or above. Further, in case of a charge density reach n equal to hundred and eight in the avalanche approaches the gap charge filled field and the applied electric field will gets the same magnitude where this is leading to the streamer mechanism. Thus gap charge fields considered to play significant characteristics in the growth of avalanches in the spark discharges and the corona.

2.3 Electrical Performance and Properties of SF_6 and CO_2 Gases

The SF_6 gas is most usable (widely) in compact gas insulated power equipment, especially at HV level. This relies more on its superior physical and electrical properties than other insulation equipment.

The SF_6 thermodynamic stability comes from the symmetrical molecular structure which is composed of six atoms from fluorine around the middle a Sulphur atom, as illustrated below. There are four bonds plus two “bonds” distributed over six S-F pairs and the angle is equal to 90°C for each bond.

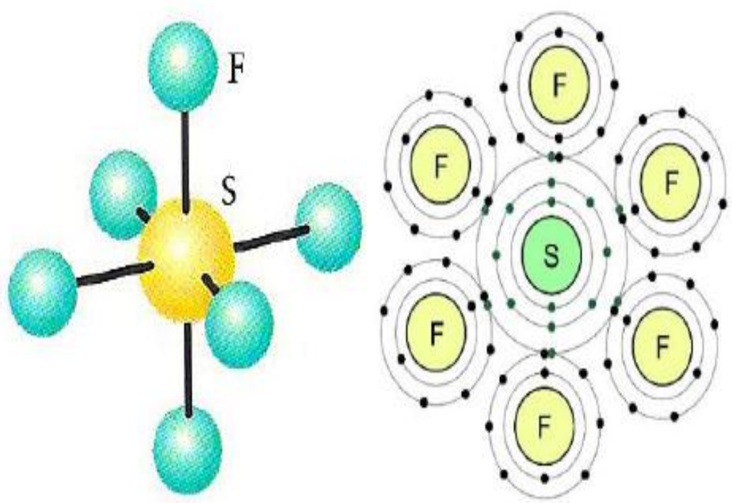


Figure 2.3: Molecule arrangement of SF_6 (Daniel, 1999)

The SF_6 gas has a strong electronegative property that is why there is an affinity to impound free electrons created by ionization of atoms through arcing phenomenon. These created (-)ve ions which are slightly more heavy and immobile when are matched with the free electrons forming in a maximum electric field being required to make ionization.

SF_6 is usually made from Sulphur (S_2) and Fluorine (F_2), in an exothermic reaction. Significant heat is necessary for molecular breakdown and SF_6 is relatively stable at high temperatures. Therefore, it's chemical properties suitable to the wide range of solid conducting and insulating materials used in HV power system at maximum temperatures 200 °C. The SF_6 is having good properties has excellent transition properties, this along with the other key properties of SF_6 gas are given in Table below.

Table 2.1: Summaies the characteristics of SF_6 gas (Maller and Naidu, 1981)

Properties	Data
Relative Density at 0.1Mpa	6.164 kg/m3
Thermal conductivity at 0.1MPa 0°C	0.0121 Wm-1K-1
Boiling point at 0.1Mpa	−64°C (209 K)
Solubility in water	Slightly soluble
Liquefied Pressure at 21°C	2.1MPa
Global Warming Potential (GWP)	23,900
Toxicity	No1
High concentrations of SF_6 will lead to suffocation	

The Carbon dioxide (CO_2) is odorless, non-flammable, colorless, and relatively acidic liquefied gas. It has been discovered the CO_2 is heavier when is compared to the air and is soluble in water.

The CO_2 in general is created scientifically by the help of CO_2 sources which are prepared in the petrochemical industry, or it can be also by burning natural gas in cogeneration processes. Table 2.2 shows different gas properties.

Table 2.2: Fundamental gas properties of SF_6 and CO_2 (Christophorou et al., 2004)

Items	SF_6	CO_2
Molecular mass	146.1	44.0
Density (kg/m3) *1	5.9	1.8
GWP *2	23,900	1
ODP *3	-	-
Boiling temperature (^oC) *4	-51	-78
Liquefaction pressure at -20 ^oC (MPa)		
Dielectric strength (%)	100	30

Star Notation No. :-

*1 At 300K, 1atm

*2 Global Warming Potential, Integrated period: 100 years

*3 Ozone Depletion Potential

*4 At 1 atm

2.4 Environmental Characteristics of SF_6, and CO_2 Gas Mixtures

This section investigates the environmental effects of the various gas mixtures considered and evaluates the case for and against each gas and gas mixture with regards to the potential that each has to damage our environment.

2.4.1 Atmospheric lifetime

The atmospheric lifetime is described based upon the simple one-box model. The lifetime defined as (t) of species (X) in the box (the atmosphere) is expressed as the approximated time required for X molecule to remains in the atmosphere, which is the function of the mass m (kg) of X in the atmosphere to the removal rate F_{out} + L + D (kg s-1); so that (Jacob, 1999):

$$t = \frac{m}{F_{out} + L + D} \text{ (Yr)} \qquad (2.3)$$

where: m = mass (kg), F_{out} = flow of substance X out of the box (kg/yr), yr= year, L = chemical loss of substance X (kg/yr), D = deposition of substance X (kg/yr) (Jacob, 1999).

2.4.2 Ozone-depletion potential (ODP)

Naturally, the Ozone is present in the atmosphere, it is mostly concentrated in the stratospheric region around 10^{-16} km to 50 km in altitude. The ozone in the stratosphere is absorbing harmful ultraviolet radiation created by the sun (Fahey, 2007).

The other gases concentration, particularly halogen source gases in the stratosphere are getting higher due to human activities. The abbreviation of Ozone Depleting Substances (ODS) came from those gases that can reduce the amount of ozone in the stratospheric region. Halogen gases can be converted to reactive gases containing chlorine and bromine that react with ozone and reduce it. Halogen gases contain fluorine (F) and iodine (I) atoms (Fahey, 2007).

The ozone depleting potential (ODP) is used in order to highlight the potential of a compound to extinguish ozone over its lifetime in the atmosphere compared to the effects of CFC-11. In this index, the ozone depleting potential of CFC-11 is fixed as 1 and the ODP of a compound is defined as the ratio of the impact of the chemical on the ozone compared to the impact of a similar mass of CFC-11**.**

$$\mathrm{ODP_i} = \frac{\mathrm{Global}\ \Delta\mathrm{O_3}\ \mathrm{due\ to\ substance\ i}}{\mathrm{Global}\ \Delta\mathrm{O_3}\ \mathrm{due\ to\ CFC-11}} \tag{1.4}$$

The SF_6 ozone depleting potential is approximately zero because it is chemically inert and does not readily react with other gases found in the stratosphere. Therefore, it is not readily converted to a reactive gas that would react with and deplete ozone (Kuffel and Kuffel, 2000; Nguyen et al., 2010).

2.4.3 Global warming potential (GWP)

To physical index GWP used to define the impact that certain emissions contribute to global warming. It has been designed in this manner so that it does not take into account uncertain locally resolved climate change data such as winds, temperature, precipitation, etc. and problematic baseline emission scenarios. The GWP index is based on one kilograms of particular compound (i) relative to that of one kilograms of the reference gas CO_2, developed by the IPCC (1990) (Pachauri et al., 2008; Scofield, 2013). The GWP index is also adopted to be use in the Kyoto Protocol. The global warming potential of element gas i is described by:

$$\mathrm{GWP_i} \equiv \frac{\int_0^H \mathrm{Ri\ (t)dt}}{\int_0^H \mathrm{Rr\ (t)dt}} = \frac{\int_0^H \mathrm{ai\ .\ [Ci\ (t)]dt}}{\int_0^H \mathrm{ar\ .\ [Cr\ (t)]dt}} \qquad (2.5)$$

where:

H: time horizon, Ri = global mean radiative forcing (RF) of component gas i, ai=RF per unit mass increase in atmospheric abundance of component gas i (radiative efficiency), Ci (t) = time-dependent abundance of gas i.

ar = RF per unit mass increase in atmospheric abundance of the reference gas CO_2 (radiative efficiency)

Cr (t) = time dependent abundance of CO_2 gas

The denominator and numerator are called the Absolute GWP (AGWP) of component reference gas CO_2 and gas (i) respectively.

The GWP of SF_6 and CF_3I relative to CO_2 are shown in Table 2.3.

Table 2.3: Global warming potential for SF_6 and CF_3I

Name	Chemical Formula	Lifetime (Years)	Radiative Efficiency (W m-2 ppb-1)	SAR (100-yr)	20 Yrs	100 Yrs	500 Yrs
Carbon Dioxide	CO_2	-	1.4×10-5	1	1	1	1
Sulphur Hexafluoride	SF_6	3200	0.52	23900	16300	22800	32600
Trifluoroiodo methane	CF_3I	0.005	-	-	1.2 - 5	< 5	< 5

SAR = Second assessment report by the IPCC (1995)

CHAPTER 3
INTRODUCTION IN TO ARC MODEL

In this chapter, the electric arc created during the operation of HV CBs will be described and defined. Moreover, some simulations tools used to represent and describe the arc in HV circuit breakers simulation will be represented. Also there are several models mentioned in the history of circuit breaker arc modeling are described (Cobine, 1958).

3.1 The Electric Arc in Gases

The existing of the electric arc is not created only in nature but it's also appears whenever two conductors are separated to interrupt a circuit current (Cobine, 1958). The electric arc is created before the current is extinguished, this can be described in such way when the current is extinguished the arc is extinguished as well.

The arc plasma is a self sustained discharge having a bit of voltage drop and it's capable of supporting great amplitudes of current (Schavemaker, 2002). For this reasons it was thought that the arc was an obstacle to current interrupting. Now day's researchers and developers working in such a way to make the art and science of circuit interruption control the arc to act as a variable resistor, in such a way that current interruption is obtained. The technical basis of circuit breakers or current interruption lies in creating arc plasma (electric arc) with the highest possibly conductivity, carrying a high current, cooling it effectively and converting it into insulation medium as soon as possible.

The electric arc behaves as nonlinear resistance during the circuit breakers interruption (Sergio, 2012). While the contacts are opening the current flows through the arc created from the plasma (the plasma which is created between the circuit breaker's contacts). After the current has passed it is zero value that the TRV builds up through the contacts. However, when the current is interrupted a few amperes continue to flow a few microseconds after the current zero called post arc current, Figure 3.1 describe the phenomena of electric arc during the current zero. This phenomenon is possible since the insulation medium of HV circuit breaker will still be hot and some ionization will still be present, letting post-arc current flow through the hottest paths (Giménez, 1999).

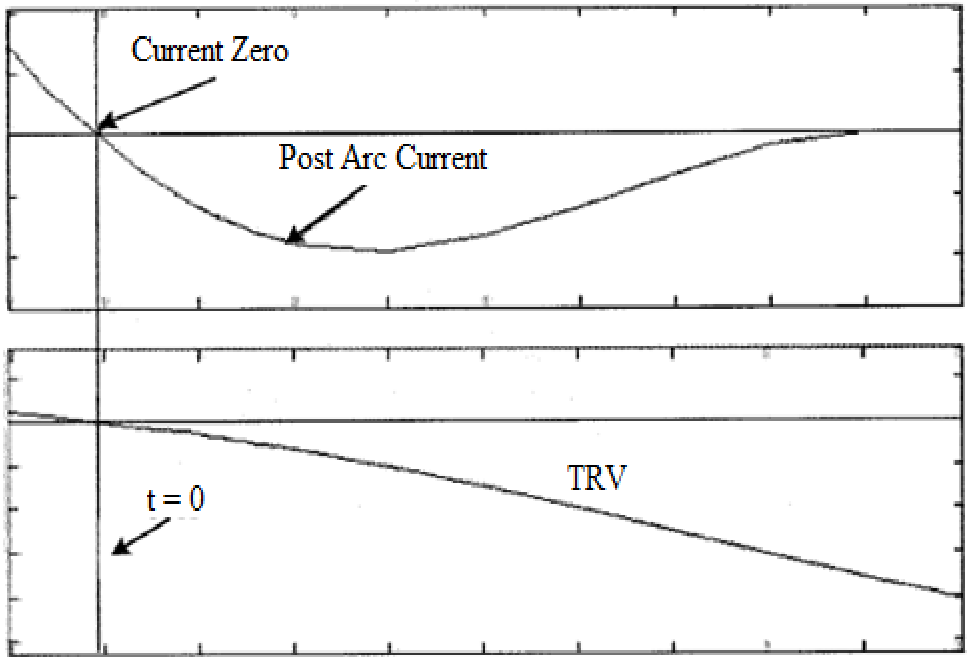


Figure 3.1: The arc current and TRV on HV gas circuit breaker

The phenomena's of electric arc occurrence in CB's and interrupters is not trivial. It can't be described entirely in a quantitative way that is why the use of arc models is useful to characterize, study, and understand the performance of circuit interruption. During the earlier time the power system transients created by HV circuit breakers were not represented accurately. Some methods of approximations were used to describe the circuit breakers including ideal switch models, current, voltage, or time controlled switches etc. Those approximations were good for studying the transient recovery voltage, but inappropriate for other applications such as the dielectric failure and thermal breakdown (Orama-Exclusa, 2003). The arc modeling of the nonlinear behavior of the electric arc was needed to overcome these issues.

There are some researches and developments efforts have been directed in order to use the advantages of computer methods to design and evaluate the HV circuit breakers, which are leading to the creation of arc models to describe the HV circuit breakers performance and their interactions with the electrical power system networking (Sergio, 2012). Moreover, by using the computer methods are leading to reduce the cost and the space when realizing synthetic test circuits.

The arc re-ignition or breakdown could exist because of the combination of two factors, firstly the exchange of heat between the extinction medium and the arc; and secondly the electrical stresses created by the system through circuit breaker contacts. These stresses are imposed by the arc-quenching medium, the power systems network, and the HV circuit breaker technology (Schavemaker and Van der Slui, 2000). As the information mentioned above it could be explained that there are two factors to prompt the HV circuit breaker breakdown as it can be seen in Figure 3.2, these factors/mechanisms are summarized as follow (Sergio, 2012):

- The dielectric breakdown: This happen when the stress through the breaker contacts is greater than the stress of the insulation medium can handle, which cause to the re-ignition of the electric arc.
- The thermal breakdown: This happens when the process of heat exchange through the arc and the extinction medium, the capability of the interrupter to cool down the arc is not fast enough.

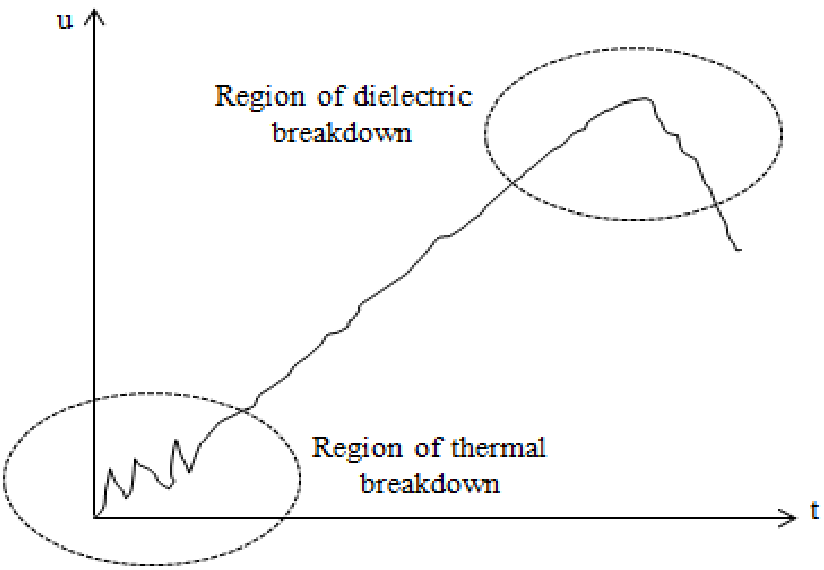


Figure 3.2: Thermal and dielectric breakdown regions (Kapetanovic, 2011)

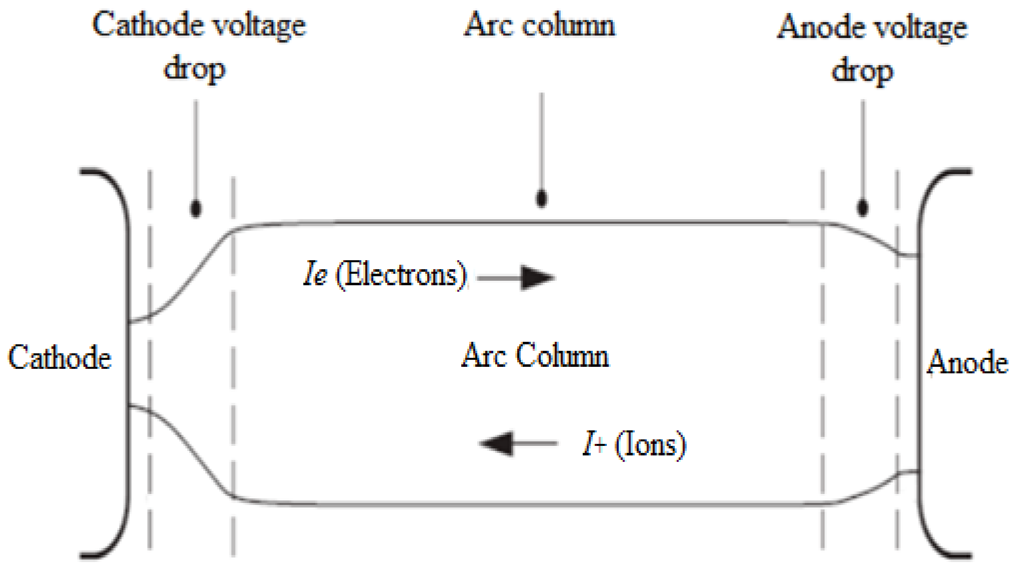


Figure 3.3: Regions of electric arc (Kapetanovic, 2011)

The electric arc consists of three regions which differ from one another in the processes that take place in them. Adjacent to the negative electrode (cathode), is the region of cathode voltage drop. Then follows the arc column and finally, adjacent to the positive electrode (anode), the region of anode voltage drop. These regions are depicted in Figure 3.3, the size of anode and cathode regions voltage drop are very small compare it to the arc column (Kapetanovic, 2011).

The volt-ampere characteristic of an Alternating Current (AC) arc plotted for one power frequency cycle has a shape as presented in Figure 3.4. The arc extinguishes when conditions are fulfilled for the intensity of deionization to be higher than that of ionization until current is interrupted, it should be noted that the current in an AC arc can be interrupted at two essentially different instants in time:

(A) At the end of a current half cycle, at the instant when the current passes through a natural current zero.

(B) In the middle of a current half cycle.

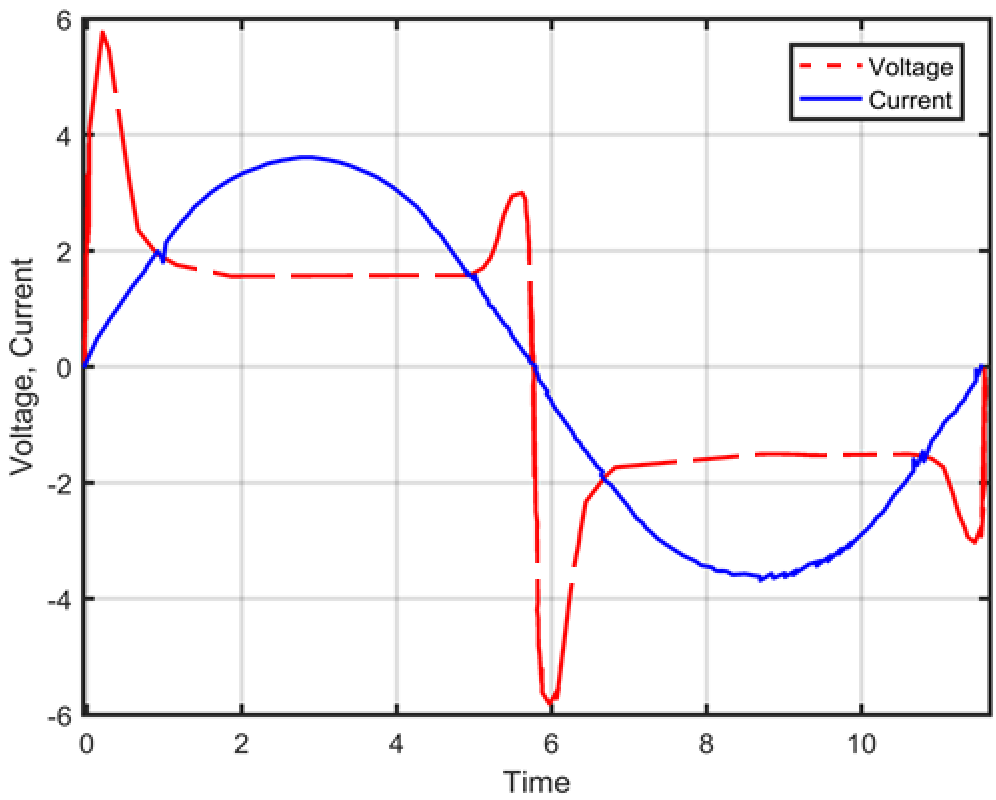


Figure 3.4: Typical variations of arc voltage and arc current during one power frequency cycle

3.2 Arc Modeling

The advantage of arc models offered to researchers and developments in the area of HV power circuit breakers an opportunity to gather the maximum information from a single standard test of a circuit breaker. The arc models can be classified to two types: physical and mathematical models. The following section gives a brief general description of these types of arc models.

3.2.1 Physical arc models

The physical models can be classified from basic principles (e.g. physical, chemical or thermodynamics laws). Generally, all of the physical models equations and parameters can be evaluated by theory; these types of models are known as white box models in identification theory and system modeling (Nelles, 2011).

These models can be classified into three sub-regions of the arc (Nakanishi, 1991; Kapetanovic, 2011): the high current region, the current zero region, and the post arc region.

3.2.2 P-T (black box) arc models

Generally most of the arc models used in arc synthetic circuit interaction studies is mathematical models which are describing the arc phenomena under well-known relationships. These black box models are based entirely on the measured data (Nelles, 2011), The black box arc model considers a switching arc as a two port the conductance of which changes in time as a function of circuit parameters, on the one hand, and an arc parameters on the other. They predict the transfer function using a chosen mathematical equation, usually a differential equation, and fitting the remaining parameters into a tested arc current and arc voltage traces (Nelles, 2011).
Both models structure and parameters are evaluated from experimental modeling and limited previous knowledge is exploited. In black box models, we are interested in the correct electrical behavior of the arc, while the description of the physical process is of no important.

3.3 General form of Dynamic Arc Equation

In 1938, Cassie (Flurscheim, 1985) created the first arc equation that intended to describe an arc with constant current density and volume varied directly with current; it’s also had a fixed resistivity. The model tried to describe an electric plasma in an air blast CB supposing that the air flow penetrated the hole cross sectional area of electric plasma, which is causing a dissipation per unit volume constant. The model actually does a moderately good representation of this high current region, Cassie’s assumptions lead to the differential equation described as follow:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau}\left(\frac{u^2}{U_c^2} - 1\right) \tag{3.1}$$

where:

g arc conductance

u arc voltage

τ arc time constant, in seconds. The time constant can be represented as a measure of the arc will to survive. τ is a representation of the inertia inherent in the arc since it can't be extinguishing instantaneously**.**

U_c is the arc voltage during the steady state, where heats generated by the arc and power loss are equal.

In 1943, Mayr (Flurscheim, 1985) created another arc model with losses occurring from the arc edges, and the conductance of the arc varied exponentially with the energy stored on it. This arc model hoped to describe what happens in a high pressure gas circuit breaker near current zero, the model actually does a moderately good representation of this low current region. Mayr's arc model can be described by the equation given below:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau}\left(\frac{u.i}{P} - 1\right) \tag{3.2}$$

where

g arc conductance

u arc voltage

i arc current

τ arc time constant, in seconds. The time constant can be interrupted as a measure of the arc will to survive. τ is a representation of the inertia inherent in the arc since it can't be extinguishing instantaneously.

p is the power dissipated from the arc to the surrounding gas, in Watts.

From the time when Cassie and Mayr created their mathematical models which are describing the nonlinear behavior of the arc, work has been devoted to modifying arc models and their later applications to fit measured data. P.H. Schavemaker surveyed the different types of arc models (Schavemaker, 2011).

3.4 Different Tools for Studying the Arc Circuit Interaction

There is several software tools are used in order to calculate the behavior of the electric plasma with respect to the classification of arc models which are mentioned earlier. It is difficult to directly analyze the transient phenomena's observed in the interruption process by hand calculations. Therefore, software tools have been implemented to interact with the complexity of those models and systems equations such as black box models. There are several types of software to simulate the power systems transients, such as Alternative Transient Program/Electromagnetic Transient Program (ATP/EMTP) and MATLAB/

SIMULINK (Sergio, 2012). These software tools are giving some opportunities to study the interaction of HV networks in the time domain by calculating the DE that describes the performance of several elements.

3.4.1 ATP/EMTP

This is a worldwide program for simulating the transient behavior of the electromechanical and electromagnetic nature. Also, it can be used to simulate the most complicated power systems and control systems of arbitrary structure. The ATP has widespread modeling capabilities and further important features in addition to the computation of transients (Schavemaker, 2011).

One of our main operating principles here is used:

- Dynamic systems also can be simulated using Transient Analysis of Control Systems (TACS) and MODELS control system modeling without any electric network.
- The compatibility to interfere between the program modules TACS and written language are giving extra opportunities which enable modeling of some control systems and elements with nonlinear characteristics.

3.4.2 MATLAB/SIMULINK

In general, the black box models can be represented clearly by using the Arc Model Blockset (AMB) (Schavemaker, 2011). The Arc Model Blockset is a library that presently consists of several models can be used together with the SIMULINK Power System Blockset. The arc is described as a non-linear resistance changing with the time-domain and can be defined mathematically using a differential equation in order to study the arc circuit interaction in power system networks. The arc models which are combined in the Arc Model Blocksets are Cassie, KEMA, Habedank, Modified Mayr, Mayr, Schwarz, and Schavemaker.

The arc models which are combined in AMB have been modeled in such a way voltage controlled current sources and the DE describing the electric arc is formed by means of the MATLAB Differential Equation Editor (DEE) (Ong, 1998). MATLAB can be used to make arc circuit interaction studies during the interruption process of power circuit breakers in gaseous mediums.

3.5 Arc Model Configuration on MATLAB/SIMULINK

Generally SIMULINK is based on several part of blocks interconnected together in order to setup a system. Every one of them containing three basic elements: an input of a vector signals given as (u), an output of a vector signals given as (y), and a vector of state variables given as (x), where Figure 3.5 shows the SIMULINK block. The system is initialized before starting the computation; the SIMULINK blocks are arranged in the consequence in which they need to be modified. Hereafter, the system is simulated by using the means of numerical integration combined with one of the implemented Ordinary Differential Equation (ODE) solvers. The computation can be summarized as follows:

- The SIMULINK block output is simulated in the consequence order.
- The SIMULINK block is calculating the derivative of its states and these states based on the inputs, current time, and the state variables.
- The derivative vector generally is used by the solver in order to calculate a new state vector for the subsequent time step and these steps will continue up to the end of the simulation time.

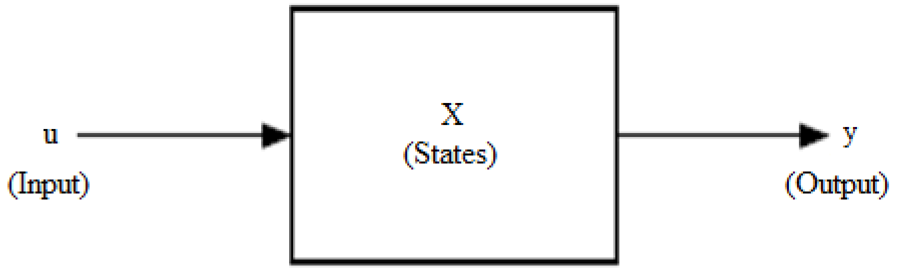


Figure 3.5: MATLAB/SIMULINK block (SLUIS, 2001)

The library of Power System Block (PSB) is including MATLAB blocks that describe common devices and components discovered in HV systems. Therefore, electrical networks can be formed, by including of both PSB blocks and SIMULINK. The RLC circuit built up in the PSB is shown below.

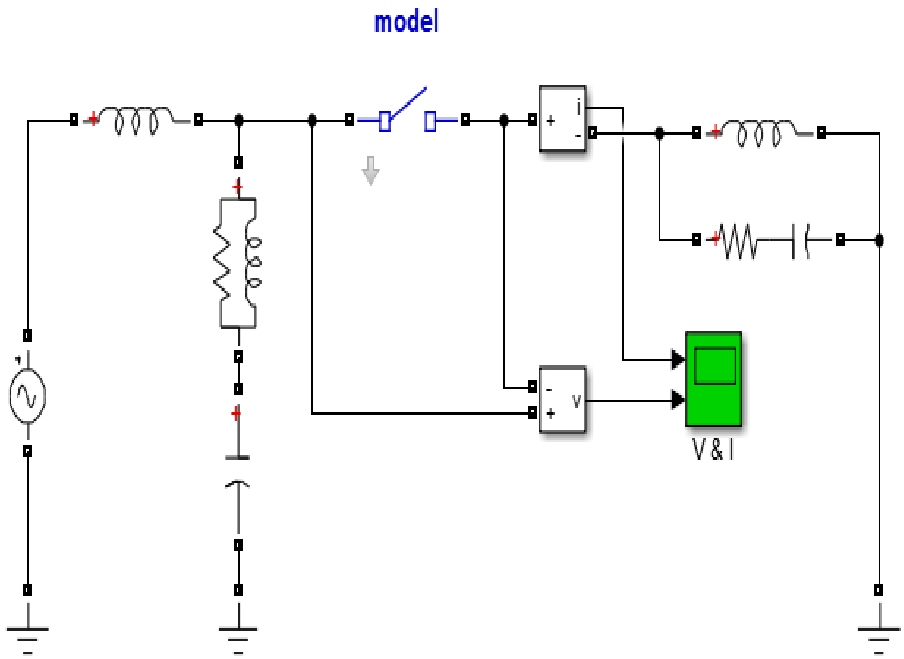


Figure 3.6: Illustartes the single phase test circuit arc model (Schavemaker, 2011)

3.6 Implementation

The arc models are implemented in such a way voltage controlled the current sources. The reading of measurement block and the controlled source represented as links through the electrical signals (where voltages measured over the components and the currents measured passing through the lines) and SIMULINK blocks (representing the transfer functions) and vice versa, respectively. Figure 3.7 was given as an example in order to describe the mask of the Mayr model. As starting the system is initialized then the state space model for the electric network will be computed and the equivalent SIMULINK system is setup.

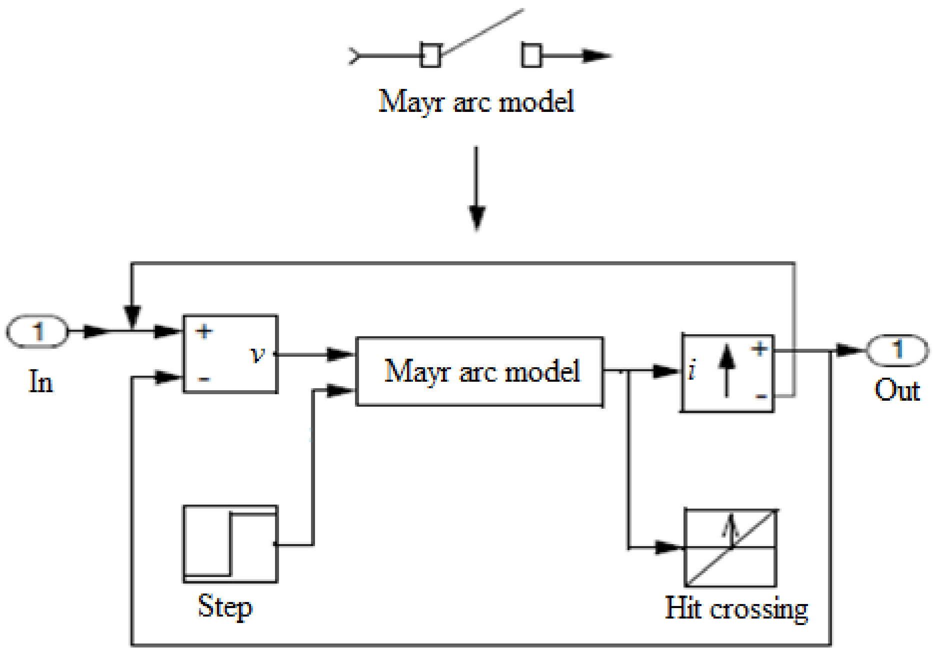


Figure 3.7: The mask components of the Mayr arc model (Schavemaker, 2011)

Through the following subsection, a function of various elements in the Mayr arc model will be described below:

3.6.1 Differential equation editor (DEE)

This is the equation of each arc model used in MATLAB/SIMULINK block in order to define the parameters of the model, the symbols in the Figure 3.8 as follow:

u(1) is representing the 1^{st} input of the DEE block.

u(2) is representing the 2^{nd} input of the DEE block which is representing the contacts being opened of the CB: u(2) = 0 is given when the contacts are in close position, while u(2) = 1 is given to represent the contacts are being opened.

x_0 is representing the initial value of the state variable, i.e. the arc conductance initial value is given as: $g(0)$.

x(1) is the state variable (x) of the DE which is the natural logarithm of the g.

y is representing the output of the DEE block which is equal to the arc current: *i*.

Then the system equations solved as follow:

$$\left(\frac{dx(1)}{dt} = \frac{u(2)}{\tau}\left(\frac{e^{x(1)}.u(1)^2}{P} - 1\right)\middle|\, \frac{1}{g}\frac{dg}{dt} = \frac{u(2)}{\tau}\left(\frac{.u^2}{P} - 1\right)\right) \tag{3.1}$$

$$y = e^{x(1)}\,u(1)\Big| \quad i = g\,u \tag{3.2}$$

τ and P are representing the Mayr model parameters and is defined by means of the Mayr model dialog which can appears whenever the arc model block is opened.

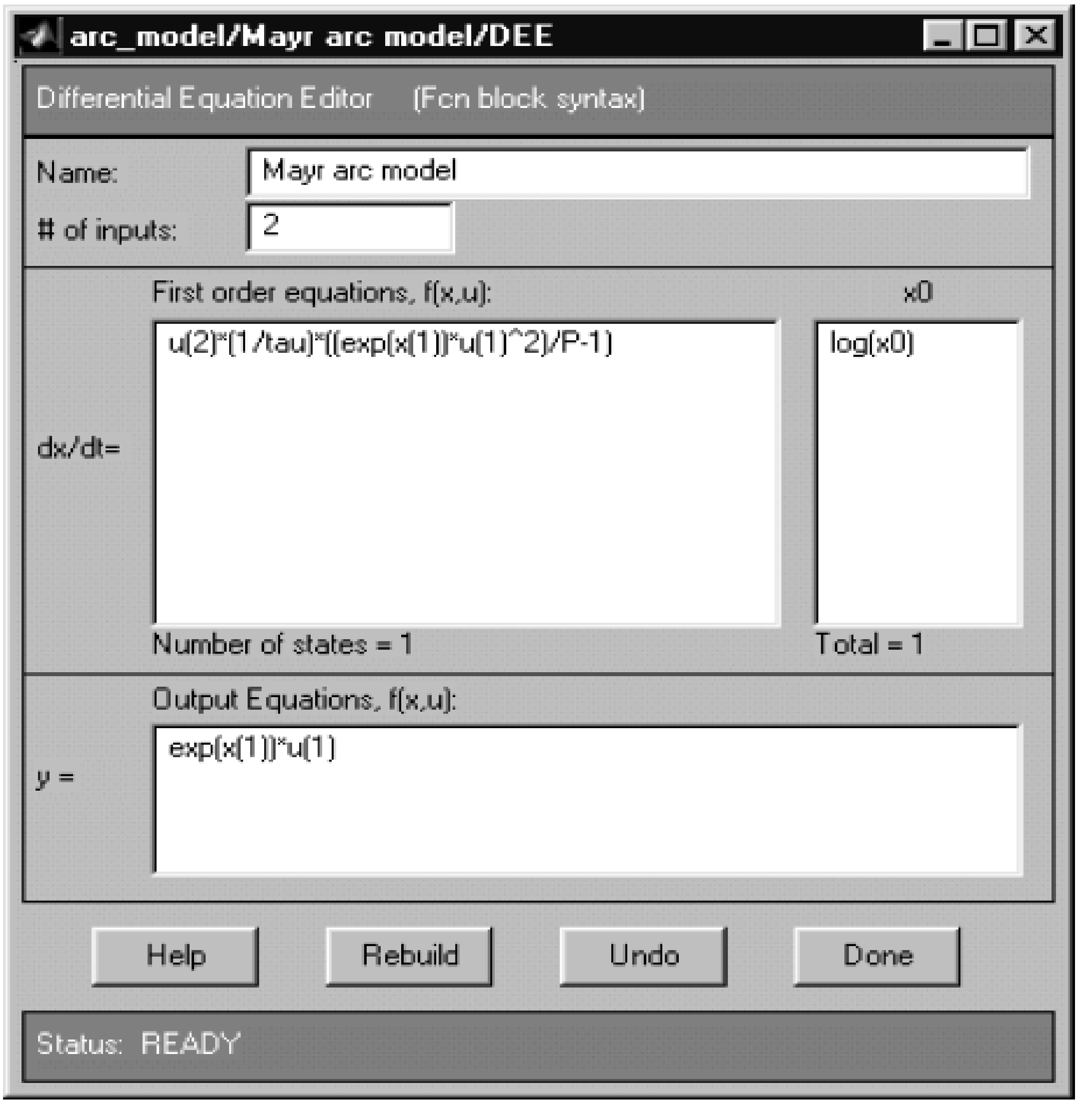


Figure 3.8: Shows the DEE of the arc model (Schavemaker, 2011)

3.6.2 Hit crossing

This SIMULINK block is used to detect when input crosses the zero value. Therefore, by modifying the step size the block will ensure that the model finds the zero crossing point. This is an important point while the current and voltage zero crossing circuit breaker, the CB performs as a variable resistant (nonlinear) and this is the important moment in the interruption process of CB which should be computed accurately.

3.6.3 Step

This SIMULINK block is used to control circuit breaker contact which is identifying the separation time of the contact. A step is set from the zero value to one at the exact contacts being opened time, the differential equation below is solved when the contacts of circuit breaker are closed:

$$\frac{dlng}{dt} = 0 \tag{3.3}$$

Also, the model become as a conductance at the value $g(0)$. From the circuit breaker contacts separation time on, Mayr equation is calculated as follow:

$$\frac{dlng}{dt} = \frac{1}{\tau}\left(\frac{g.u^2}{P} - 1\right) \tag{3.4}$$

The arc conductance $g(0)$ initial value and the start time of the circuit breaker contacts separation can be specified by means of the arc model dialog. The block parameter can be seen in Figure 3.9.

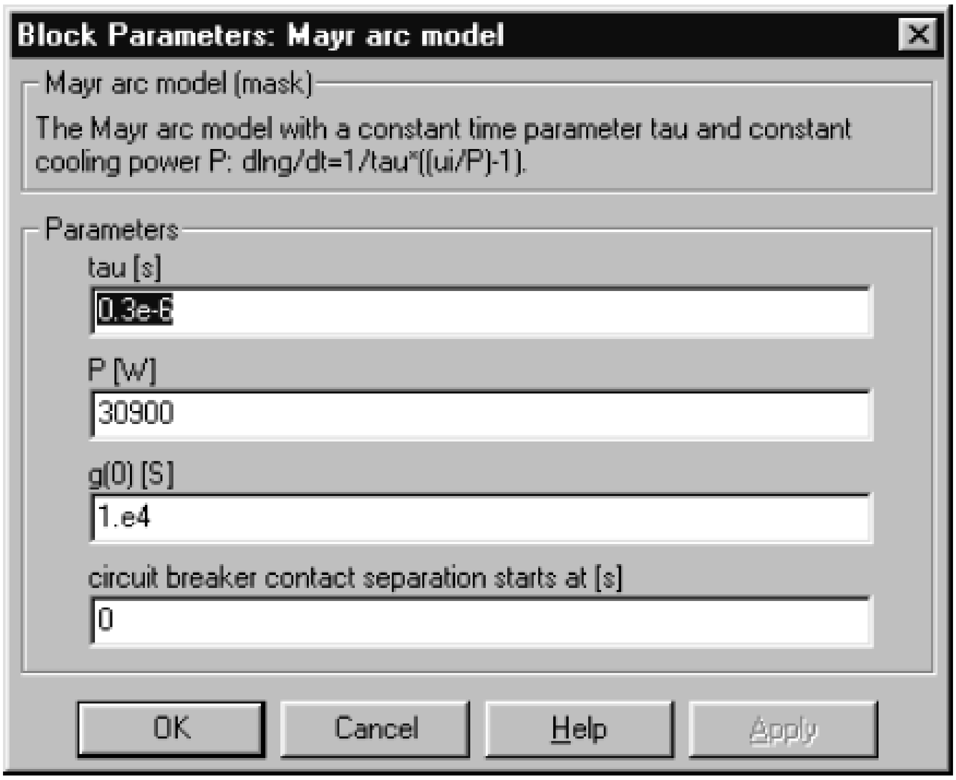


Figure 3.9: Block parameters of Mayr arc model (Schavemaker, 2011)

3.7 The Configuration of Short Line Fault

The SLF can be described as when a fault takes place across overhead transmission line within a few couple of hundred meters to a few kilo-meters from the terminals of a HV circuit breaker. The interruption of a short line fault creates a high thermal stress on the arc plasma within the first few μs (microseconds) after the interval of current interruption because of the electromagnetic waves which are reflecting from the SC (short circuit) back to circuit breaker terminals resulting a transient recovery voltage.

Generally in the HV power laboratory, it is not sufficient to use the real overhead transmission line for testing the SLF that is why the transient waveform voltage of the line side is reproduced by using the artificial line. The artificial line used to generate transient recovery voltage of the line as specified by the International Electrotechnical Commission (IEC) and American National Standard Institute (ANSI). W. A. van der Linden from KEMA high power laboratory in 1978, he designed an artificial line in order to test the HV circuit breaker under SLF conditions. Figure 3.10 illustrates the synthetic circuit which is representing the artificial line of KEMA high power laboratory.

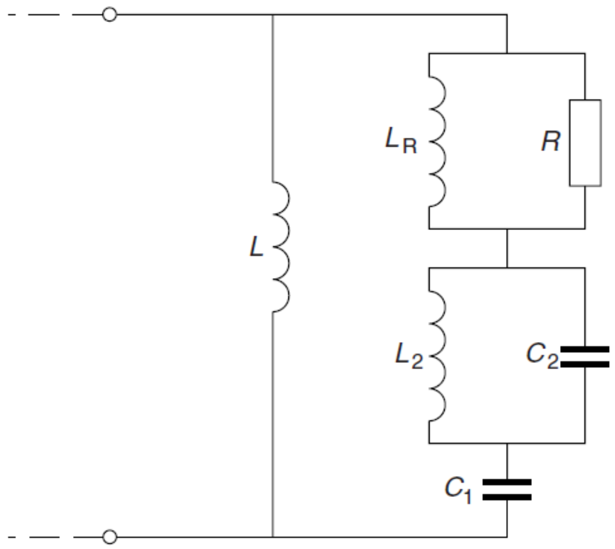


Figure 3.10: The artificial line TRV

where, L_R = 0.145 X L, L_2 = 0.0725 X L, C_1 = (0.333 X L)/$(Z_{line})^2$, C_2 = 2 X C_1 and R = Z_{line}

The inductance given as L, moderates the current to the required breakers rated short circuit breaking current. This inductance value L can be calculated as follow:

$$\mathrm{L} = \left(\frac{1-x}{x}\right)\frac{u}{2\pi f i} \tag{3.5}$$

where f: the frequency of power system, u: the phase voltage, i: the rated short circuit (SC) breaking current, x: ration between the SLF current and the nominal rated TF (terminal fault) current.

3.8 Comparison of Different Arc Models

In this section, the equation governing several arc models will be given to describe the performance of each arc model. Hereunder, a few well-known arc models:

3.8.1 Cassie arc model

The model described in the previous chapter, was Cassie arc model based on the assumption of a circuit breaker which is used to measure the high level of current interval. Figure 3.11 and 3.12, illustrate the voltage and current arcs waveforms of Cassie model, respectively.

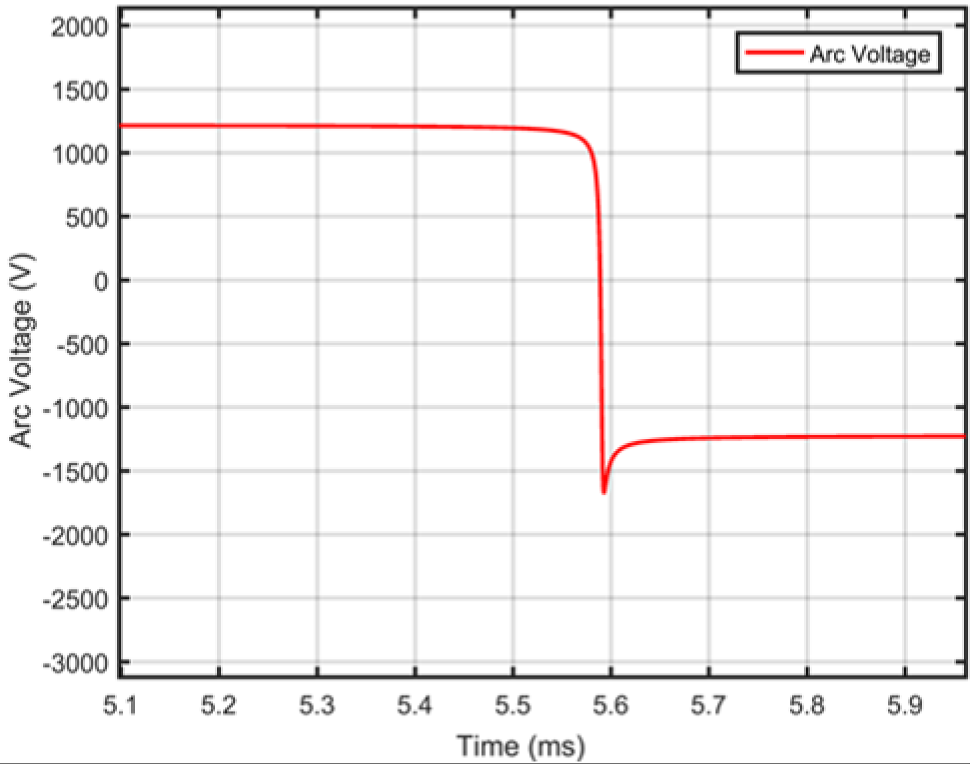


Figure 3.11: The arc voltage waveform of Cassie model

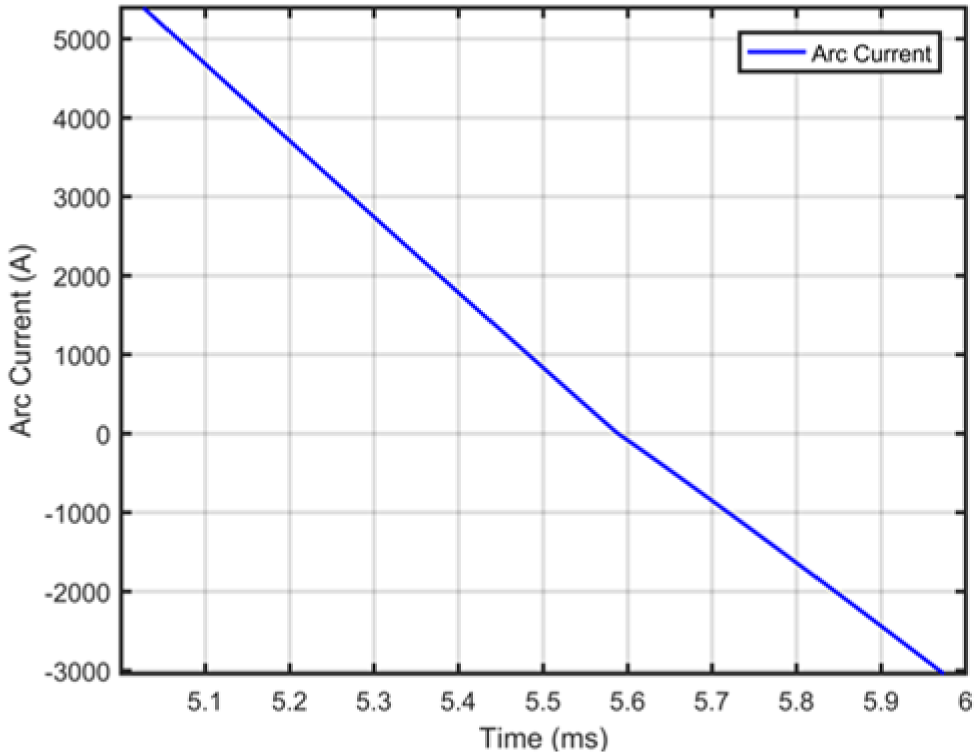


Figure 3.12: The arc current waveform of Cassie model

3.8.2 Mayr and Schwarz arc models

The Mayr model described earlier was based on the assumption of a CB which is used to measure the vicinity of current zero. Schwarz model agrees with Mayr model in vicinity of the current zero measurement, however, the arc parameters of τ and P are not constant. The Schwarz model assumes that the parameters of τ and P are free functions of arc conductance g. Figure 3.13 and 3.14, show the arc voltage and arc current waveforms of Schwarz model respectively.

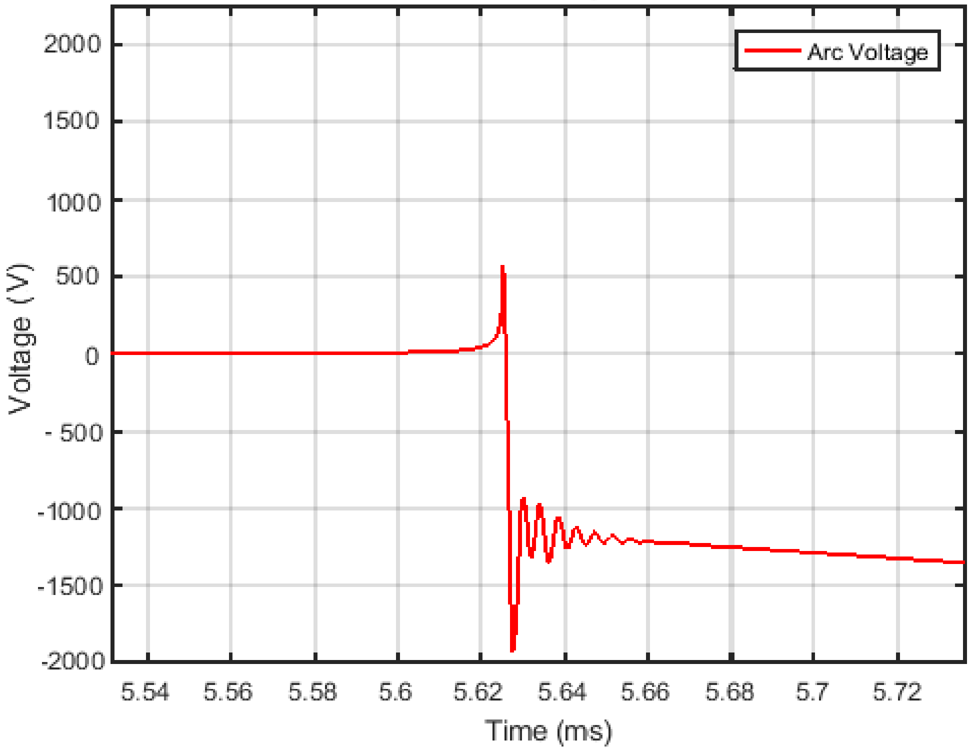


Figure 3.13: The arc voltage waveform of Schwarz arc model

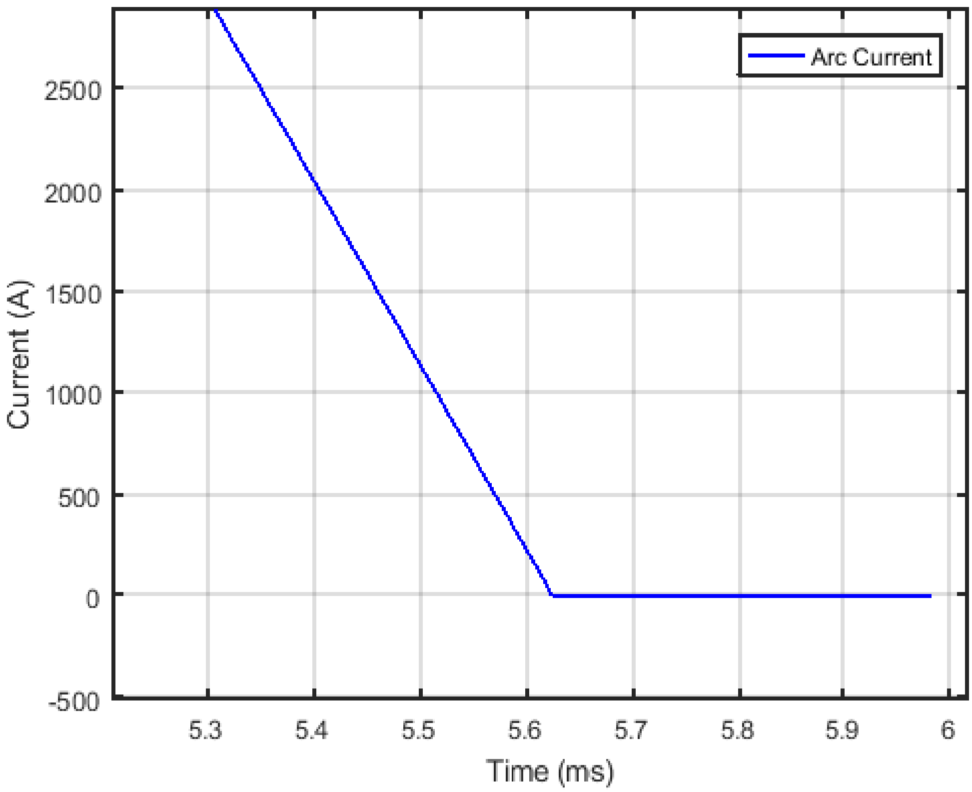


Figure 3.14: The arc current waveform of Schwarz arc model

CHAPTER 4
THE HYBRID ARC MODEL IMPLEMENTATION

This chapter presents the SLF interrupting performance of CO_2 CB's evaluation by using the I_{zero} experimental test. As circuit breakers interruption capabilities are determined by arc model calculation, a proposed arc model will be introduced by combining one Cassie model and two Schwarz models with different arc parameters values connected consequently in series. Then the performance of the proposed arc model will be compared with the measurement data sets waveforms. Moreover, the modification of the proposed model into a BB and using nonlinear least square will be illustrated then the relative error will be calculated.

4.1 The Proposed Arc Model

As mentioned earlier in the literature, it is difficult to directly calculate the performance of circuit breaker (the success or failure of current interruption) by analyzing the gas flow. It's possible to analyze the current interruption phenomena when arc models written by DEs are interconnected with a synthetic circuit, by using a method involving the creation of a program such as the Runge–Kutta method (Zaima, 1993). On the other hand, many arc models have been carried out for many years in order to evaluate the interruption performance of a circuit breaker such as the Cassie and Mayr. These arc models can be easily combined with a circuit in MATLAB/SIMULINK in order to determine the success/failure of circuit breaker current interruption. Also there are several arc models are used in EMTP such as Urbanek (St-Jean, 1983), Schwarz (St-Jean, 1983), and Kopplin (Thuries, 1986) models.

4.1.1 The configuration of the proposed arc model on MATLAB/SIMULINK

The circuit which is shown below display the proposed arc model for circuit breaker using the MATLAB/SIMULINK program. This Figure shows a synthetic circuit used to represent a circuit breaker interrupting a SLF condition. In the left side a source supplying voltage and artificial line is used to reproduce a TRV for the circuit breaker, while in the right side the RLC circuit at the line side used to represents a transmission line that is short circuited.

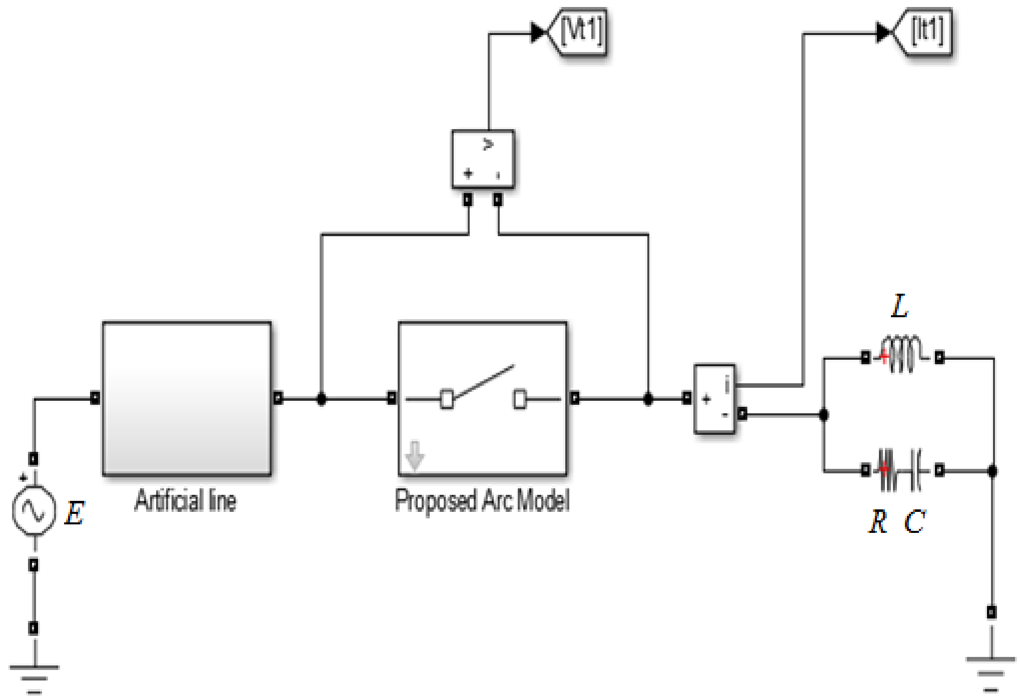


Figure 4.1: The proposed arc model circuit during SLF interruption

$$
\begin{aligned}
\mathrm{E} &= \frac{\mathrm{V_{rated}}}{\sqrt{2/3}} \\
\mathrm{L} &= \frac{\mathrm{E}}{\mathrm{di/dt}} \\
L &= 1.6\ \mathrm{L} \\
R &= \frac{\mathrm{dv}}{\mathrm{dt}} \div \frac{di}{dt} \\
C_{trv} &= \frac{\mathrm{L}}{R_{trv}^2}
\end{aligned} \tag{4.1}
$$

where: E: source supply voltage, V_{rated}: the rated voltage, L: TRV inductance, *L*: line inductance, *C*: line capacitance, *R*: line resistance.

All the explanations and simulations mentioned previously are confirming that the arc varying with respect to time domain, so the current and voltage arc crosses the point (zero) at same time. When the input power to the arc channel becomes zero at this moment the I_{zero} crossing is the place where the interruption takes a place.

Figure 4.2 and 4.3 illustrate the measured arc voltage and arc current oscillograms, respectively. These measurements were produced by CO_2 circuit breaker at the rated voltage of 72.5kV/31.5kA/50Hz 90% SLF (Uchii et al., 2011). The proposed arc model produces the arc voltage and arc current employing a hybrid model combining Cassie model and two Schwarz models having different arc parameters values connected consequently together. Cassie model is valid in the interval of high current before the current zero interval and the other two Schwarz models capture the current intervals close to extinction peak and in the near to I_{zero}, respectively. In the proposed model we assign Cassie and the two Schwarz models to cover the whole range of the arc current by combining the Cassie model in series with the series combination of the Schwarz arc models. The total arc conductance is given by:

$$\frac{1}{g_t} = \frac{1}{g_c} + \frac{1}{g_{m1}} + \frac{1}{g_{m2}} \tag{4.2}$$

where: g_t: total arc conductance, g_c: Cassie arc conductance, g_{m1}: Schwarz model 1 arc conductance, g_{m2}: Schwarz model 2 arc conductance.

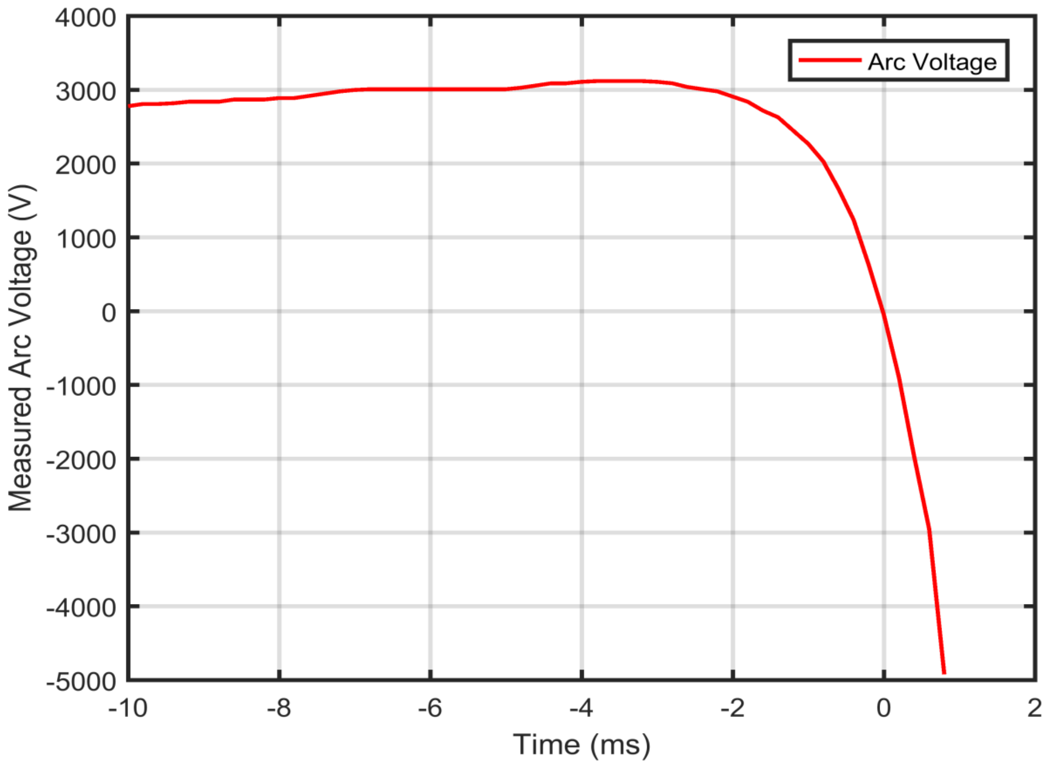


Figure 4.2: The measured oscillogram of CO_2 arc voltage (Uchii et al., 2011)

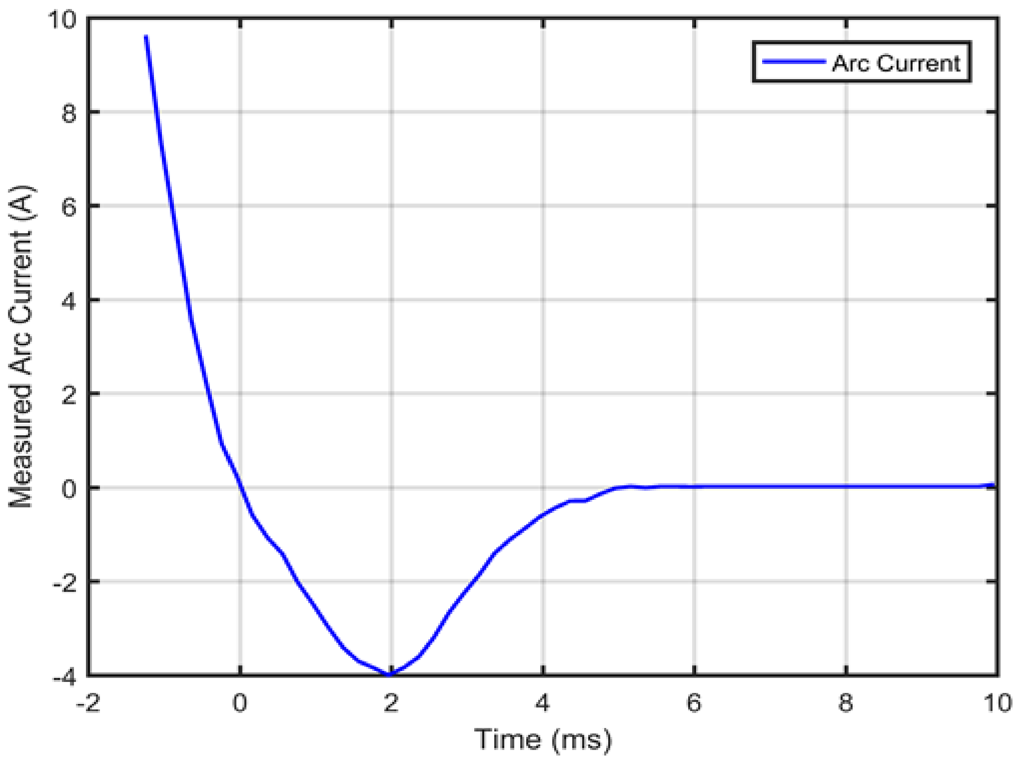
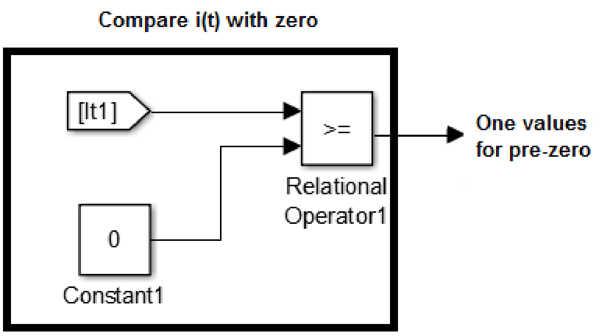


Figure 4.3: The measured oscillogram of CO_2 post arc current (Uchii et al., 2011)

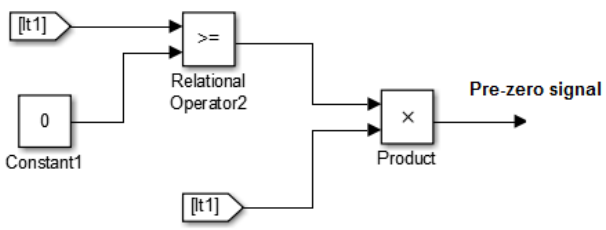
4.1.2 Control signal to simulate the I_{zero} measurements in the proposed model

The control signals are created by the advantages of the logical components/blocks in SIMULINK expressions in order to detect the current pre-zero and post-zero crossing intervals. During the pre-zero intervals, the pre-zero signal is generally high until I_{zero} is reached. However in the post-zero intervals, the post-zero signal turns to be higher while the pre-zero signal is low. This is achieved by using a relational operation block in MATLAB/SIMULINK for comparing the arc current with the value zero as shown in Figure 4.4 (a) and (b).

After detecting the pre-zero and post-zero interval, then two STEP blocks are adjusted with a few microseconds similar to the measurement data sets range connected together by using AND gate block. These blocks are working as giving values one for the time between those range and zero values for those out of the range too, the output from these blocks are then connected together with the calculated signals of arc current (It1) by using PRODUCT block which is used to make a multiplication resulting an output of the arc current. The same goes for the post-zero interval simulated voltage (Vt1)



(a) Comparing current with the value zero



(b) Activating the pre-zero arc current

Figure 4.4: The logical control of pre-zero and post-zero current zero detection

4.1.3 The performance of the proposed arc model

The evaluation of the proposed arc model, in this section we will be concentrating in arc voltage and arc current during the I_{zero} measurements at di/dt=130% as were showing in Figure 4.2 and 4.3, respectively (Uchii et al., 2011).

Figure 4.5 and 4.6 illustrates the voltage and current arcs for the measured and simulated waveforms which are produced by the synthetic circuit of the proposed arc model for CO_2 circuit breaker. As can be seen from these Figures the simulated values for the voltage and current agree very well with those of the measured values.

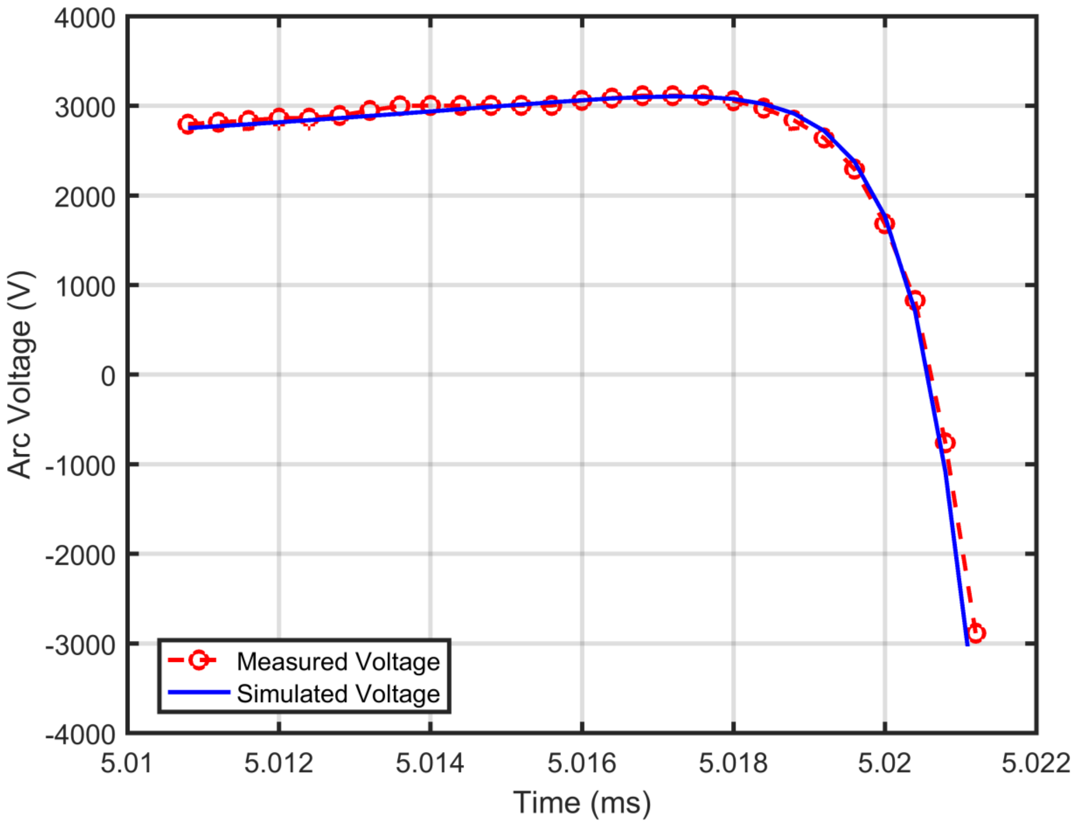


Figure 4.5: Arc voltage of the proposed arc model with the measurements

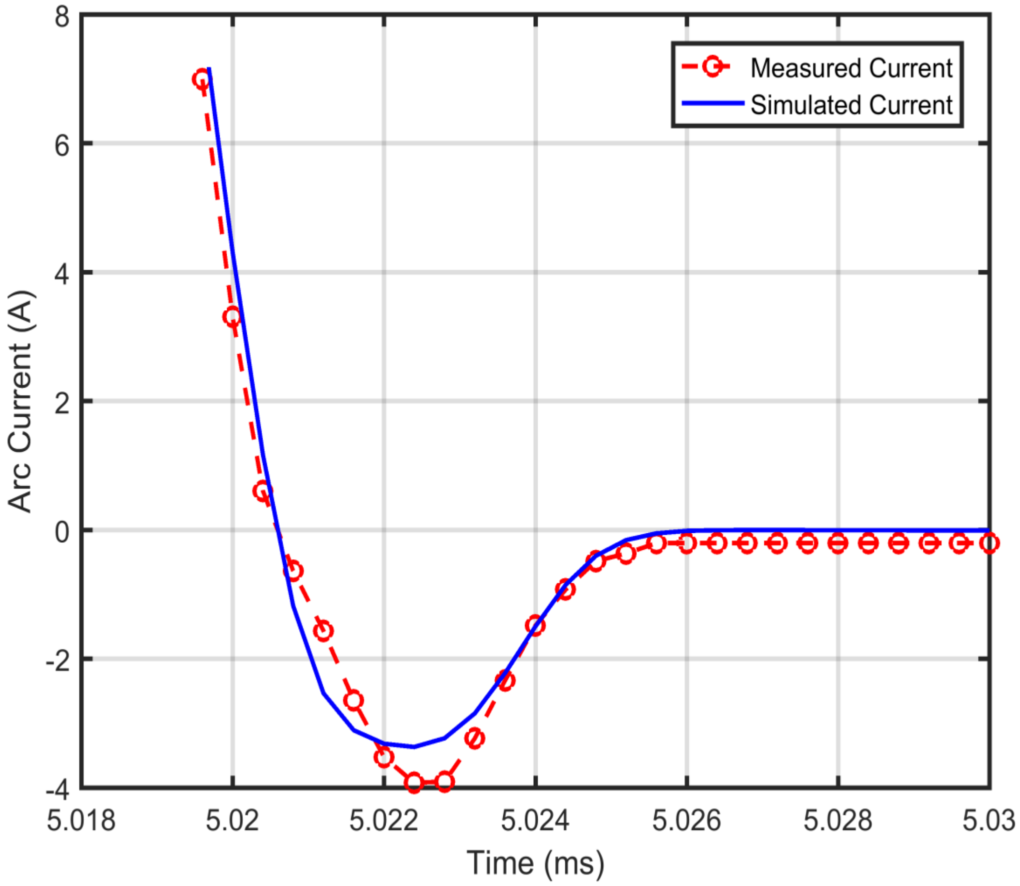


Figure 4.6: Arc current of the proposed arc model with the measurements

Table 4.1 illustrates the values of the arc parameters calculated in the present study which are used to simulate the waveforms in Figure 4.5 and 4.6.

Table 4.1: The Arc parameters which are used in the synthetic circuit of the proposed arc model

Parameter	Cassie	Schwarz 1	Schwarz 2
$\boldsymbol{\tau_c}$	$2.66\mu s$	-	-
$\boldsymbol{v_o}$	$1244.5V$	-	-
$\boldsymbol{\tau_o}$	-	$3.4671\mu s$	$1.1689\mu s$
$\boldsymbol{a}$	-	0.18326	0.11062
$\boldsymbol{P_o}$	-	$461kV$	$25.02kV$
$\boldsymbol{b}$	-	0.29859	0.0013689

In table 4.1, we give the calculated parameters for Cassie, Schwarz 1, and Schwarz 2 arc models respectively. In the proposed model which is the series combinaton of Cassie, Schwarz 1 and Schwarz 2 models we use 10 parameters totaly yielding a very good fit of simulation results of arc voltage and arc current with those of the measured values. Figure 4.7, illustrate the contribution of each arc model to create the toatal arc voltage which is given by Equation 4.2.

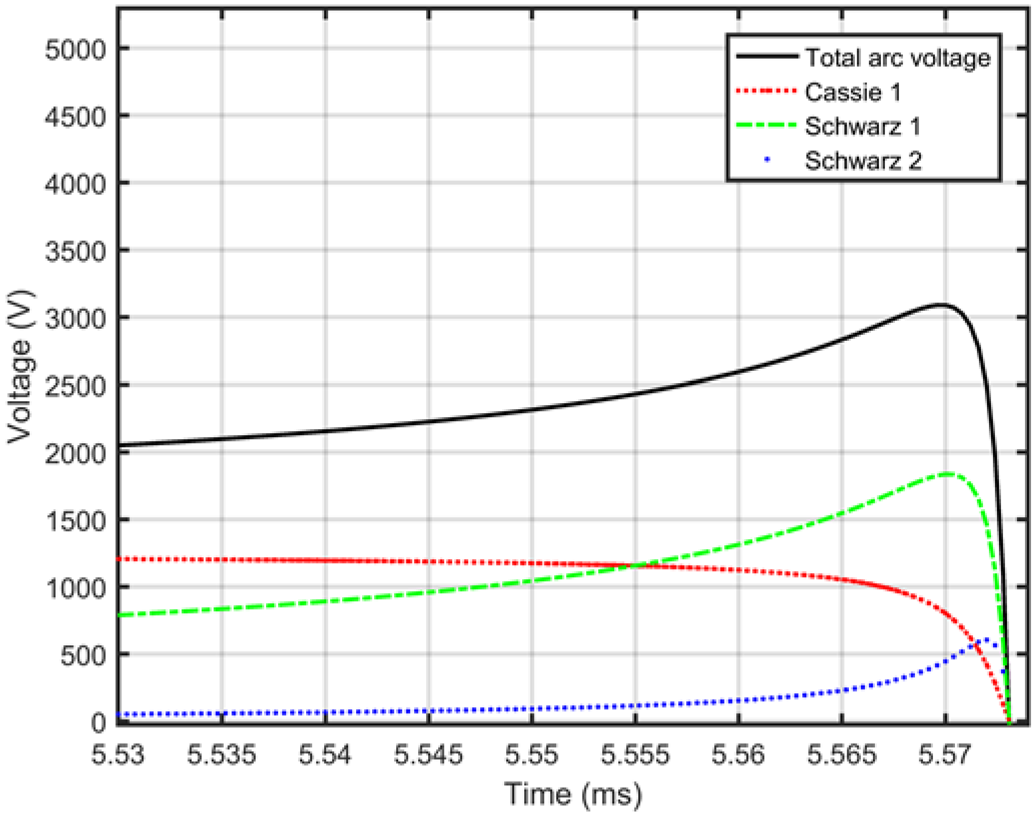


Figure 4.7: The total arc voltage consumed by each arc model

4.2 The Black-box Arc Model for CO_2 Circuit Breaker

4.2.1 Black box

The proposed model can be represented as a BB model since it is based on observed data. The external synthetic circuit sees the arc as an equivalent electrical conductance that changes with time and the other parameters discussed in the present section. The oscillograms of current and voltage through the arc are the input to the implemented proposed arc model (black box) arc model since the aim to describe the synthetic circuit arc interaction during interruption process. The black box arc model receives these measurement data sets and starts to predict the parameters of our proposed arc model. Figure 4.8 demonstrates the link of the synthetic circuit in the black box format.

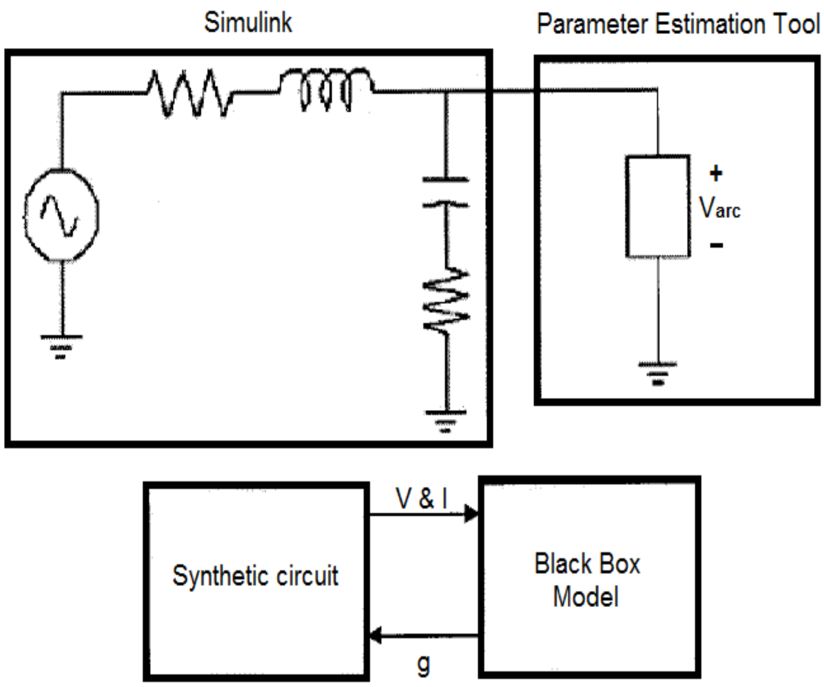


Figure 4.8: The link of synthetic circuit of the proposed arc model in SIMULINK with parameter estimation tool in the form of a black box

4.2.2 Evaluating the predicted arc parameters using nonlinear least square method

For predicting the arc parameters of the proposed arc model by the black box, the following steps are considered:

- The oscillograms are inserted from the experimental data sets.
- Initial guess is given for the parameters (also there is an option in the program to give an initiation guess by default).
- The conductance is calculated by using the model oscillograms.
- An optimization nonlinear least square is performed.
- The proposed arc model parameters are extracted.

The measured test oscillograms of voltage and current arcs are inserted as matrix form. A nonlinear least square method has been used to fit the tested voltage and current arcs with the proposed model. Figure 4.9 gives the flowchart for the calculation of the proposed arc model parameters.

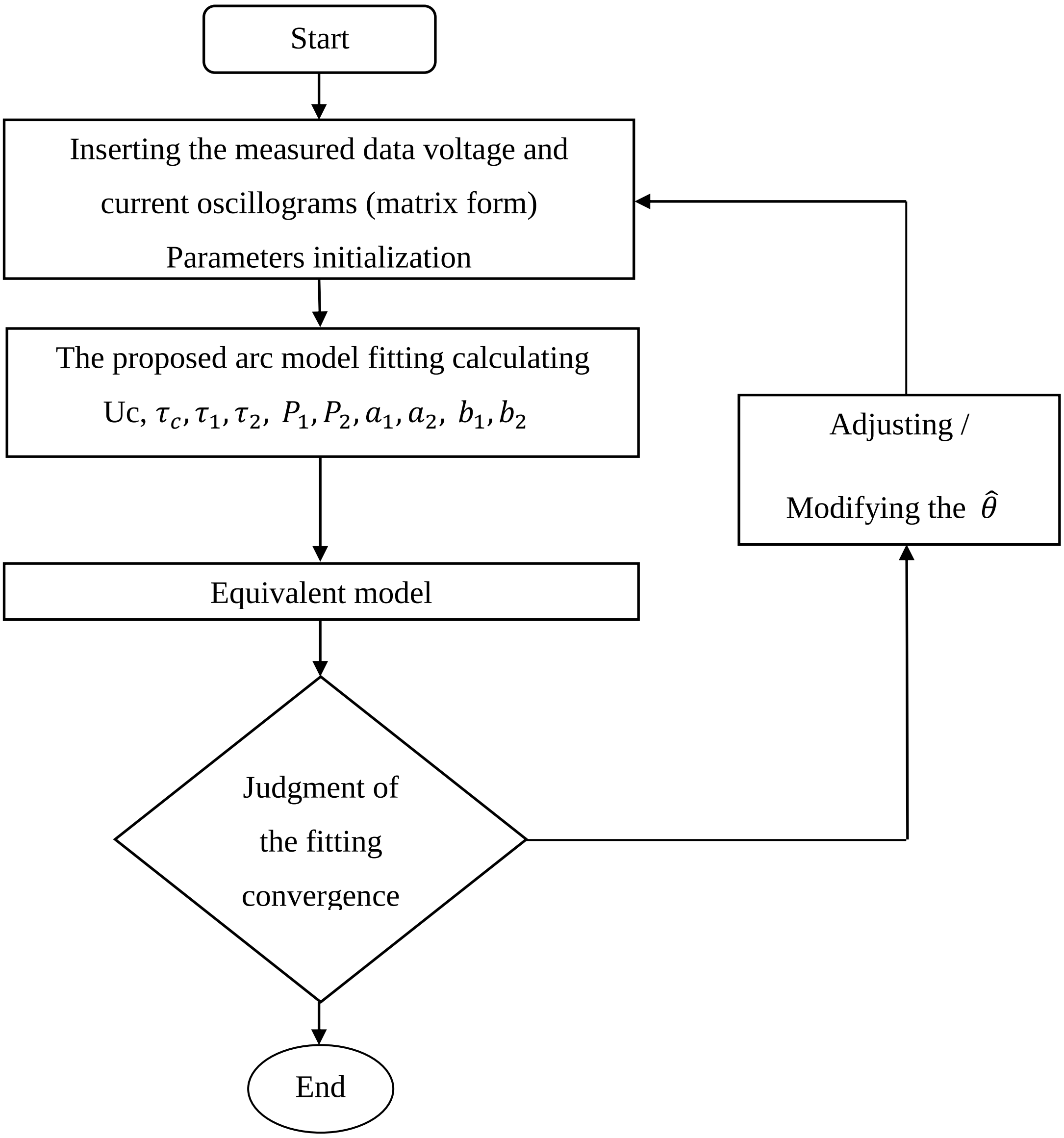


Figure 4.9: The flowchart of the black box model arc parameters calculation

A brief description about the nonlinear least square optimization, first the data is arranged as inputs and outputs data sets measurements N as follow:

$$\begin{aligned} F^N &= [o^N, u^N] \\ o^N &= [o(1), o(2), \dots, o(N)]^T \\ u^N &= [u(1), u(2), \dots, u(N)]^T \end{aligned} \tag{4.3}$$

where u(t): input and o(t): output are the proposed model data sets. Then these data sets are fitted to the model.

$$\hat{o}(t, \theta) = \hat{g}(t, \theta) \tag{4.4}$$

where $\hat{o}(t,\theta)$ is a prediction of o(t), and θ representing the parameters vector which is going to be evaluated. Since the arc parameter evaluation usually is calculated using an optimization approach which requires minimizing the cost function $C_N(\theta, F^N)$ of the error between the system and the model output, the optimal parameter set $\hat{\theta}$ is chosen such that:

$$\hat{\theta} = \arg\min C_N(\theta, F^N) \tag{4.5}$$

where

$$C_N(\theta, F^N) = \frac{1}{N}\sum_{t=1}^{N} l\big(\varepsilon(t,\theta)\big) \tag{4.6}$$
$$\varepsilon(t,\theta) = o(t) - \hat{o}(t,\theta)$$

ε(t,θ): error and the *l*(.): some appropriate norm (common choices are the norm 1, norm 2 and the infinity norm).

The general standard method used in nonlinear least squares to determine the estimated parameters is Gauss-Newton method (Nelles, 2011; Ong and C. , 1998). This method is an iterative method of the form:

$$\hat{\theta}^{(i+1)} = \hat{\theta}^{(i)} + \gamma.\Delta\hat{\theta}^{(i)} \tag{4.7}$$

where $\hat{\theta}^{(i)}$ is the optimal evaluate parameters at i-th iteration and the $\Delta\hat{\theta}^{(i)}$: Gauss Newton for search direction which will be calculated by solving the linear least squares approach given as:

$$\Delta\theta^{(i)} = arg\ min\left\| r^{(i)} - J^{(i)}.\Delta\theta \right\| = (J^T J)^{-1} J^T\, r \tag{4.8}$$

where $r^{(i)}$: residual vector, $J^{(i)}$: jacobian matrix at i-th iteration which are given by the following form:

$$r^{(i)} = \varepsilon\big(t, \theta^{(i)}\big), J^{(i)} = \left.\frac{\partial\hat{o}(t,\theta)}{\partial\theta}\right|_{\theta=\hat{\theta}^{(i)}} \tag{4.9}$$

The program starts to iterate up to satisfy one of the following role:

- The error is less than the assigned tolerance.
- The stopping criterion is satisfied.
- Reaching the maximum number of iterations.

After toolbox satisfying one of those roles it will return the optimized parameters to the model for simulation of the circuit breaker.

4.2.3 The performance of the black box prediction

After prediction of the parameters by the black box of the proposed arc model, then the simulations results with these parameters fitted has been compared with the arc voltage and arc current measurements. From Figure 4.10 and 4.11 it is clear that the arc voltage and arc current simulated signals with measurements are well estimated. The values which are in the table 4.2 contain the best parameters values which fit to measurement oscillograms.

Table 4.2: The arc parameters which are predicted by the black box model

Parameter	Cassie	Schwarz1	Schwarz2
$\boldsymbol{\tau_c}$	$3.6208\mu s$	-	-
$\boldsymbol{v_o}$	$1239.4V$	-	-
$\boldsymbol{\tau_o}$	-	$3.9082\mu s$	$1.4927\mu s$
$\boldsymbol{a}$	-	0.19425	0.14878
$\boldsymbol{P_o}$	-	$509.75kV$	$27.10\mathrm{k}V$
$\boldsymbol{b}$	-	0.28921	0.00049999

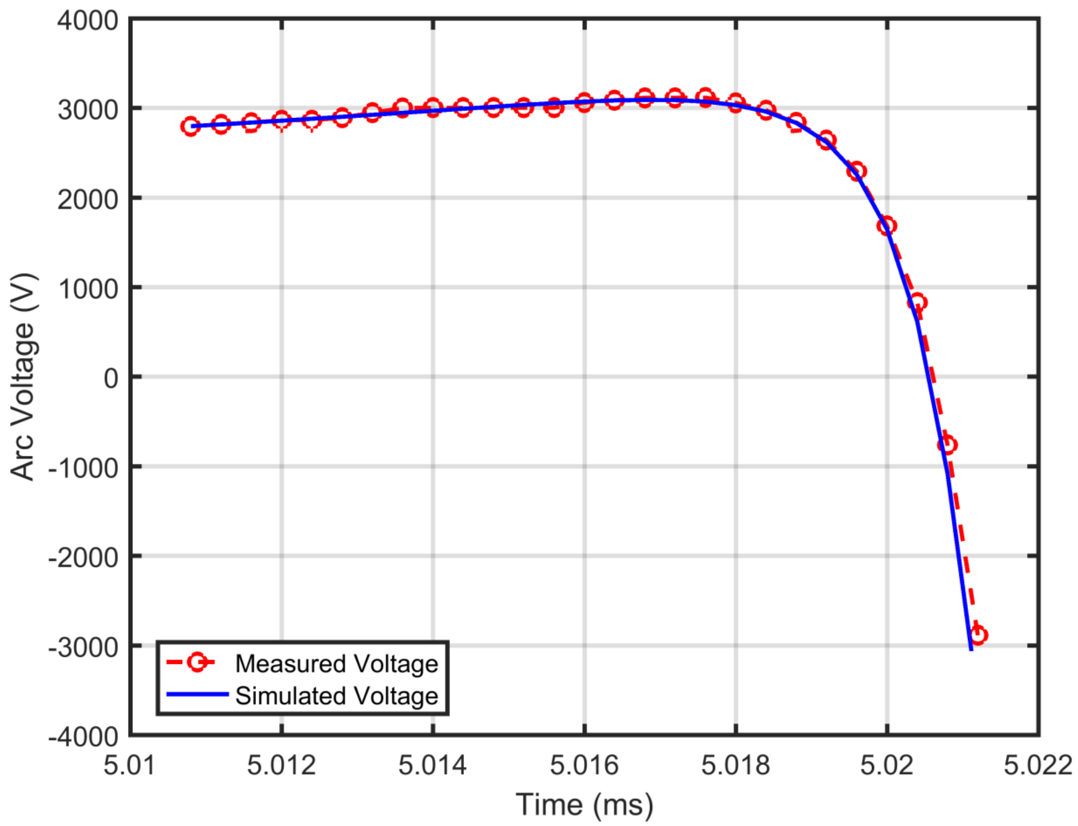


Figure 4.10: The arc voltage of the simulated circuit with the actual and fitted parameter

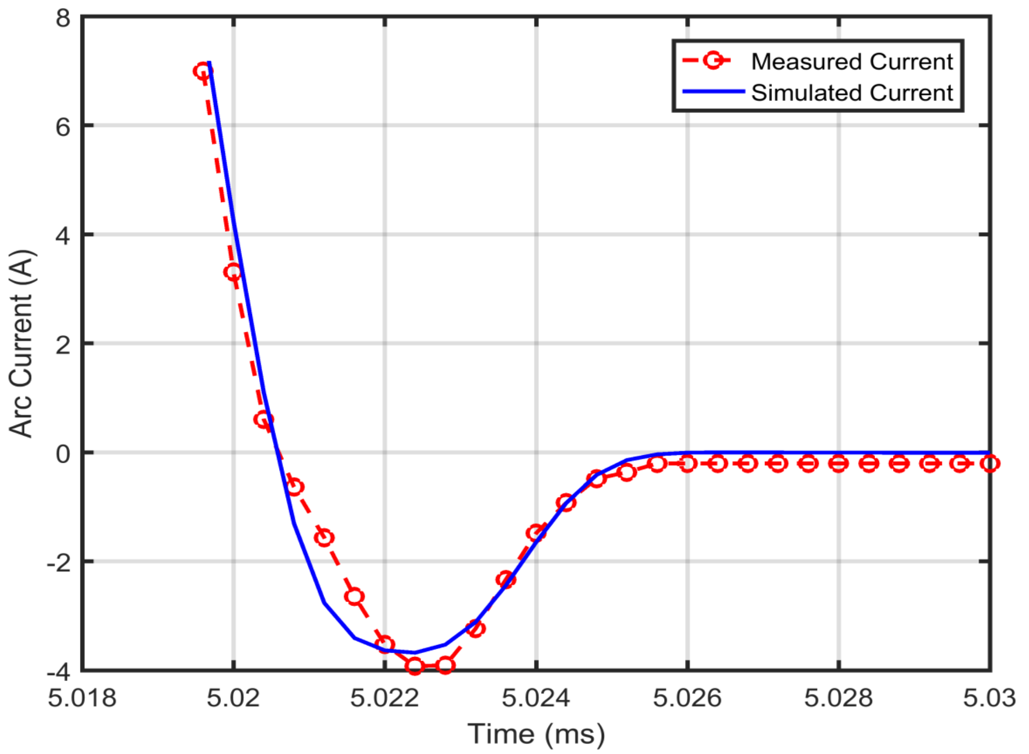


Figure 4.11: The arc current of the simulated circuit with the actual and fitted parameters

The Figure 4.12 illustrates the relationship of the arc voltages of the CO_2 circuit breaker in Figure 4.2 with the arc current in Figure 4.3. The values on the x-axis (the horizontal-axis) are logarithms. The time which is given in the Figure is used from the vicinity of the waveform at maximum value of the interrupting current to the area near the current-zero.

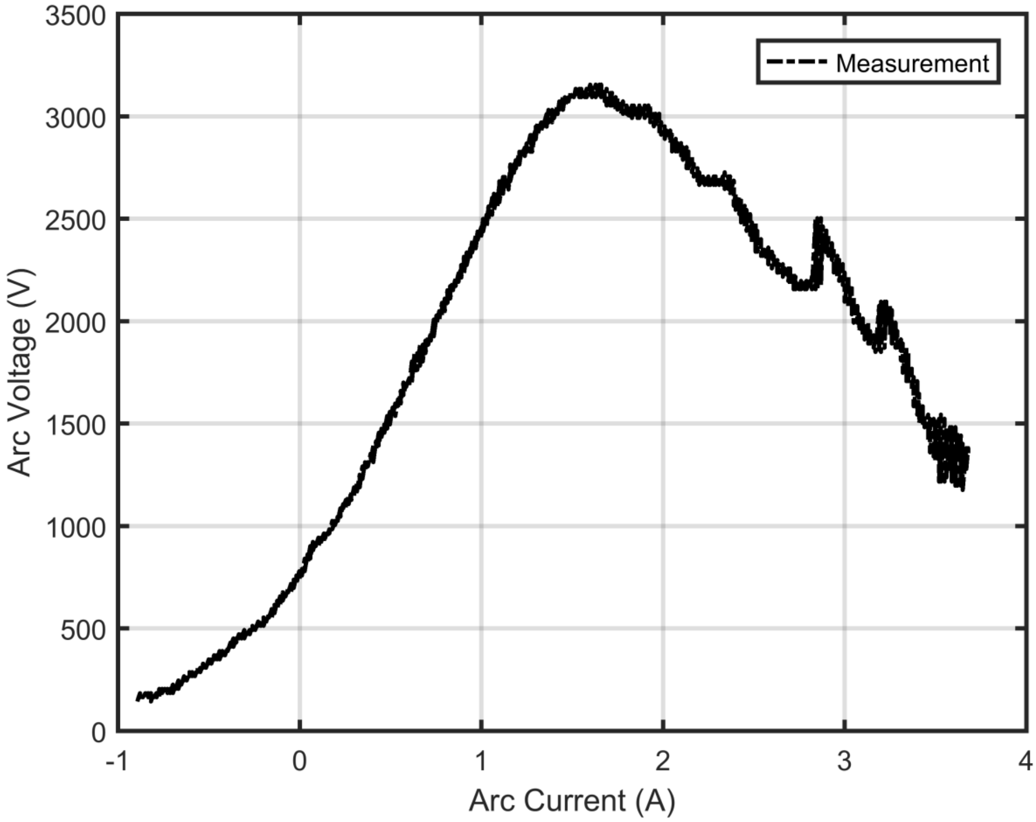


Figure 4.12: The measurement oscillogram of CO_2 arc voltage versus the arc current (Uchii et al., 2011)

The Figure 4.13 shows the arc voltage versus the arc current. It represents the interval from a point prior a few microseconds to the current zero. The horizontal axis is a logarithmic scale. In the interval of high current region the model one (Cassie model) is approximately 1.212kV, while during the interval of extinction peak by model two (Schwarz 1) the current reach approximately 100A and 10A or below by the third model (Schwarz 2).

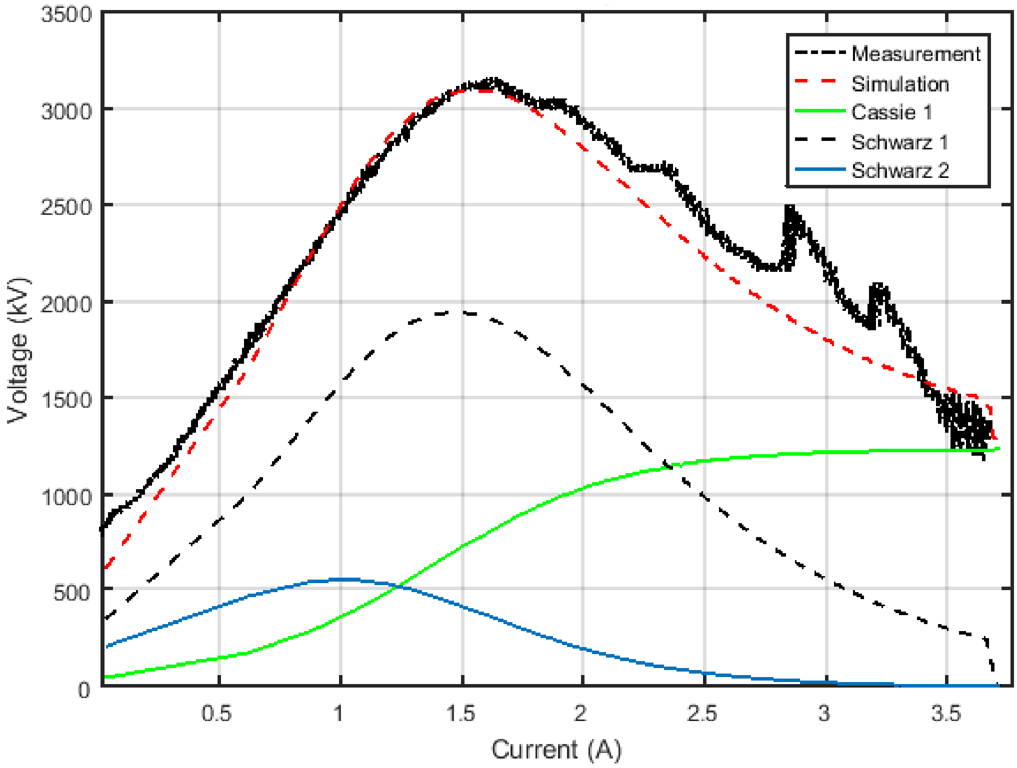


Figure 4.13: The arc volltage via arc current of the simulated circuit with the actual and fitted parameters

From Figure 4.14 and 4.15, it can be clear the *r-square* between the simulation and measurement waveforms of the proposed arc model by using the parameters data sets in Table 4.1 are approximately performing a good result since the *r-square* of the arc voltage and arc current are 0.9968 and 0.9756 respectively.

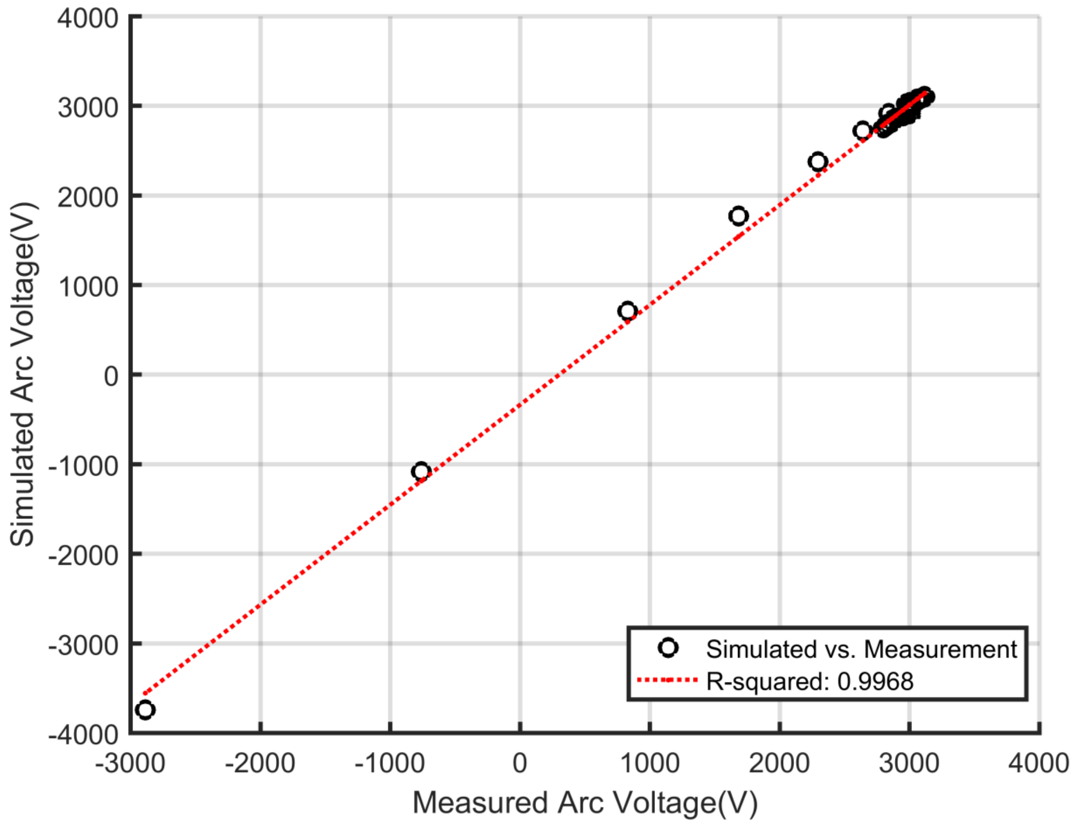


Figure 4.14: The *r-square* of the simulated and measured arc voltage of the proposed model

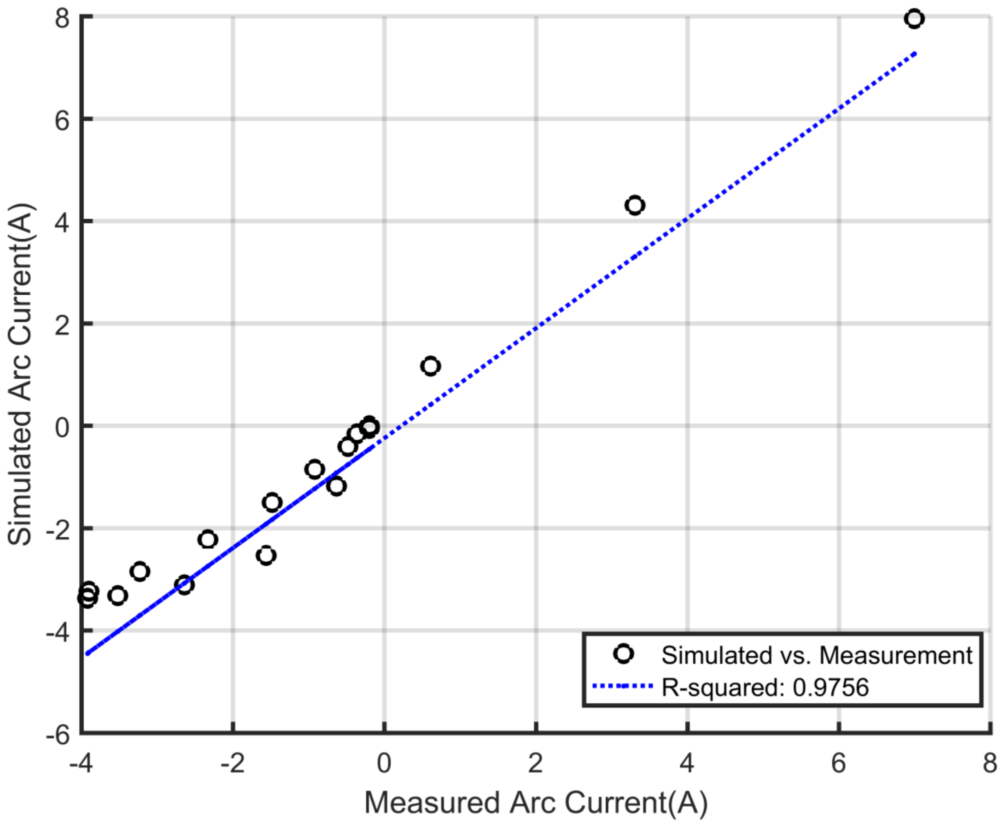


Figure 4.15: The *r-square* of the simulated and measured arc current of the proposed model

The Table 4.3 shows the data sets of the measurement, the proposed arc model, and the r-square. Each data set containing the voltage and current arcs, and the last columns used to demonstrate the r-square which is calculated between the measurement and the proposed arc model.

Table 4.3: Comparison of the voltage and current arcs from experimental data sets with the voltage and current arcs of the proposed model and including the relative error

Comparison of the Measurement Data Sets with the Proposed Model					
Measurement		**Model**		**Relative Error**	
v	**i**	**v**	**i**	**v**	**i**
[voltage]	**[ampere]**	**[voltage]**	**[ampere]**	**[voltage]**	**[ampere]**
2799.18	7.00	2754.77	7.96		
2818.27	3.31	2775.61	4.31		
2838.83	0.61	2797.13	1.17		
2866.70	-0.63	2819.37	-1.17		
2866.56	-1.56	2842.29	-2.53		
2893.57	-2.64	2865.93	-3.10		
2950.04	-3.52	2890.21	-3.31		
3001.47	-3.92	2914.61	-3.36		
3005.65	-3.90	2940.17	-3.23		
3005.65	-3.23	2965.74	-2.84		
3005.65	-2.33	2991.51	-2.22		
3007.20	-1.48	3016.96	-1.49		
3005.71	-0.92	3041.63	-0.85		
3061.54	-0.48	3064.83	-0.40	0.9968	0.9756
3089.00	-0.36	3084.99	-0.15		
3116.87	-0.20	3099.87	-0.05		
3116.86	-0.20	3107.84	-0.01		
3118.17	-0.20	3103.49	0.00		
3059.55	-0.20	3079.12	0.00		
2977.26	-0.20	3024.05	0.00		
2840.99	-0.20	2916.99	0.00		
2642.72	-0.20	2723.21	0.00		
2294.91	-0.20	2379.76	0.00		
1684.91	-0.20	1773.41	0.00		
830.64	-0.20	709.38	0.00		
-760.21	-0.20	-1080.46	0.00		
-2884.50	-0.20	-3740.26	0.00		

The performance after the implementation of the proposed model to the black box model are more precisely, this can be seen from Figure 4.16 and 4.17 where the *r-square* for arc voltage and arc current are 0.9992 and 0.9771 respectively. The parameter values in Table 4.2 are used to simulate the waveforms of Figure 4.16 and 4.17.

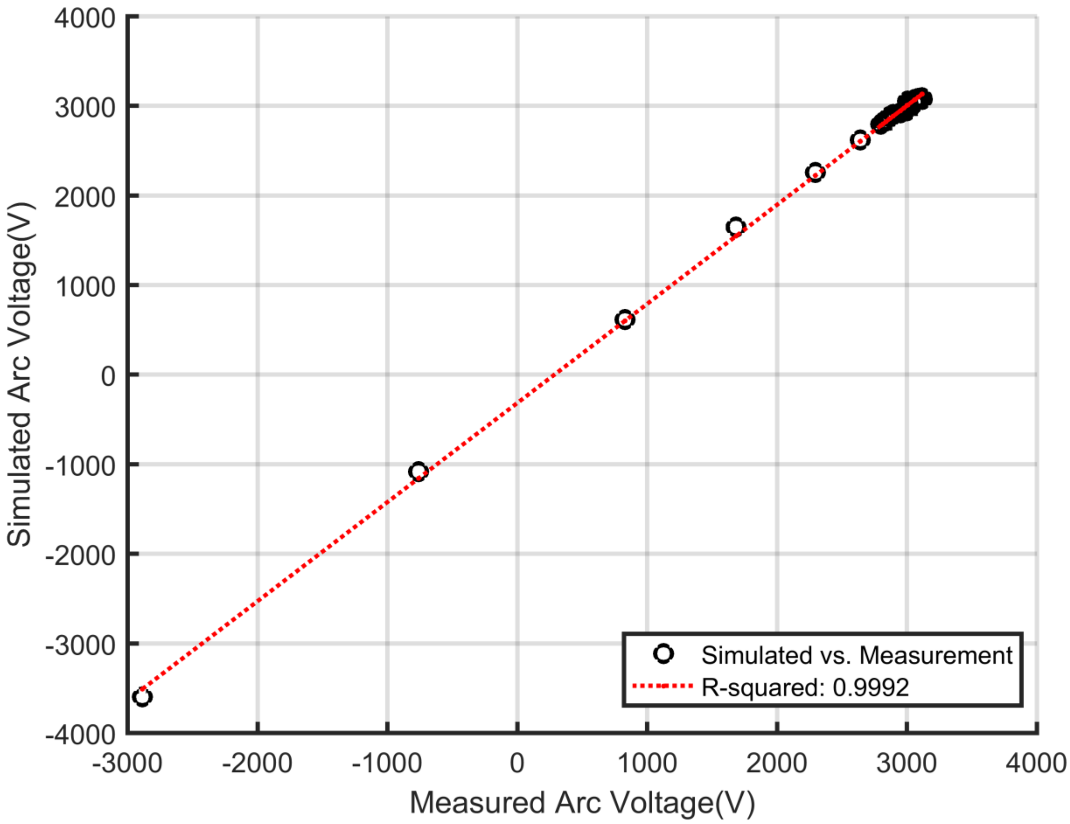


Figure 4.16: The *r-square* of the simulated and measured arc voltage of the black box model

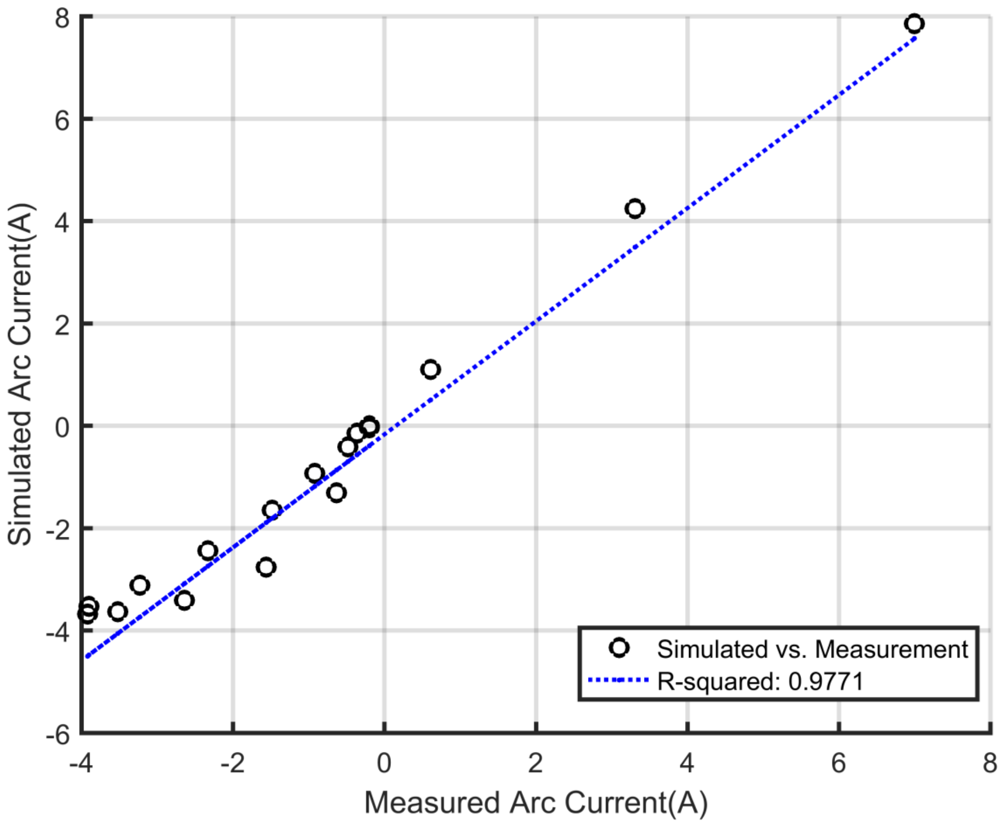


Figure 4.17: The *r-square* of the simulation and measurement arc current of the black box model

The Table 4.4 shows the data sets of the measurement, the black box model, and the *r-square*. Each data set containing the voltage and current arcs, and last columns used to demonstrate the *r-square* which is calculated between the measurement and the black box model.

Table 4.4: Comparison of the voltage and current arcs from experimental data sets with the arc voltage and arc current of the BB model and including the relative error

Comparison of the Measurement Data Sets with the Black Box Model					
Measurement		**Model**		**Relative Error**	
v [voltage]	**i [ampere]**	**v [voltage]**	**i [ampere]**	**v [voltage]**	**i [ampere]**
2799.18	7.00	2799.39	7.86		
2818.27	3.31	2819.36	4.25		
2838.83	0.61	2839.85	1.10		
2866.70	-0.63	2860.84	-1.30		
2866.56	-1.56	2882.36	-2.76		
2893.57	-2.64	2904.30	-3.40		
2950.04	-3.52	2926.22	-3.63		
3001.47	-3.92	2948.83	-3.67		
3005.65	-3.90	2971.53	-3.52		
3005.65	-3.23	2994.07	-3.11		
3005.65	-2.33	3016.14	-2.44		
3007.20	-1.48	3037.37	-1.65		
3005.71	-0.92	3057.05	-0.92		
3061.54	-0.48	3073.93	-0.41	0.9992	0.9771
3089.00	-0.36	3086.86	-0.14		
3116.87	-0.20	3093.06	-0.03		
3116.86	-0.20	3090.69	0.00		
3118.17	-0.20	3074.09	0.00		
3059.55	-0.20	3035.01	0.00		
2977.26	-0.20	2962.80	0.00		
2840.99	-0.20	2836.22	0.00		
2642.72	-0.20	2621.87	0.00		
2294.91	-0.20	2260.51	0.00		
1684.91	-0.20	1649.25	0.00		
830.64	-0.20	615.92	0.00		
-760.21	-0.20	-1079.27	0.00		
-2884.50	-0.20	-3594.33	0.00		

4.3 Numerical Analysis

The report of estimation progress illustrates the number of iteration, number of times the cost function has been estimated, and the cost functions value at the end of each iteration. The Figure 4.18 shows the performance of the estimated cost function since the cost function can be described as an error (the difference between the simulated model with measured output). The method which is used during the estimation was nonlinear least squares, this method minimizes the cost function by changing the parameter values. The Figure 4.18 illustrates the change of the parameters values during the iterations which called parameter trajectory (see appendix A). Also the data sets simulated the Figure 4.18 is shown in Table 4.5.

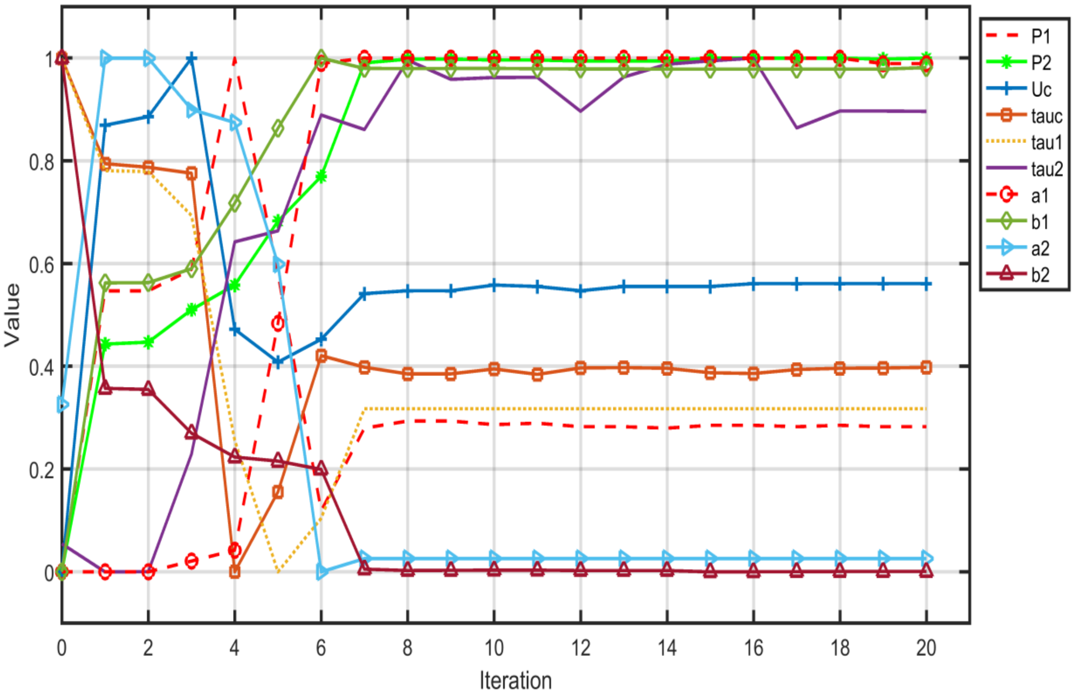


Figure 4.18: The estimated arc model prameters during the iteration

Table 4.5: The changes in parameters during the iteration

Parameter trajectory									
P_1	**P_2**	**U_c**	**t_{auc}**	**t_{au1}**	**t_{au2}**	**a_1**	**b_1**	**a_2**	**b_2**
[kW]	**[kW]**	**[kV]**	**[us]**	**[us]**	**[us]**	**-**	**-**	**-**	**-**
5.00E+05	2.50E+04	1.20	4.01	3.36	0.69	0.100	0.100	0.103	0.100
5.04E+05	2.52E+04	1.23	3.85	3.27	0.67	0.100	0.222	0.120	0.036
5.04E+05	2.52E+04	1.23	3.84	3.27	0.67	0.100	0.222	0.120	0.036
5.04E+05	2.53E+04	1.24	3.83	3.23	0.77	0.101	0.228	0.118	0.028
5.07E+05	2.53E+04	1.22	3.21	3.06	0.95	0.103	0.256	0.117	0.023
5.04E+05	2.54E+04	1.21	3.34	2.96	0.96	0.130	0.287	0.110	0.022
5.01E+05	2.54E+04	1.22	3.55	3.00	1.06	0.162	0.317	0.094	0.021
5.02E+05	2.55E+04	1.22	3.53	3.08	1.05	0.162	0.313	0.095	0.001
5.02E+05	2.55E+04	1.22	3.52	3.08	1.11	0.162	0.313	0.095	0.001
5.02E+05	2.55E+04	1.22	3.52	3.08	1.09	0.162	0.313	0.095	0.001
5.02E+05	2.55E+04	1.22	3.53	3.08	1.09	0.162	0.313	0.095	0.001
5.02E+05	2.55E+04	1.22	3.52	3.08	1.09	0.162	0.312	0.095	0.001
5.02E+05	2.55E+04	1.22	3.53	3.08	1.06	0.162	0.312	0.095	0.001
5.02E+05	2.55E+04	1.22	3.53	3.08	1.09	0.162	0.312	0.095	0.001
5.02E+05	2.55E+04	1.22	3.53	3.08	1.10	0.162	0.312	0.095	0.001
5.02E+05	2.55E+04	1.22	3.52	3.08	1.11	0.162	0.312	0.095	0.001
5.02E+05	2.55E+04	1.22	3.52	3.08	1.11	0.162	0.312	0.095	0.001
5.02E+05	2.55E+04	1.22	3.53	3.08	1.05	0.162	0.312	0.095	0.001
5.02E+05	2.55E+04	1.22	3.53	3.08	1.06	0.162	0.312	0.095	0.001
5.02E+05	2.55E+04	1.22	3.53	3.08	1.06	0.162	0.312	0.095	0.001
5.02E+05	2.55E+04	1.22	3.53	3.08	1.06	0.162	0.313	0.095	0.001

The parameters values were vary according to their usage in the arc model during the iteration. As these parameters of the arc model have different magnitude, a normalization method is used in order to plot them in one Figure. The equation below describes the normalization process which is used to arrange the parameters values between 0 and 1:

$$\phi_n = \frac{\phi - min(\phi)}{max(\phi) - min(\phi)} \tag{5.2}$$

where ϕ_n is the normalized arc parameter, the Table 4.6 is illustrating the minimum (min) and the maximum (max) values of the arc parameters.

Table 4.6: Limit values for parameters of the arc model

Parameter	Limit values	Units
	X-axis	
Iteration	0 - 20	-
	Y-axis	
P_1	500060 - 507280	W
	0 – 1	-
P_2	25001 - 25540	W
	0 – 1	-
U_c	1200 – 1236	V
	0 – 1	-
t_{auc}	3.21e-6 – 4.01e-6	Second
	0 – 1	-
t_{au1}	2.96e-6 – 3.36e-6	Second
	0 – 1	-
t_{au2}	3.3884e-7 – 1.11e-6	Second
	0 – 1	-
a_1	0.099927 – 0.16238	-
	0 – 1	-
b_1	0.10021 – 0.31691	-
	0 – 1	-
a_2	0.093989 – 0.12031	-
	0 – 1	-
b_2	0.000903 – 0.099917	-
	0 - 1	-

CHAPTER 5
CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

Several research activities being carried out in this thesis, in order to design a model and to simulate the performance of the electric arcs during current interruptions in HV circuit breakers. These efforts are performed in order to provide the community of HV circuit breaker researchers and developers with some tools for understanding such a phenomenon which might hopefully be helpful in the design of new equipment's. The engineers are concentrating in such a goal because of the electric arc created during the current interruption process is the primary element of a circuit breaker and also it represents out of control issue. The activity which has been carried out combined experimental data sets used to provide an empirical reference and a theoretical analysis used to give a description of the experimental confirmation. According to the knowledge taught, we have proposed a black box model to study the current zero measurement in straight forward manner and to investigate in the arc performance in a predictive manner.

The remarkable evidence recommending that by using the parameter estimation toolbox nonlinear least square approach might lead to better parameters estimation without filtering the measurement data sets, since by filtering the measurement data sets may cause to the loss of some data concerning arc parameters, which is affecting the parameter extraction procedure and also the prediction capability and model performance.

Through the simulation of the arc model, it could be clear that the simulation is helping in selecting the suitable value for each element of the experimental circuit since the simulated waveform shows the effect of each element whenever its capacity and value are varied. This might be an advantage to check and confirm each element before the actual test, in order to reduce the number of actual test and the cost as well.

5.2 Future Works

This thesis study presented here might lead to important topics for further investigation. Those topics can be described as follows:

- Firstly, the elements which are used to simulate synthetic circuit of the short line fault have to be calculated properly in order to ensure all the results are simulated accurately and similar to the experiment test.
- Secondly, all the elements that appear during the experiment test should be included to synthetic circuit of the model.
- The results which are obtained from the synthetic circuit can be confirmed by the standard calculation such as IEC, British Standard (BS), and Institute of Electrical and Electronic (IEEE).
- This thesis can be implemented by additional investigations in system identification approach in order to find a better representation of the electric arc circuit breaker simulations.
- The improvement of this thesis can be also achieved by implementing the model to minimize the running time for parameter extraction.

REFERENCES

Browne, T. E. (1984). *Circuit interruption: Theory and techniques*. New York: M. Dekker.

Christophorou, L., & Olthoff, J. (2013). *Gaseous Dielectrics VIII*. Springer Verlag.

Christophorou, L.G., Olthoff, J.K., & Vassliliou, P. (2004). *Gasous Dielectric X*. Boston, MA: Springer US.

Daniel, J. J. (1999). *Introduction to Atmospheric Chemistry* (Doctoral dissertation, Princeton University Press).

Flurscheim, C. H. (1985). *Power circuit breaker theory and design*. England: Peter Peregrnus Ltd.

Giménez, G. W., & Gómez, T. J. (1999). *Modelización de interruptores eléctricos de potencia* (Doctoral dissertation, Universitat Politécnica de Catalunya).

Hosseini, S., Eshagh, E., & Edalatian, A. (2013). The Modeling of Electric Arc in High Voltage Circuit Breakers with Use of Schavemaker Model and Negative Feedback. *International journal of science and engineering investigations*, *2*(16). 112-120.

Jaeger, H. M., & Nagel, S. R. (1996). Granular solids, liquids, and gases. *Reviews of modern physics*, *68*, 1259-1273.

Jørstad, J. S. (2012). *Effect of Barriers in Air Insulated Rod-Plane Gaps* (Master's thesis, Norwegian University of Science and Technology, Norwegian).

Kapetanovic, M. (2011). *High voltage circuit breaker*. Sarajevo: JTP Creative Marketing of KEMA – JTP Branding & Marketing.

Kasuya, H., Katagiri, H., Kawamura, Y., Saruhashi, D., Nakamura, Y., Mizoguchi, H., & Yanabu, S. (2009). Measurement of decomposed gas density of CF3I-CO2 mixture. *Proceedings of the 16th International Symposium on High Voltage Engineering (Vol. 4, pp. C4-41).* SAIEE, Innes House, Johannesburg.

Kuffel, E., Zaengl, W. S., & Kuffel, J. (2000). *High voltage engineering: Fundamentals*. Oxford: Newnes.

Maller, V.N., & Naidu, M.S. (1981). *Advance in high voltage insulation and arc interruption in SF6 and vacuum*. Pergamon press.

MathWorks. (2017). *MATLAB: optimization toolbox: user's guide version 1.5.* MathWorks. Inc.

Mayr, O. (1943). Beiträge zur Theorie des statischen und des dynamischen Lichtbogens. *Archiv für Elektrotechnik, 37*(12), 588-608.

Naidu, M. S., & Kamaraju, V. (2013). *High voltage engineering*. New Delhi: McGraw-Hill Education (India) Pte Ltd.

Nakanishi, K. (1991). *Switching phenomena in high-voltage circuit breakers*. New York: M. Dekker.

Nelles, O. (2011). *Nonlinear system identification: From classical approaches to neural networks and fuzzy models*. Berlin: Springer.

Nguyen, N., Denat, A., Bonifaci, N., Lesaint, O., & Hassanzadeh, M. (2010). Impulse partial discharges and breakdown of CF3I in highly non-uniform field. *In Proc. of XVIII Int'l Conf. on Gas Discharge and Their Applications*, 330-333.

Ong, & C.-M. (1998). *Dynamic simulation of electric machinery: Using MATLAB/SIMULINK*. Upper Saddle River, NJ: Prentice Hall.

Orama-Exclusa, L. R., & Rodriguez-Medina, B. (2003). Numerical arc model parameter extraction for SF6 circuit breaker simulations. In *In International Conference on Power Systems Transients-IPST*.(pp. 250-255). USA.

Phaniraj, V., & Phadke, A. (1988). Modelling of circuit breakers in the Electromagnetic Transients Program. *IEEE Transactions on Power Systems, 3*(2), 799-805.

Phontusa, S., & Chotigo, S. (2008). The proposed humidity correction factor of positive DC breakdown voltage of sphere-sphere gap At h/δ Lower than 13 g/m^3. *2008 IEEE 2nd International Power and Energy Conference*, 1524-1527.

Ramirez, C., & Calva, P. (2001). Simulation of electric power circuit breakers in the EMTP incorporating electric arc models: application to reactor bank switching and short line fault. *Annual Report Conference on Electrical Insulation and Dielectric Phenomena (pp. 192)*. IEEE.

Schavemaker, P. (2011). *Arc Model Blockset for use with MATLAB Simulink and Power System: Blockset-User's Guide*.

Schavemaker, P. H. (2002). *Digital testing of high-voltage SF6 circuit breakers*.

Schavemaker, P., & Van der Slui, L. (2000). An improved Mayr-type arc model based on current-zero measurements [circuit breakers]. *IEEE Transactions on Power Delivery*, *15*(2), 580-584.

Schwarz, J. (1971). Dynamisches Verhalten eines gasbeblasenen, turbulenzbestimmten Schaltlichtbogens. *ETZ-A*, *93*, 389-391.

Scofield, J. H. (2013). Efficacy of LEED-certification in reducing energy consumption and greenhouse gas emission for large New York City office buildings. *Energy and Buildings*, *67*, 517-524.

Sergio, R. P. (2012). *Modelización de los sistemas de electrificación ferroviaria, en corriente alterna y continua, con sistemas recuperadores de energía para el estudio de la eficiencia energética* (Doctoral dissertation, Universitat Politècnica de Catalunya).

Sjöberg, J., Zhang, Q., Ljung, L., Benveniste, A., Delyon, B., Glorennec, P.,Juditsky, A. (1995). Nonlinear black-box modeling in system identification: a unified overview. *Automatica*, *31*(12), 1691-1724.

Sluis, & L. (2002). *Transients in power systems*. Chichester. Wiley.

Smeets, R., & Kertész, V. (2000). Evaluation of high-voltage circuit breaker performance with a new validated arc model. *IEE Proceedings - Generation, Transmission and Distribution*, *147*(2), 121.

St-Jean, G., & Wang, R. (1983). Equivalence Between Direct and Synthetic Short-Circuit Interruption Tests on HV Circuit Breakers. *IEEE Transactions on Power Apparatus and Systems*, *PAS-102*(7), 2216-2223.

Thuries, E., Van Doan, P., Dayet, J., & Joyeux-Bouillon, B. (1986). Synthetic Testing Method for Generator Circuit Breakers. *IEEE Transactions on Power Delivery*, *1*(1), 179-184.

Thuries, E., Van Doan, P., Dayet, J., & Joyeux-Bouillon, B. (1986). Synthetic Testing Method for Generator Circuit Breakers. *IEEE Transactions on Power Delivery*, *1*(1), 179-184.

Urquijo, J. D., Juárez, A. M., Basurto, E., & Hernández-Ávila, J. L. (2007). Electron impact ionization and attachment, drift velocities and longitudinal diffusion in CF 3 I and CF 3 I–N 2 mixtures. *Journal of Physics D: Applied Physics*, *40*(7), 2205-2209.

Zaima, E., Okabe, S., Nishiwaki, S., Ishikawa, M., Suzuki, K., & Toda, H. (1993). Application of dynamic arc equations to high frequency arc extinctions in SF/sub 6/ gas circuit breakers. *IEEE Transactions on Power Delivery*, *8*(3), 1199-1205.

APPENDIX A
NUMERICAL ANALYSIS

The report of estimation progress illustrates the number of iteration, number of times the cost function has been estimated, and the cost functions value at the end of each iteration. The figures below illustrate arc parameters during estimation process.

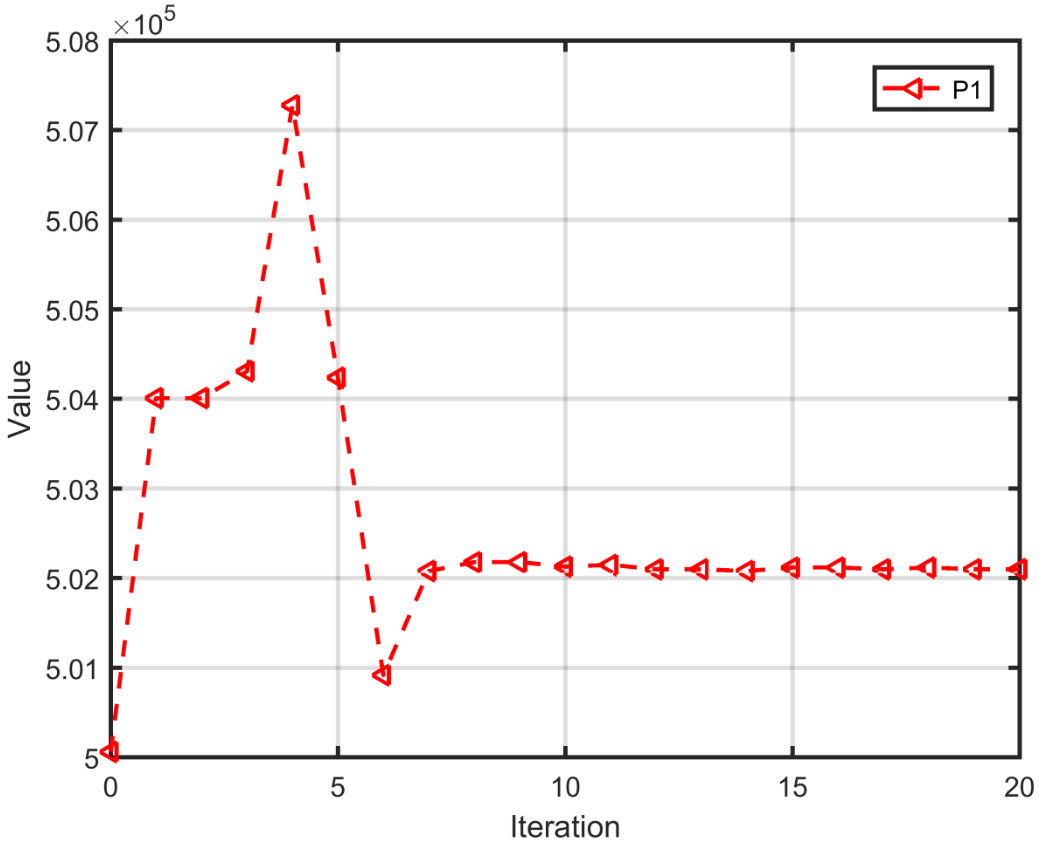


Figure A.1: The power losses P_1 of Schwarz 1 model during the iteration

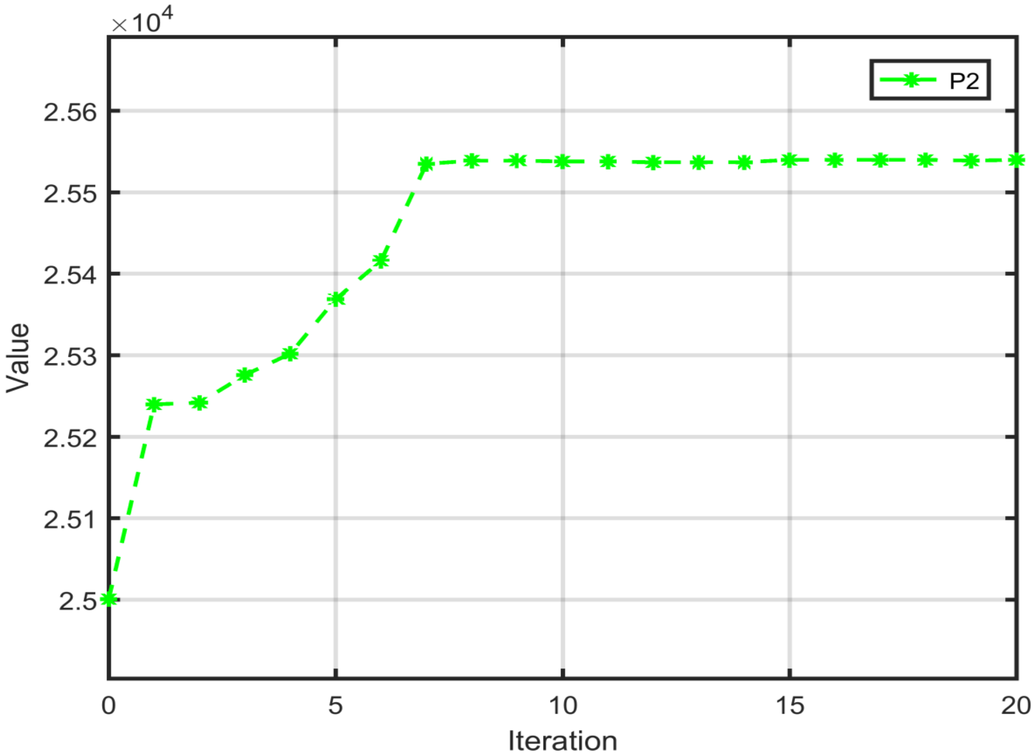


Figure A.2: The power losses P_2 of Schwarz 2 model during the iteration

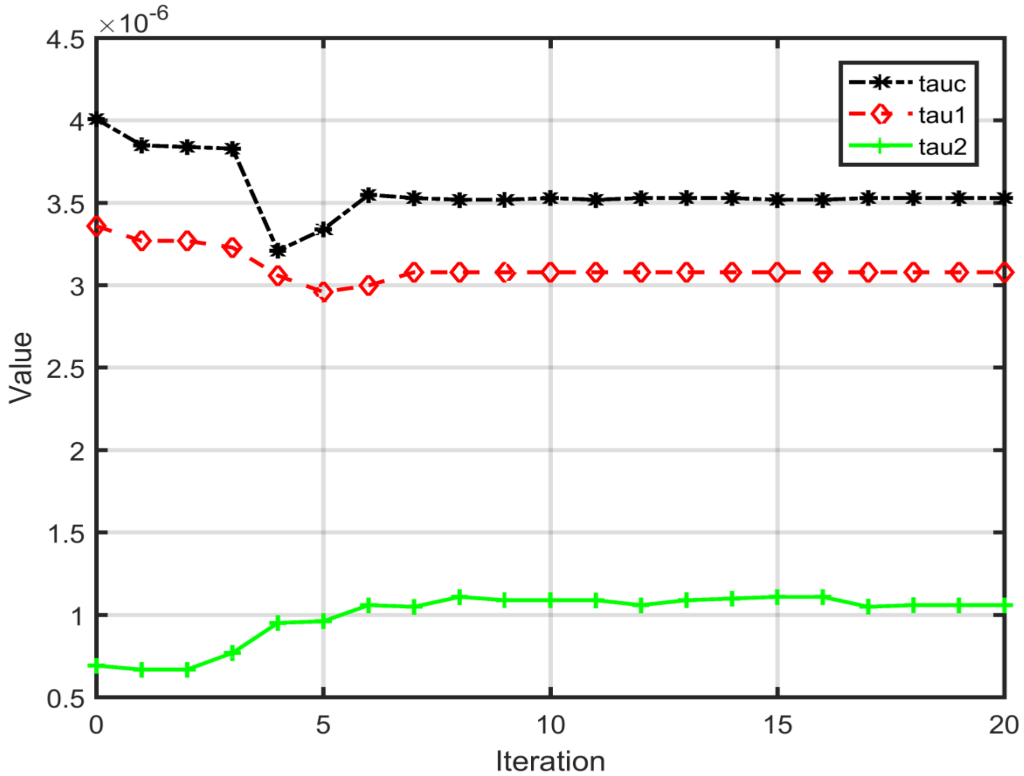


Figure A.3: The time constant of Cassie, Schwarz 1,Schwarz 2 during the iteration

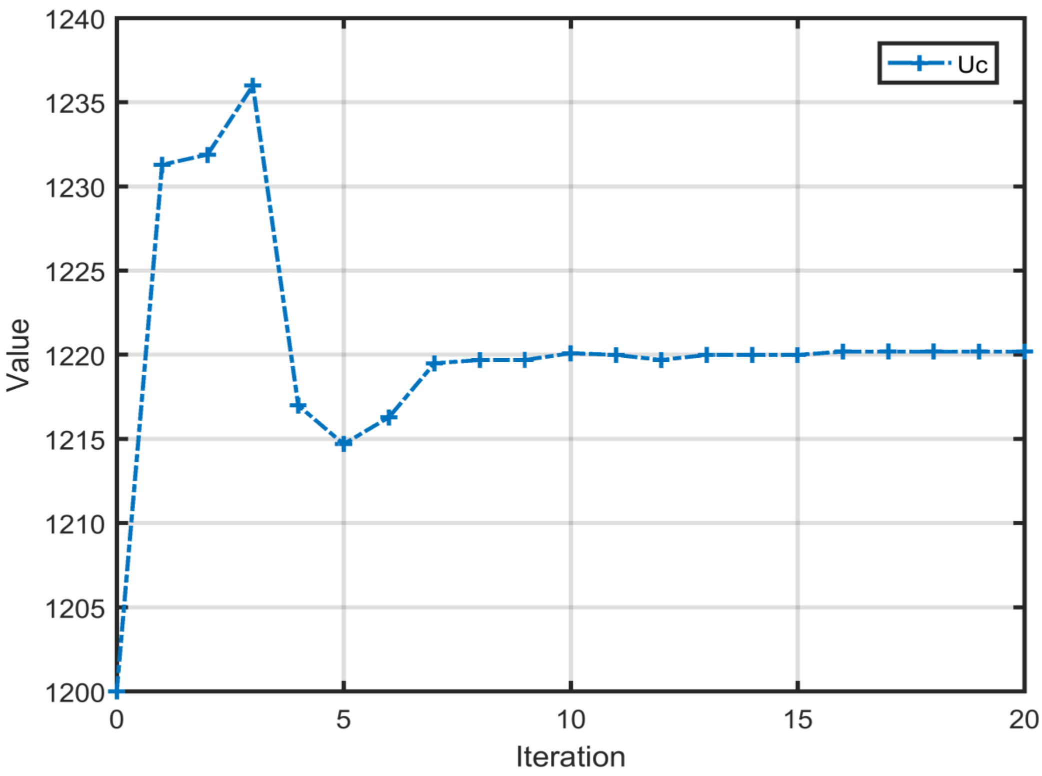


Figure A.4: The Cassie of Cassie, Schwarz 1,Schwarz 2 during the iteration

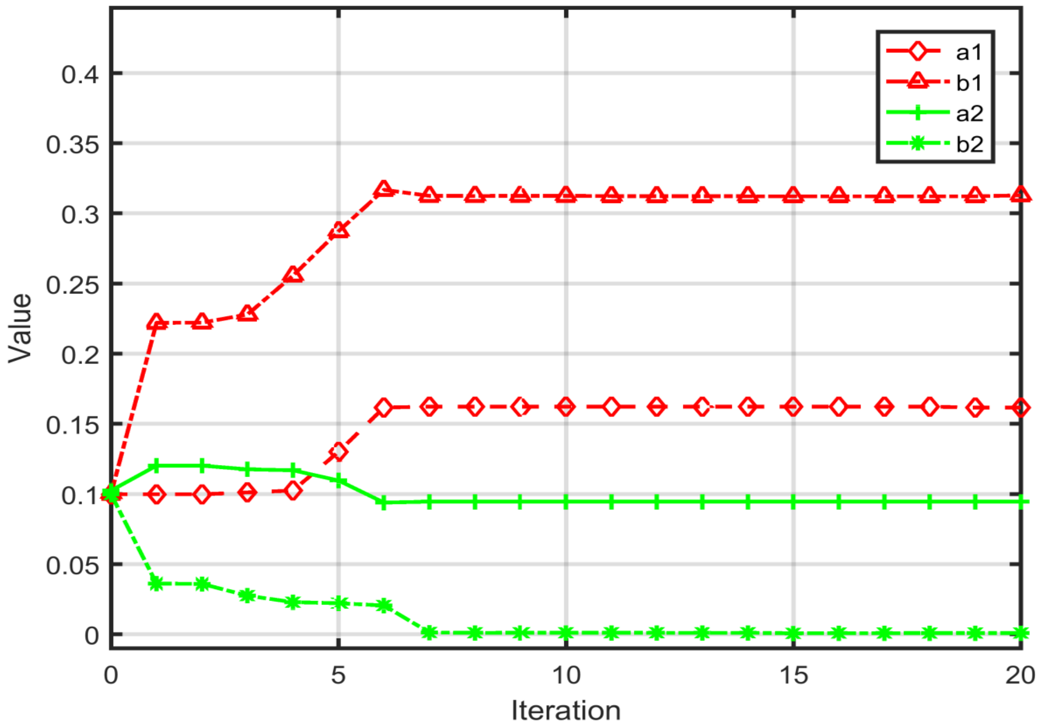


Figure A.5: The Schwarz 1 and Schwarz 2 parameters during the iteration

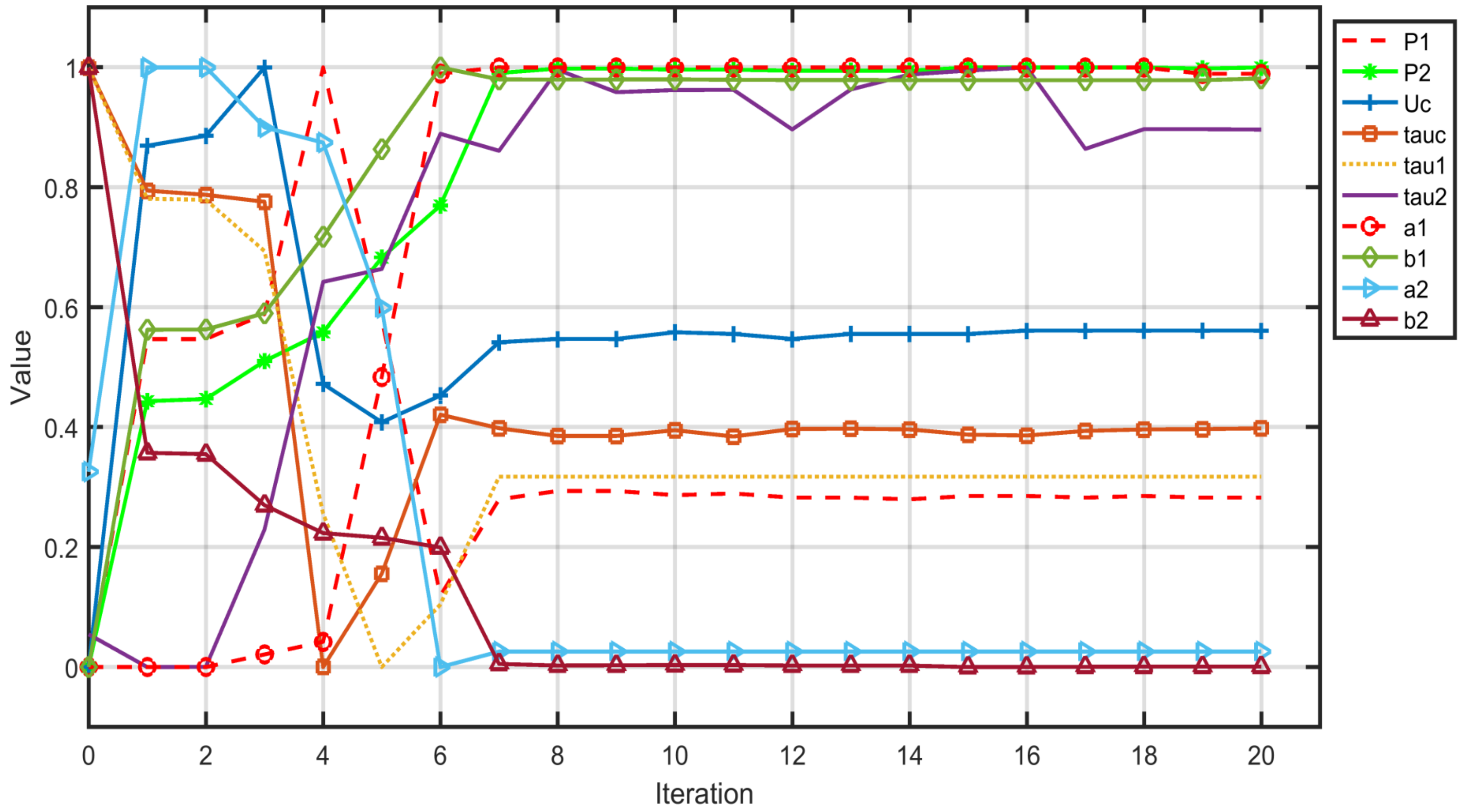


Figure A.6: The normalized values of arc parameters during the iteration