__Original Research Article__

A study of DC switching electric arc characteristics for low voltages

ABSTRACT

Aims: The purpose of this paper is to investigate the DC electric arc characteristics for low voltages. And explore the relationship among arc time, arc voltage and arc current.

Study design: The experimental setup mainly consisted of a switch contact pair, variable resistive load, and a variable power supply. An oscilloscope was used to collect the voltage variations of the switch and the load. The voltage variation data were used to do further analysis.

Place and Duration of Study: Department of Physics and Electronics, University Of Kelaniya, Sri Lanka between September 2021 and May 2022.

Methodology: Voltage variations between the contact pair and the load voltage were measured using an oscilloscope for both switching on and off operations. The experiment was performed for four voltage levels; 60 VDC, 80 VDC, 100 VDC, and 120 VDC. For each voltage level, four load conditions were tested. Therein, a total of 16 different conditions were tested. Five tests were done for each condition. The average values were taken for analysis.

Conclusion: When the switch contacts start to separate, the arc voltage must reach the arc starting voltage to form an arc. Moreover, according to the supply voltage and current, there is always a maximum voltage value that arc can reach, which is less than the supply voltage (arc ending voltage). After the arc was formed in DC systems, the arc voltage variation with time can be modeled using the trigonometry tan function.

Keywords: [Direct current, electric arc, Mathematical modeling, Mathematical modelling]

1. INTRODUCTION

Comparing Direct current (DC) and alternating current (AC) power systems, it is evident that DC significantly outperforms AC in terms of efficiency, dependability, and simplicity. In recent years, numerous DC power systems, such as photovoltaic power generation, fuel cells, and electric vehicles, have gained popularity. They have been adopted in aircraft, ships, urban transit systems, home micro grids, and nuclear power plants [1]. It is well-known that DC is more difficult to be interrupted because there is no natural zero-crossing point, as found in an AC system. The potential for DC arc flash events has increased with the broader application of DC power systems. . Under such conditions, DC switching must be considered a necessary technical element for safely interrupting current in DC power systems.

Commonly, it is assumed that the transition between states of a mechanical switch (on to off and vice versa) occurs instantly. Nonetheless, a closer inspection reveals that the switch does not respond instantly and exhibits a nonlinear behavior of voltage with time between the contacts during switching operations. Primarily, the "on-to-off" operation of a switch heavily tends to generate an electric arc between its dielectric regions [2].

The switching electric arc discharge is a critical problem in DC power systems. For conventional mechanical switches, longer-duration arcs cause higher degradation and reduce the lifetime of the devices. Arc affects contact erosion and resistance, resulting in increased power loss. Various methods are used to extinguish DC arc discharge, such as air breaks, magnetic blowouts, arc shunts, etc. These methods are practically effective and have been used for many years [3].

After a discharge in the extinguishing gas, a plasma channel is formed between the two electrodes to form the electric arc. When using a switch in a circuit, the electric arc is primarily observed when the current-conducting contacts are separated (to turn off the circuit) and is difficult to observe when the contacts are brought together (to turn on the circuit). When a current flows through switched-on circuit contacts and the contacts begin to move apart, the magnetic energy stored in the circuit's inductive components prevents the current from being interrupted and forces it to continue [4]

Better switching operation requires that an electric switch be capable of rapidly switching the circuit's current. In opening contact operations, the contact mass is transferred from the anode to the cathode due to the longer duration of the arc. Thus, an oxidized metal film is deposited on the contact surface, which causes the contact resistance to increase.

Other research has been conducted on how the arc behaves during switching, arc characteristics such as the arc existing time and arc column motion, and modelling arc incidents in AC systems [5] [6] [7]. However, there were few studies on modelling and testing DC electric arcs. Multiple standard DC arc models are used to estimate the DC arc in power systems based on reported experimental and theoretical work.

These can be classified primarily into three categories.

1. The mathematical representation of the physical phenomena in an electric arc is the basis for physics-based models. These models describe the arc by combining electromagnetism, fluid dynamics, and thermodynamics with complex differential equations.

2. To capture the arc effects on an electric circuit in terms of the arc's voltage-current relationship or apparent impedance, equivalent circuit models are utilized.

3. On the basis of experimental data, heuristic models are used to describe arc phenomena, frequently combining a mathematical model with additional ad hoc parameters or equations to improve correlation with observations.

Numerous variables affect arc behavior, including voltage and current, contact material, separation speed etc. Due to the vast number of variable dependencies, it is exceedingly challenging to develop an exact mathematical model for the electric arc.

Multiple mathematical "black box" models and physical models have been proposed for the "AC breaking arc." A black-box model that corresponds to the "DC breaking arc" has not yet been proposed [8-12]. In [10], a heuristic model approximating the hyperbolic tangent function is proposed. This model, however, does not account for the relatively slow voltage increase in the arc elongation region (Figure 4) and the rapid increase in the arc termination region.

In accordance with the heuristic approach, this paper contributes to the description of an electric arc and, consequently, to the modelling of a series fault for transient simulations of DC systems As a first step, DC breaking experiments were conducted to obtain the arc voltage during contact breakage; the DC breaking process was then analyzed to determine the arc parameters. Analyzing the relationship between source voltage and current and arc parameters, two variables—supply voltage and supply current—are used to construct an arc model. The trigonometric tangent function was used to develop the arc model while avoiding the aforementioned problems. And the remaining portion of this paper compares the developed arc model to the experimental results.

This study focuses primarily on DC power interruption at source voltages less than 120 volts and currents less than 15 A, at which many appliance switches operate..

2. EXPERIMENTAL DETAILS

The primary components of the experimental setup were a pair of switch contacts, a variable resistive load, and a variable power supply as shown in the figure 1. Using a servo motor mechanism, the contact pair can be separated and contacted while the movement speed remains constant. The resistance to load is variable. Using an oscilloscope, the voltage variations of the switch and the load were measured.

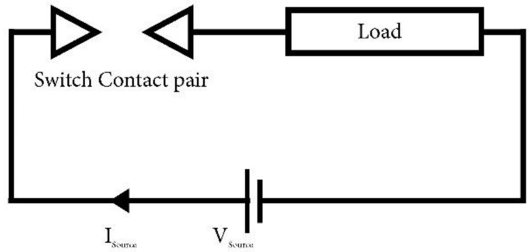

Fig. 1. Simple representation of the experimental setup.

The experiments began when the contacts were separated from one another. Then, the contacts gradually moved closer to one another until they touched. It was the "switch ON" action of a mechanical switch that completed the circuit and powered up the load. The contacts were then moved away from one another to imitate the “switch OFF” action of a mechanical switch. Using an oscilloscope, voltage variations between the contact pair (Arc Voltage: V_{Arc}) and the load voltage (V_{Load}) were measured during both switching on and off.

Four voltage levels were utilized for the experiment: 60 VDC, 80 VDC, 100 VDC, and 120 VDC. Four load conditions were examined for each voltage level. Therein, sixteen distinct conditions were evaluated. There were five tests conducted for each condition. The average values were selected for examination.

3. RESULTS AND DISCUSSION

When the contacts touched (the circuit is turning on), no arc was observed (Figure 2). The action of turning on was completed in a few milliseconds (20 ms). When the current-conducting contacts were separated (turned off), an electric arc was observed. Figures 2 and 3 depict the arc voltage during switching on and off.

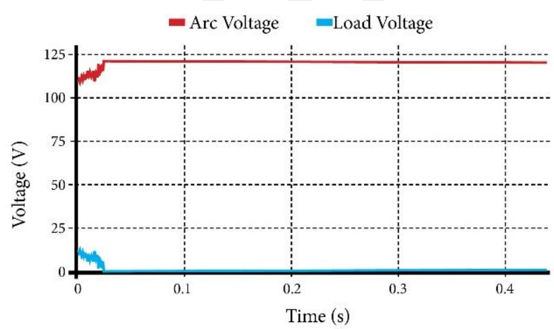

Fig. 2. Time vs Arc voltage and Load voltage (During the contact open to close switch action).

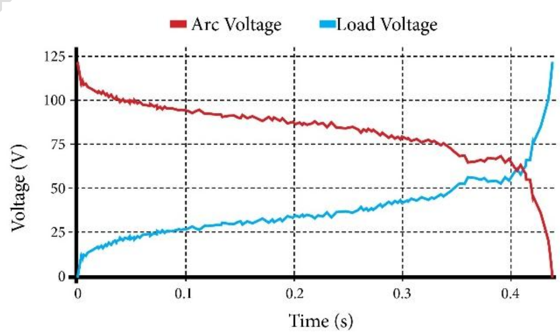

Fig. 3. Time vs Arc voltage and Load voltage (During the contact close to open switch action at 120 VDC, 14.5 A).

As depicted in Figure 3, the arc begins at approximately t = 0.002 s and ends at approximately t = 0.42 s. In this graph, three distinct regions have been identified. Initially, the arc voltage rose rapidly for approximately t = 0.01 s. At this point, the arc voltage was the threshold voltage for arc initiation (arc starting voltage, V_1. After the arc began, the arc voltage increased linearly for approximately 0.4 seconds. After reaching its maximum voltage, the arc began to extinguish. Within 0.04 seconds, the arc disappeared entirely, and the voltage returned to the source voltage. Figure 4 depicts a simplification of the graph shown in Figure 3

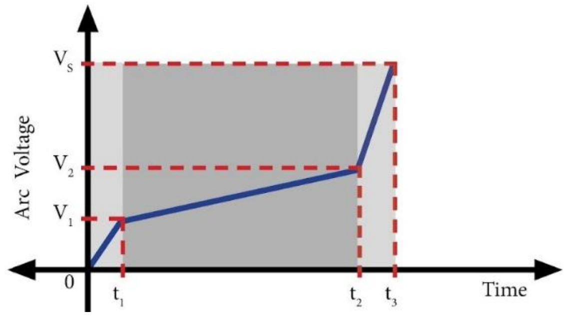

Fig. 4. Simplified graph, time vs. arc voltage (During the contacts close to open switching).

The arc voltage increases with time up to a certain level, but it has a maximum voltage that it can reach at all times. This value is less than the source voltage, and if the voltage between the contacts surpasses this threshold, the arc quickly dissipates. The arc voltage curve regions can be defined as follows:

- $t = 0$ to $t = t_1$: Arc initiation region
- $t = t_1$ to $t = t_2$: Arc elongation region
- $t = t_2$ to $t = t_3$: Arc termination region

The arc's initiation and termination regions cannot be avoided. The designers of DC switches must prioritize the arc elongation region (t_1 to t_2), where the arc is stable, and attempt to minimize this region as much as possible.

Using the gradients of the "arc voltage-time" graph (Figure 3), the t_1, t_2, and t_3 points were determined. Figure 5 depicts three prominent peaks that correspond to the times t_1, t_2, and t_3.

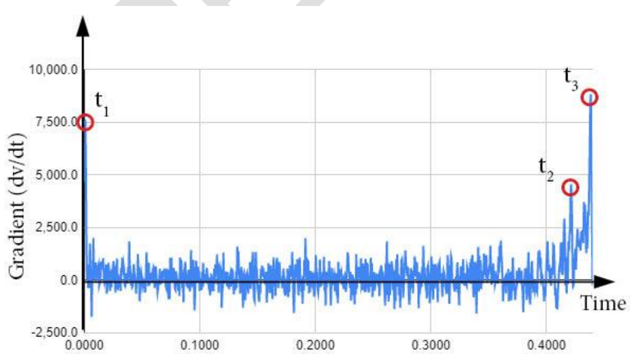

Fig. 5. Time vs the gradient of the voltage (During the contacts close to open switching).

A nonlinear tangent function can represent the behavior of arc voltage with time at the switch on action (Figure 3). This decomposition is given in Figure 6 and Equation 1.

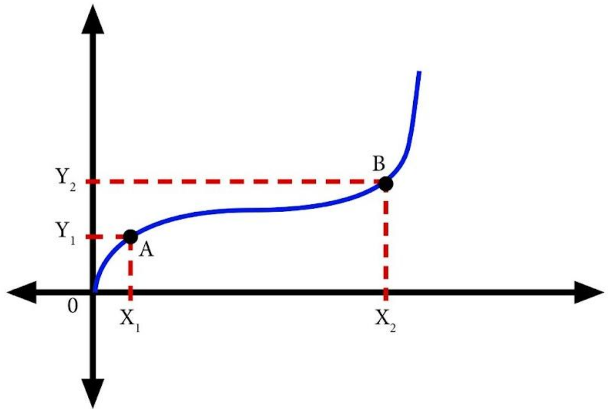

Fig. 6. Graph of the tangent function.

Here point A and point B are selected as the start point and end point of the "arc elongation region".

$$Y = a + bTan\left[\frac{(X-c)}{d}\right]\ ;\ \{0 \le x \le \ Arc\ time\} \quad (1)$$

Where a,b,d,c are constant;

$a = (Y_2+Y_1)/2$
$b \propto (Y_2+Y_1)$
$c = (X_2+X_1)/2$
$d = (X_2\text{-}X_1)/2$

At the time of switching on action starts (t=0) , the arc voltage is zero (V_{arc} = 0). So

$$0 = a + bTan\left[\frac{(0-c)}{d}\right]$$
$$a = bTan\left(\frac{c}{d}\right) \quad (2)$$

Then arc voltage can be written as

$$V_{arc} \ = b\left\{Tan\left(\frac{c}{d}\right) \ + \ Tan\left[\frac{(t-c)}{d}\right]\right\} \quad ;\ \{0 \le t \le \ Arc\ time\} \quad (3)$$

The graph for the arc voltage according to the equation 3 is shown in figure7.

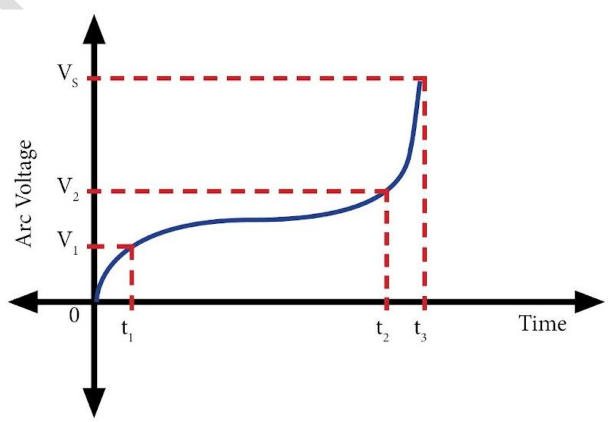

Fig. 7. Time vs arc voltage graph represented by the nonlinear tangent function.

Since,

$b \propto (X_2 - X_1)$

for the data, the coefficient of proportionality was found to be $\frac{1}{13.12}$

So $\quad b = \frac{(X2 - X1)}{13.12}$

Then the Equation can be updated as follows

$$V_{arc} = \frac{(V_2 - V_1)}{13.12}\left\{Tan\left(\frac{t_2 + t_1}{t_2 - t_1}\right) + Tan\left[\frac{2T - (t_2 + t_1)}{t_2 - t_1}\right]\right\} \quad ; \ \{0 \leq T \leq \ Arc\ time\} \qquad (4)$$

Where;

V_{arc} = Arc Voltage (volts); T = Time ; t_1 = Arc starting time; t_2 = Arc ending time; V_1 = Arc starting voltage; V_2 = Arc ending voltage

3.1 A. Behavior of arc starting voltage V_1, arc ending voltage V_2, arc starting time t_1, and ending time t_2 with supply voltage V_s and supply current I_s

The supply voltage (Vs) and supply current (Is) were utilized to construct models for V1, V2, (t2 + t1), and (t2 + t1) using the "Linear regression" technique. Consequently, the subsequent models were derived.

$$V_1 = 0.0001(V_s) + 0.0032\ (I_s) + 11.7243 \qquad (5)$$

$$V_2 = 0.9081(V_s) + 1.0900\ (I_s) - 16.0022 \qquad (6)$$

$$(t_2 - t_1) = 0.0039(V_S) + 0.0158\ (I_S) - 0.2426 \qquad (7)$$

$$(t_2 + t_1) = 0.0038(V_s) + 0.0158\ (I_s) - 0.2336 \qquad (8)$$

The following conclusions can be drawn by analyzing results of linear regression models.

1. The arc starting voltage (V_1) is independent of the supply voltage and current (V_s, I_s).

2.The arc ending voltage is proportional to both the supply voltage and supply current.

3.The time between the arc's beginning and end (t_2 - t_1) is proportional to both the supply voltage (V_s) and supply current (I_s).

4.Sum of the arc starting time and arc ending time (t_2+t_1) is proportional to both the supply voltage (V_s) and supply current (I_s).

As the coefficients of Vs and Is in Equation 5 are negligible, the preceding conclusion 1 is justifiable. Consequently, it is plausible to assert that the arc starting voltage is constant. Moreover, another study has reached the same conclusion [9].

The r_2 values in the Equations 6,7,8 are respectively 0.98, 0.97, 0.98 which validates the aforementioned conclusions 2,3 and 4. Using the supply voltage (V_s) and supply current (I_s), the V_1, V_2, (t_2 + t_1), and (t_2 + t_1) values can be successfully calculated.

For further calculations, the following simplifications are made to Equations 5, 6, 7, and 8.

K, P, Q, R, A1, B_1, C_1, A_2, B_2, and C_2 are switching system constants.

$$V_1 = K \qquad (9)$$

$$V_2 = PV_s + QI_s - R \qquad (10)$$

$$(t_2 - t_1) = A_1(V_s) + B_1(I_s) - C_1 \qquad (11)$$

$$(t_2 + t_1) = A_2(V_s) + B_2(I_s) - C_2 \qquad (12)$$

According to Equations 9,10,11 and 12, the (t_2 - t_1), (t_2 + t_1), V_2, and the V_1 in Equation 4 can be represented using supply voltage V_S and supply current I_S.
Hence, Equation 1 can be rearranged as follows.

$$V_{arc} = \frac{(PV_s+QI_s-R-K)}{3.12}\left\{Tan\left(\frac{A_2V_s+B_2I_s-C_2}{A_1V_s+B_1I_s-C_1}\right) + Tan\left[\frac{2T-(A_2V_s+B_2I_s-C_2)}{A_1V_s+B_1I_s-C_1}\right]\right\} \quad ; \ \{0 \le T \le \ Arc\ time\} \quad (13)$$

Here

V_{arc} = Arc Voltage (volts); T = Time (seconds); V_S = Supply Voltage (volt); I_S = Supply Current (Ampere)

The switching system should be used to determine the constants P, Q, R, K, A_1, B_1, C_1, A_2, B_2, and C_2. These values may be influenced by the contact separation velocity, contact area, contact material, and surrounding medium. For a more complete explanation, additional research is necessary.

For the above experiment setup, the optimal constant values are.

P = 0.908; Q = 1.090 Ω ; R = 16.002 V; K = 11.724 V; A_1 = 0.004; B_1 = 0.016 Ω; C_1 = 0.243 V; A_2 = 0.004; B_2 = 0.016 Ω; C_2 = 0.234 V

3.2 Error Analysis.

The derived model was used to calculate arc voltages for each condition. The data values (x) and the calculated values (x_{calc}) were compared to determine the model's error. To calculate the error, two methods are described below. In both cases, N represents the number of data.

Method 1 : Standerd error of estimation (SEOE). The following equation was used to calculate the error.

$$SEOE = \sqrt{\frac{\sum(x-x_{cacl})^2}{N}} \quad (14)$$

Method 2 : Standerd relative error of estimation (SREOE). The following equation was used to calculate the error.

$$SEOE = \sqrt{\frac{\sum(\frac{x-x_{cacl}}{x})^2}{N}} \quad (15)$$

The average error for the SEOE model is 9.26 V, while the error for the SREOE model is 0.27 V. That means the predicted values can vary from the actual values by an average of 9.26 V, or 27%.

These results suggest that for a particular switching system, the arc voltage can be predicted with an accuracy of over 70 percent using only two variables: the supply voltage and current. Before applying this model to a switching system, however, we must calculate the above 10 constant values for the system using the same method.

3.3 Arc initiation conditions.

The arc duration is the amount of time it takes for the arc voltage to increase from the arc starting voltage (V_1) to the arc ending voltage (V_2). To form a stable arc, V_2 must be as much higher than the V_1. So the first condition that needs to be fulfilled for the arc initiation is; "Arc voltage must be equal to the V_1".

According to Figures 9 and 10, when $V_1 = V_2$, the arc starting voltage is equal to the arc ending voltage. That means the arc vanishes at the point of it starts.

$$V_1 = V_2$$
$$K = P(V_S)+Q(I_S) - R \quad (16)$$

At the region of Figure 10, where $V_2 < V_1$, the arc theoretically reaches the extinguishing voltage prior to arc initiation. In short, the arc cannot be initiated under these circumstances. Therefore, this region ($V_2 < V_1$) is the arc-free zone. This may be the criterion for switching the contacts without creating an electric arc.

$$Q(I_S) < (R+K) - P(V_S) \qquad (17)$$

For the experimental setup described in section III, the arc initiation condition is as follows.

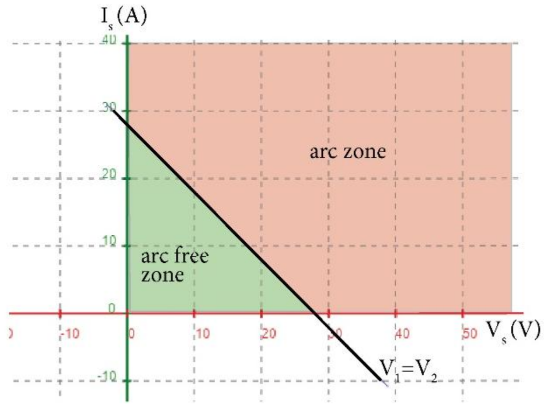

Fig. 8. Arc region and arc free region of DC switch according to the supply voltage (V_s) and current (I_s).

4. CONCLUSION

The electric arc can be observed when the current conducting contacts are separated. For an arc to form, the arc voltage must reach the arc starting voltage when the switch contacts begin to separate. In addition, based on the supply voltage and current, arc voltage can never exceed the supply voltage (arc ending voltage). In DC systems, once the arc has formed, the arc voltage variation with time can be modeled using the tan function. This behavior permits the identification of three regions of the DC electric arc. Regions of arc initiation, arc elongation, and arc termination. The arc start voltage is nearly constant throughout the measured range. The voltage at the end of the arc varied linearly with the supply voltage and current. For the experimental range, the time between the arc's initiation and termination is also a linear function of the supply voltage and current. Using the aforementioned findings, a new DC arc model has been developed to predict the arc voltage as a function of time using the supply voltage and current.

By considering the arc starting voltage and arc ending voltage, the arc initiation condition can be determined. This method can determine the range of current that does not initiate electric arcs at specific voltage levels.

CONSENT

"All authors declare that 'written informed consent was obtained from the patient (or other approved parties) for publication of this case report and accompanying images. A copy of the written consent is available for review by the Editorial office/Chief Editor/Editorial Board members of this journal."

REFERENCES

1. Andrea, J., Bournat, M., Landfried, R., Teste, P., Weber, S., & Schweitzer, P. (2016). Model of an Electric Arc for Circuit Analysis. International Conference on Electric ContactsAt: Edinburgh.
2. He, J., Wang, K., & Li, J. (2021). Application of an Improved Mayr-Type Arc Model in Pyro-Breakers Utilized in Superconducting Fusion Facilities. Energies.
3. Kim, W., Kim, Y.-J., & Kim, H. (2018). Arc Voltage and Current Characteristics in Low-Voltage Direct Current. Energies, 11.
4. Ou, C., Nakayama, R., Zen, S., Takeuchi, N., & Yasuoka, K. (2018). Influence of Arc Discharge on Contact Erosion and Contact Resistance in a Hybrid DC Switch. 2018 IEEE Holm Conference on Electrical Contacts.
5. Pedro, K. (2017). Electric Arc Modeling in Circuit Breakers for Electromagnetic Transients Analysis.
6. Rau, S.-H., & Lee, W.-J. (2016). DC Arc Model Based on 3-D DC Arc Simulation. IEEE Transactions on Industry Applications, 52, 5255-5261.
7. Sawa, K., Tsujimura, S., & Motoda, S. (2015). Fundamental characteristics of arc extinction by magnetic blow-out at DC voltages (lt;500V) II. 2015 IEEE 61st Holm Conference on Electrical Contacts (Holm).

8. Schau, H. (2017). Risk parameters of DC fault arcs — Research work on DC arcs in LV systems. 2017 12th International Conference on Live Maintenance (ICOLIM).
9. Smeets, R., & Kertész, V. (2013). Application of a validated AC black-box arc model to DC current interruption. 2013 2nd International Conference on Electric Power Equipment - Switching Technology (ICEPE-ST).
10. Tsusaka, A., Hasegawa, K., Matsumura, T., Yukita, K., Goto, Y., Miyamoto, A., ... Yokomizu, Y. (2019). A study on estimation of arc parameters for low voltage DC arc breaking process. 2019 IEEE Third International Conference on DC Microgrids (ICDCM).
11. Uriarte, F. M., B, H., Hotz, a., J, T., Kwasinski, Alexis, . . . E., R. (2012). A DC Arc Model for Series Faults in Low Voltage Microgrids. IEEE Transactions on Smart Grid, 3(4), 2063-2070.
12. Zhang, G., Liu, Y., Qi, L., Xu, Y., & Kurrat, M. (2018). Parameter Estimation of Black Box Arc Model based on Heuristic Optimization Algorithms. 2018 IEEE Holm Conference on Electrical Contacts.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

SEOE : Standerd error of estimation
SREOE : Standerd relative error of estimation