Parameter Estimation of DC Black-Box Arc Models using Genetic Algorithms

Felipe P. Pessoa, Jhair. S. Acosta and Maria C. Tavares*

***Abstract*—This paper presents a method for estimating the black-box arc parameters using genetic algorithm. The proposed method is applied to represent a DC short-circuit in a railway system protected by a High-Speed Circuit Breaker (HSCB). The simulated cases were compared with experimental data, and the results show very good agreement between model predictions and experiments. This method could potentially be used by HSCB's manufacturers to extract and provide arc model parameters to end users based on their test results.**

***Keywords*—Black-box arc models, DC circuit breakers, DC short-circuit.**

I. Introduction

THE recent developments in power electronics, static converters and renewable energy have led to an increase in the use of direct current (DC) systems. These advances made possible to perform voltage conversions that previously were only available for alternating current (AC) by means of transformers.

DC applications can be found in different systems. Distributed renewable energy systems normally have DC components, such as photovoltaic modules (Fig. 1a) and DC links that decouple the rotation speed of wind systems [1]. In addition, the increment of electric vehicles and railway systems [2] (Fig. 1b), serve as motivation for expanding the DC distribution systems.

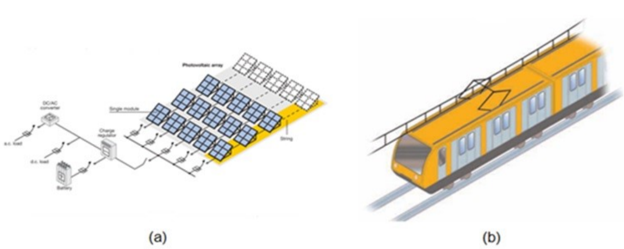

Fig. 1. Direct current applications (a) photovoltaic system and (b) railway system [3].

However, the current interruption in DC systems is difficult because it lacks the natural zero crossing. Therefore, it is necessary to implement techniques to force the current to zero before the interruption. In DC High-Speed Circuit Breakers (HSCB), the main mechanism to extinguish short-circuit currents are arc chambers. Thus, during the circuit breaker opening process, the electric arc generated by the contacts separation is directed to the arc chamber, where it is elongated and cooled.

The electric arc has a fundamental role in the short-circuit current extinction process. Accordingly, if the arc elongation is enough, its voltage level creates a negative current variation rate that will eliminate the fault current.

Several arc models, such as the black-box arc, have been widely used for AC applications, especially for analyzing the arc characteristics of SF6 and air circuit breakers, counting with several contributions like [4], [5], [6] and [7]. On the other hand, there are still few studies applied to DC circuit breakers, which are commonly employed in railway systems and DC micro grid, according to [8], [9] and [10].

In this work, we proposed an estimation method for some arc parameters' black-box models based on genetic algorithm. The most used mathematical models presented in technical literature are considered. Experimental data of a DC HSCB applied in a railway system were used to validate the method.

II. DC current interruption

Most DC networks are composed by inductive and resistive components, which can usually be represented by a simple circuit, as shown in Fig. 2.

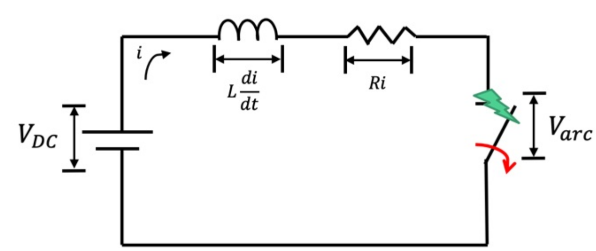

Fig. 2. Example of DC circuit.

For this circuit, it is possible to write the following equation:

$$V_{DC} = L\frac{di}{dt} + Ri + V_{arc} \tag{1}$$

Rearranging the terms of (1):

$$\frac{di}{dt} = \frac{1}{L}\left(V_{DC} - Ri - V_{arc}\right) \tag{2}$$

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Where:

V_{DC}	Source Voltage [V];
L	Circuit inductance [mH];
R	Circuit resistance [Ω];
i	Circuit current [A];
V_{arc}	Arc voltage [V].

To reduce the fault current, the rate of change over time must be negative:

$$\frac{di}{dt} < 0 \tag{3}$$

Thus:

$$V_{arc} > V_{DC} - Ri \tag{4}$$

In addition, it is possible to conclude that rate of change of the current extinction is inversely proportional to the circuit inductance, thus the time of arc extinction in the DC system is proportional to the circuit time constant ($\tau = L/R$). Fig. 3. shows the oscillography related to a short-circuit test performed at ABB SACE power testing laboratories.

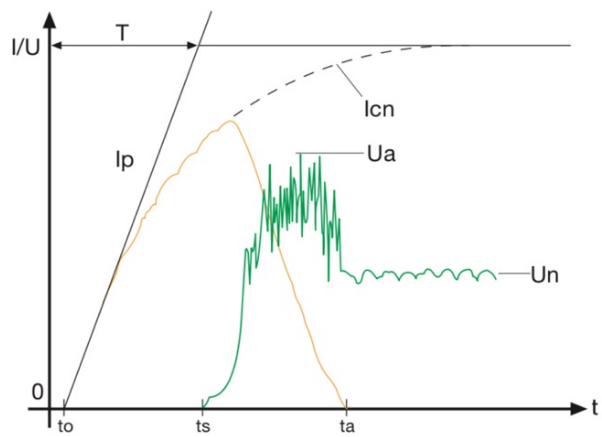

Fig. 3. Short-circuit curves in DC system [3].

When the short-circuit occurs at instant t_0, the current I_p (orange curve) begins to increase according to the circuit time constant, following the path described by I_{cn} until the breaker operation. When the circuit breaker contacts start to separate at time t_s, the electric arc is initiated. The current continues rising for a short time after the contact separation, until it starts to decrease due to the growing arc resistance inserted to the circuit. As can be seen in Fig. 3, the arc voltage U_a (green curve) increases to a higher value than the source voltage U_n, and at time t_a, the short-circuit current is completely extinguished.

In practical application like in naval ships, the proper identification of the maximum over-voltage is crucial to properly protect the inboard DC medium voltage systems. For railway systems, the evaluation of transient fault current is also very important for protection of the track system, protection coordination between substations and trains, and protection of the train on board equipment.

III. Types of Arc Models

The mathematical models for representing the electrical arc are usually divided into the following categories [11]:

- Physical models;
- Black-box models; and
- Formulae and diagrams.

Physical models are the most complex models, since the arc description is based on dynamic fluid equations and the laws of thermodynamics, in combination with Maxwell's equations. These models are based on the equations of mass conservation, the amount of movement and energy. They are commonly used by manufacturers in the design of new circuit breakers to reduce costs with prototypes.

Black-box models describe the electric arc using differential equations. They are mathematical models based on physical considerations that establish the relationship between the arc conductance and electrical parameters such as voltage and current. Although these models are not suitable for circuit breaker design, they are very important in simulations of electrical circuits, because they describe with good accuracy the interaction of the electric arc with the circuit.

Formulae and diagrams are used to describe the dependence of parameters and their scaling laws for special cases, such as short line fault limiting curves, scaling of chopping current with parallel capacitance and number of breaks. These models are derived from tests or calculations and simulations using the other models.

This work focuses on black-box models, aiming on the representation of the electric arc phenomenon by means of circuit variables during the current interruption process, without going into the physical details of the process.

IV. Black Box Arc Models

Most of the black-box models used today refer to the work developed by Cassie and Mayr, being considered by many as the most representatives of this category. The models developed later are based on one of these models or a combination of them. This paper also presents three derived models, the model developed by Schwarz, which is a modification of Mayr's equation, including two additional parameters, the Habedank model, that combines the resistances of Cassie and Mayr in series, and the KEMA model, composed of three series arc models.

A. Cassie Arc Model

One of the first electric arc model using differential equations was proposed by A.M. Cassie in 1939 [12], who describes the behavior of the electric arc by changing its conductivity due to variations in the heat flow. Cassie's model adopts the following premises [13]:

- Constant temperature in radial direction;
- Arc cooling by convection in axial direction; and
- Variable arc cross-sectional area.

Cassie's equation is described as follows:

$$\frac{1}{g_c}\frac{dg_c}{dt} = \frac{1}{\tau_c}\left(\frac{u^2}{u_0^2} - 1\right) \tag{5}$$

Where:

g_c	Arc conductance of Cassie [S]
τ_c	Time constant of Cassie [s]
u	Arc voltage [V]
u_0	Constant arc voltage [V]

Since Cassie's model assumes that the losses occur mainly by thermal convection during the time interval in which the current has a high amplitude, this model is not suitable for low currents, being usually applied to represent the high-current region.

B. Mayr Arc Model

O. Mayr [14] developed a mathematical model of the electric arc based on differential equations, however with different premises than Cassie [13]:

- Constant arc cross-sectional area;
- Heat losses due to conduction in axial direction; and
- Constant cooling power.

Mayr's equation is described as follows:

$$\frac{1}{g_m}\frac{dg_m}{dt} = \frac{1}{\tau_m}\left(\frac{u \cdot i}{P_0} - 1\right) \tag{6}$$

Where:

g_m	Arc conductance of Mayr [S]
τ_m	Time constant of Mayr [s]
u	Arc voltage [V]
i	Arc current [A]
P_0	Cooling Power [W]

The model proposed by Mayr admits that the heat loss occurs through thermal conduction in the radial direction, with the arc conductance varying exponentially with the stored energy. Due to the premises adopted by Mayr, this model proved to be more suitable for low currents (close to zero).

C. Schwarz Arc Model

In 1971, Schwarz presented the modified Mayr model (7), considering the time constant and cooling power as function on the arc conductance [15].

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau(g)}\left(\frac{u \cdot i}{P(g)} - 1\right) \tag{7}$$

Where:

$$\tau(g) = \tau_0 g^{\alpha} \tag{8}$$

$$P(g) = P_0 g^{\beta} \tag{9}$$

In which α and β are the exponential components of the time constant and cooling power.

Replacing (8) and (9) in (7):

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau_0 g^{\alpha}}\left(\frac{u \cdot i}{P_0 g^{\beta}} - 1\right) \tag{10}$$

D. Habedank Arc Model

Based on the work done by Cassie and Mayr, and with the objective of representing a wider current region, Ulrich Habedank presented his combined model, which consists of the series connection of Cassie and Mayr conductances [16]. Thus, for high currents, the arc resistance is represented mainly by the Cassie model, while for small currents, the contribution of the Mayr model is predominant.

$$\frac{1}{g} = \frac{1}{g_c} + \frac{1}{g_m} \tag{11}$$

where g is the total conductance of the arc (S).

E. KEMA Arc Model

The KEMA arc model is represented by three series conductances, each of which is a modified Mayr model. The mathematical expression of the KEMA model can be written as follows [7]:

$$\frac{dg_1}{dt} = \frac{1}{\tau_1 P_1} g_1^{\lambda_1} u_1^2 - \frac{1}{\tau_1} g_1 \tag{12}$$

$$\frac{dg_2}{dt} = \frac{1}{\tau_2 P_2} g_2^{\lambda_2} u_2^2 - \frac{1}{\tau_2} g_2 \tag{13}$$

$$\frac{dg_3}{dt} = \frac{1}{\tau_3 P_3} g_3^{\lambda_3} u_3^2 - \frac{1}{\tau_3} g_3 \tag{14}$$

$$\frac{1}{g} = \frac{1}{g_1} + \frac{1}{g_2} + \frac{1}{g_3} \tag{15}$$

$$u = u_1 + u_2 + u_3 \tag{16}$$

where g_1, g_2 and g_3 represent the arc conductance (S) in each submodel, and u_1, u_2 and u_3 their respective voltage (V). The constant λ controls the Cassie-Mayr relation in each submodel, and the recommended values of 1.4, 1.9 and 2.0 were used for λ_1, λ_2 and λ_3.

This arc model has six parameters at first, being three time constants (τ_1, τ_2 and τ_3) and three cooling powers (P_1, P_2 and P_3). However, they have a fixed relationships, which describes the specific type of circuit breaker, as follows:

$$k_1 = \tfrac{\tau_1}{\tau_2}, \quad k_2 = \tfrac{\tau_2}{\tau_3}, \quad k_3 = \tfrac{P_2}{P_3} \tag{17}$$

These relations can reduce the number of parameters of the model, as they tend to remain invariant for different tests of the same breaker. However, since they are not well known for the tested type of breaker, all the six parameters will be considered.

Considering that the models derived from Cassie and Mayr have led to improvements compared to the original ones, they present a better performance in fitting experimental data.

V. REFERENCE TEST

The reference short-circuit curves were obtained from the work of Rojek and Skrzyniarz [17], which presents the results of the short-circuit test performed on a HSCB employed in a railway traction system (Fig. 4 and Fig. 5). The data acquisition was performed using the *"grabit"* function from Matlab [18].

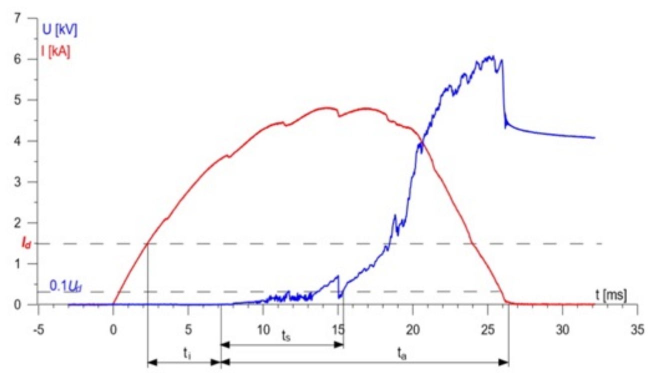

Fig. 4. Short-circuit curves for Test 1 [17].

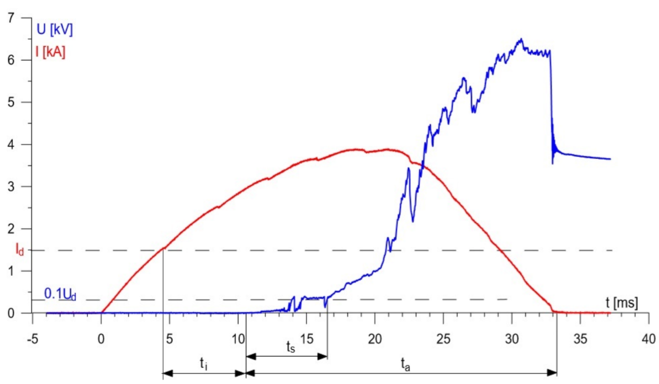

Fig. 5. Short-circuit curves for Test 2 [17].

The tests were carried on a system powered by a 6-pulse rectifier. The values of resistance and inductance in the circuit were selected in order to adjust the time constant and expected short-circuit peak value of the experiment [17]. The circuit breaker was configured with an overcurrent value $\mathrm{I_d} = 1500$ A, and the average rated voltage applied to the circuit breaker was 3.6 kV [19].

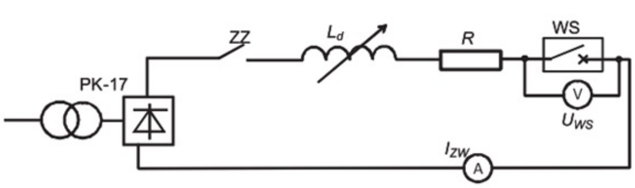

Fig. 6. Reference Test Circuit [19].

VI. PARAMETER ESTIMATION

The estimation of the arc models parameters was performed using genetic algorithms. The methodology is based on the work done by Zhang [20], with some adjustments, such as the definition of the fitness function:

$$\text{error} = \frac{\sum_{t=t_1}^{t_2} \sqrt{(g_{opti}(t) - g(t))^2}}{N} \tag{18}$$

where g is the arc conductance calculated from the reference curves, g_{opti} is the arc conductance of the model, t_1 is the initial time of the fault clearing (considering a margin of 20 μs), t_2 is the instant where the arc is extinguished, and N is the size of the sample.

The initial instant considered (t_1) is the time starting after the contact arc time (represented by t_s in Fig. 4 and Fig. 5), which is defined as the time from the instant of breaker´s contacts opening (arc ignition between contacts) until the arc reaches 10% of circuit supply voltage. This condition is considered fulfilled if there is no decrease in the arc voltage below this limit [17].

Since the arc models represents the derivative of the conductance, the fourth-order Runge-Kutta numerical integration was used for obtaining the arc conductance [21].

The flowchart of the genetic algorithm is shown in Fig. 7. Firstly, the data of the arc voltage and current waveforms are loaded into the program. Then, the arc conductance is calculated for each timestamp using Ohms law ($g = i/v$). The population is initialized according to the magnitude degree of each parameter, and the fitness function is evaluated for each solution. If the stop criterion is satisfied, the optimization process finishes, otherwise, the natural selection, crossover and mutation operators are performed. This process is repeated until stop criterion is satisfied.

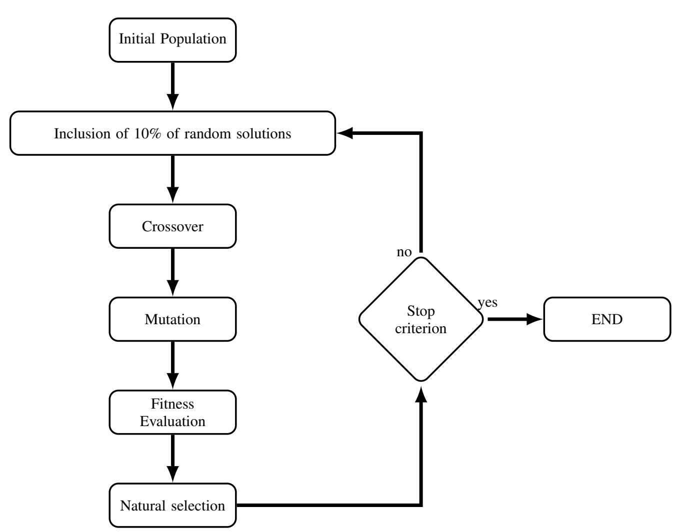

Fig. 7. GA flowchart.

VII. RESULTS

A. Parameters estimation

The optimization process was carried out for a population of 50 individuals, using tournament selection, arithmetic crossover and a mutation probability of 25%. The stop criteria chosen was the number of generations, with a value equal to 100.

The estimated parameters for the arc models are summarized in Table I, while the results are shown in Table II. The error represents the value of the fitness function, and the R^2 factor the coefficient of determination, which indicates the rated amount of variation in the measured values explained by the independent variables of the arc models. Fig. 8 shows the output conductance adjusted by the arc models for Test 1.

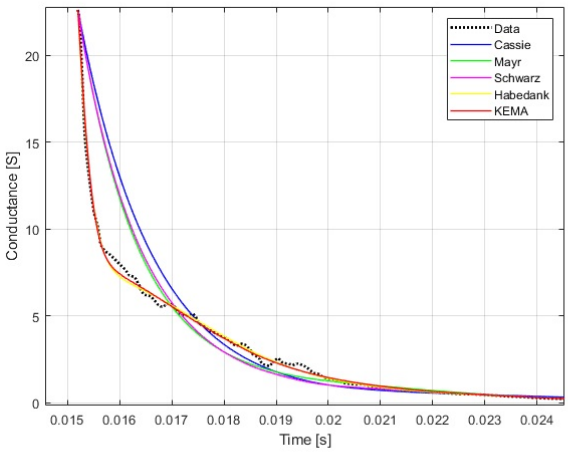

Fig. 8. Arc Model conductance output for Test 1.

TABLE I
ARC MODEL ESTIMATED PARAMETERS

Arc Model	Test Nº	τ_c / τ_1 [ms]	U_0 / P_1 [V/MW]	τ_m / τ_2 [ms]	P_0 / P_2 [MW]	α / τ_3 [μ/ms]	β / P_3 [μ/MW]
Cassie	1	1.44	6288	-	-	-	-
	2	2.14	6400	-	-	-	-
Mayr	1	-	-	1.15	21.83	-	-
	2	-	-	1.80	21.24	-	-
Schwarz	1	-	-	1.13	21.44	396	401
	2	-	-	1.79	21.19	1193	224
Habedank	1	1.41	5995	0.18	2.29	-	-
	2	1.98	6117	0.23	1.54	-	-
KEMA	1	1.35	18.03	0.16	1.50	1.62	9.58
	2	1.78	19.77	0.15	0.93	2.97	16.69

TABLE II
RESULTS FROM GA

Arc Model	Test 1 Error	Test 1 R^2 (g_{opti})	Test 2 Error	Test 2 R^2 (g_{opti})
Cassie	0.6687	85.92%	0.4939	87.70%
Mayr	0.5650	89.04%	0.4245	89.57%
Schwarz	0.5654	89.17%	0.4249	89.59%
Habedank	0.0837	99.69%	0.1034	99.36%
KEMA	0.0838	99.70%	0.0968	99.48%

As can be seen, the Habedank and KEMA models presented the least optimization error, and also the best R^2 factor for the conductance among the black-box models considered.

B. Arc Models' Performance

Short-circuit curves were simulated with Simulink using the Arc model blockset library [22]. Since the original data from the reference circuit test in Fig. 6 was not available, the resistance and inductance were adjusted so that the short-circuit current had the same time constant and expected peak value as the reference curves. The circuit parameters, as well as the initial time (t_1) and initial conductance (g_0) considered for simulation are presented in Table III. The g_0 values were obtained from the real oscillograms in Figs. 4 and 5 at t_1. The source voltage was estimated in order to obtain an average voltage of 3.6 kV at the rectifier side.

TABLE III
SIMULATION CIRCUIT PARAMETERS AND ARC SETTINGS

Test	R[Ω]	L[mH]	τ[ms]	t_1[ms]	g_0[S]
1	0.63	5.0	7.9	15.2	22.6
2	0.63	9.2	14.6	16.4	17.7

The current and voltage waveforms obtained from simulation are presented in Figs. 9 to 16, while their performances are summarized in Table IV.

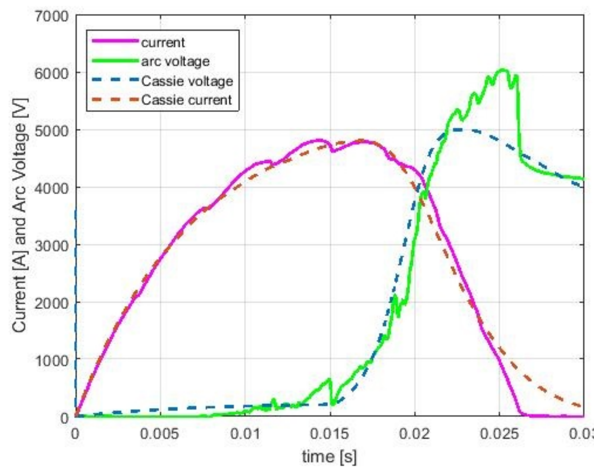

Fig. 9. Simulation of Cassie Model for Test 1.

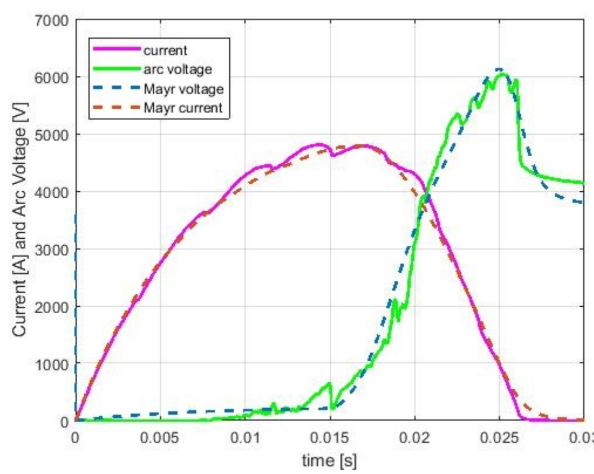

Fig. 10. Simulation of Mayr Model for Test 1.

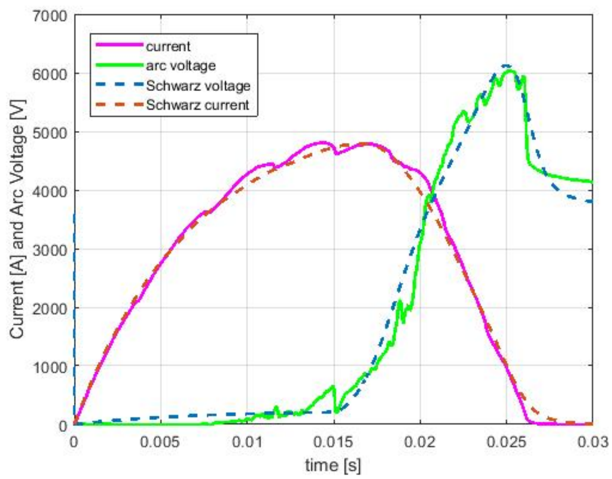

Fig. 11. Simulation of Schwarz Model for Test 1.

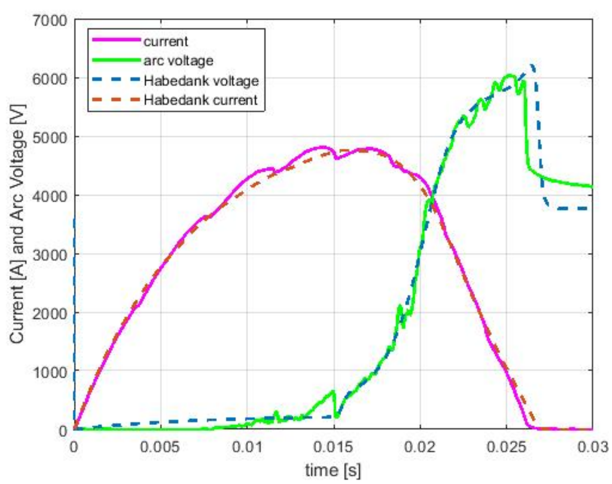

Fig. 12. Simulation of Habedank Model for Test 1.

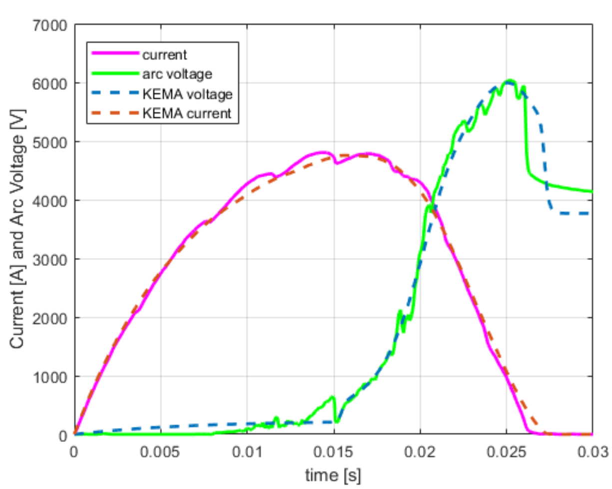

Fig. 13. Simulation of KEMA Model for Test 1.

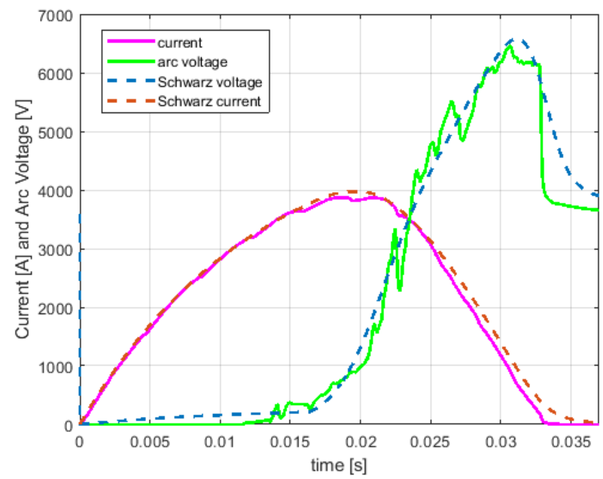

Fig. 14. Simulation of Schwarz Model for Test 2.

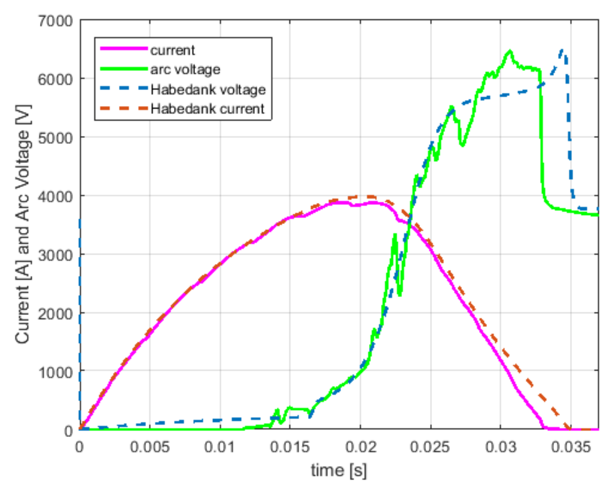

Fig. 15. Simulation of Habedank Model for Test 2.

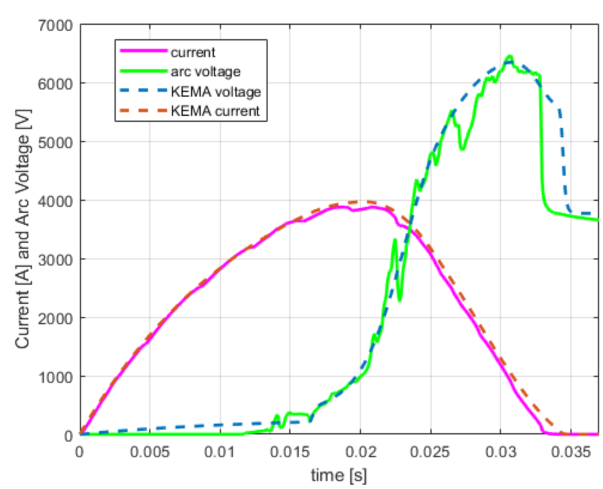

Fig. 16. Simulation of KEMA Model for Test 2.

TABLE IV
ARC MODEL SIMULATION PERFORMANCES

Arc Model	Test 1 R^2 (U_{arc})	Test 1 Peak Error	Test 2 R^2 (U_{arc})	Test 2 Peak Error
Cassie	89.00%	17.27%	85.25%	18.23%
Mayr	96.72%	1.42%	94.51%	1.61%
Schwarz	96.52%	1.38%	94.64%	1.82%
Habedank	95.04%	2.71%	85.24%	0.74%
KEMA	96.13%	0.80%	92.96%	1.84%

Considering the simulation of the short-circuit curves, except for the Cassie model, the black-box models evaluated properly represent the electric arc, with an average R^2 value above 90% and peak error below 3%. The peak error provides valuable information about the maximum overvoltage level to be considered in the network design, indicating the possible need for mitigation measures.

However, the model parameters experience variations associated to the circuit conditions, such as its time constant. This is due to the limitations presented by this type of model, as discussed in [23]. At the end, this variation can limit the application of these models when representing the circuit breaker itself. For this reason, it is desirable to check the model's ability to represent multiple circuit characteristics, at least within a defined range of variation.

VIII. Multiple Tests

In order to check the model's capacity to represent different circuit conditions, it is possible to adapt (18) to consider multiple tests, by adding the fitness function of each one, as presented in (19).

$$\text{error} = \left(\frac{\sum_{t=t_{11}}^{t_{21}} \sqrt{(g_{opti1}(t) - g_1(t))^2}}{N_1} + \frac{\sum_{t=t_{12}}^{t_{22}} \sqrt{(g_{opti2}(t) - g_2(t))^2}}{N_2} \right) \quad (19)$$

For this part, the models of Habedank and KEMA were considered, seeing that they presented the best results for the optimization process. The estimated parameters and their fitting performances are shown in Table V and Table VI.

The short-circuit curves considering the same set of parameters for each model are shown in Figs. 17 to 20, with their performances summarized in Table VII.

TABLE V
ARC MODEL ESTIMATED PARAMETERS FOR MULTIPLE TESTS

Arc Model	τ_c / τ_1 [ms]	U_0 / P_1 [V / MW]	τ_m / τ_2 [ms]	P_0 / P_2 [MW]	α / τ_3 [μ / ms]	β / P_3 [μ / MW]
Habedank	1.43	5145	0.19	2.06	-	-
KEMA	1.37	25.50	0.24	2.05	5.79	6.45

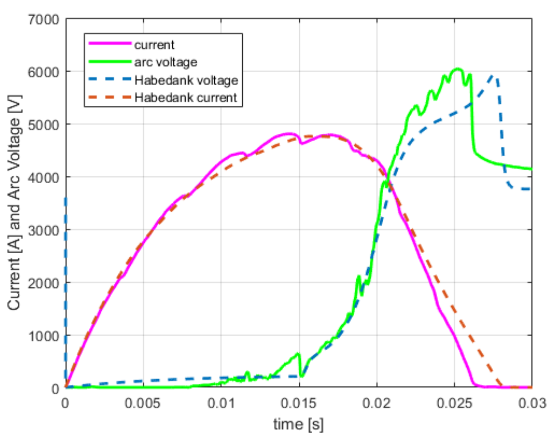

Fig. 17. Simulation of Habedank Model for Test 1.

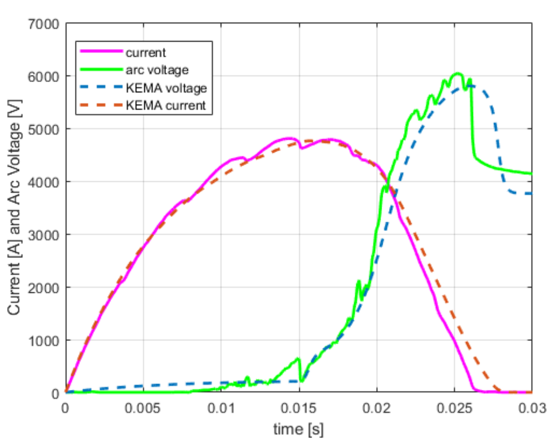

Fig. 18. Simulation of KEMA Model for Test 1.

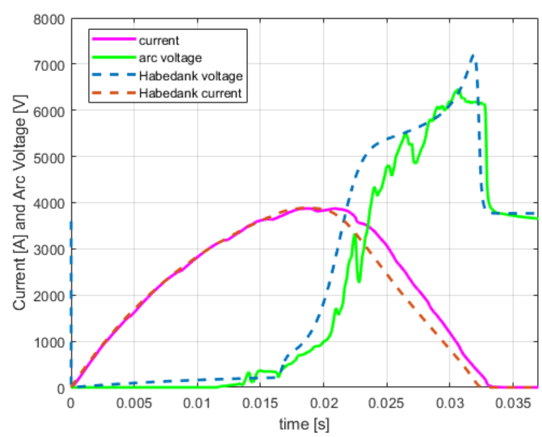

Fig. 19. Simulation of Habedank model for Test 2.

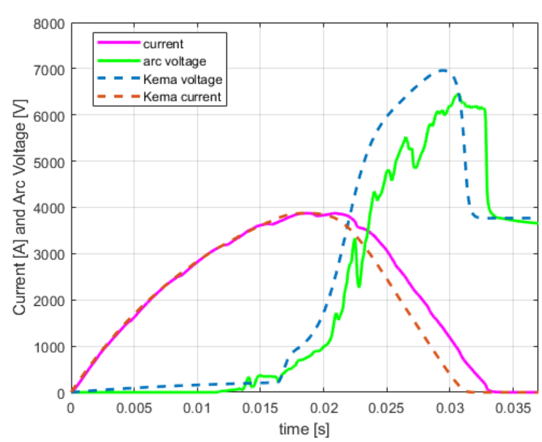

Fig. 20. Simulation of KEMA model for Test 2.

TABLE VI
RESULTS FOR MULTIPLE TESTS (GA)

Arc Model	Test 1 Error	Test 1 R^2 (g_{opti})	Test 2 Error	Test 2 R^2 (g_{opti})
Habedank	0.1450	99.39%	0.5007	83.31%
KEMA	0.1839	98.40%	0.4848	84.08%

TABLE VII
SIMULATION PERFORMANCES FOR MULTIPLE TESTS

Arc Model	Test 1 R^2 (U_{arc})	Test 1 Peak Error	Test 2 R^2 (U_{arc})	Test 2 Peak Error
Habedank	88.23%	1.62%	79.51%	11.54%
KEMA	91.60%	3.98%	68.43%	7.75%

The results show that the arc models managed to maintain a good performance for test 1, while test 2 presented a certain deterioration. This difference happens because the sum of weights approach reduces the overall fitness function, without looking the domination among solutions. For this purpose, the Pareto front approach could be used.

The performances also indicate that the models generalization ability has limitations, and considering that there was a significant variation in the time constant (approx. 85%), this solution could be improved within a different range. Despite that, it is necessary to have a large number of tests to extract the actual arc parameters' data and estimate it according to the circuit features in which the breaker will be working.

IX. CONCLUSIONS

Black-box electric arc models are widely applied for representing transients in alternating current systems, however, there are few investigations about their application in direct current systems. This work presents a method for fitting experimental oscillograms using genetic algorithm. For that, some of the main electric arc models are considered to simulate a short-circuit in a railway system protected by a HSCB. The results show that there is a very good agreement between model predictions and experiments.

The results show that the proposed fitting procedure was able to satisfactorily represent the experimental oscillograms, with an average R^2 factor above 90%, and a peak error below 3%. On the other hand, the black-box models showed some limitations for prediction, when representing the behavior of the circuit breaker itself, indicating that the estimated parameters are only suitable within a certain range of variation in the circuit conditions. The generalization capacity of the black-box models is a complex subject, and in some way remains as an open question. This issue is better discussed in [23], and some developments to work around these limitations are presented in [7].

Regarding the optimization procedure, the proposed method can also be adapted to estimate the arc parameters for different circuit conditions at the same time, or even extend to more complex black-box models with minor adjustments, like [5] and [6], representing a potential solution for manufacturers to extract and provide arc model parameters to end users based on their tests results.

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REFERENCES

[1] L. Mackay, "Steps towards the universal direct current distribution system," Doctoral Thesis, Delft University of Technology, 2018.

[2] A. Rojek and M. Sidorowicz, "Researches and tests of high-speed circuit breakers for rolling stock and substations in 3 kv dc traction power system," *Problemy Kolejnictwa*, 2013.

[3] ABB SACE S.p.A, "ABB Low Voltage Circuit-Breakers for Direct Current Applications," 2007.

[4] A. Balestrero, L. Ghezzi, M. Popov, G. Tribulato, and L. van der Sluis, "Black box modeling of low-voltage circuit breakers," *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2481–2488, 2010.

[5] F. Bizzarri, A. M. Brambilla, L. Ghezzi, and F. Rigamonti, "Circuit level model of miniature circuit breakers," *IEEE Transactions on Power Delivery*, vol. 33, no. 6, pp. 2700–2709, 2018.

[6] F. Bizzarri, G. Gruosso, M. Bonaconsa, and A. Brambilla, "A reliable and efficient black box model of sf6 medium voltage circuit breakers," *International Journal of Electrical Power & Energy Systems*, vol. 119, p. 105863, 2020.

[7] T. Ohtaka, V. Kertész, and R. P. P. Smeets, "Novel black-box arc model validated by high-voltage circuit breaker testing," *IEEE Transactions on Power Delivery*, vol. 33, no. 4, pp. 1835–1844, 2017.

[8] S.-W. Lim, U. A. Khan, J.-G. Lee, and B.-W. Lee, "Simulation Analysis of DC Arc in Circuit Breaker Applying with Conventional Black Box Arc Model," *3rd International Conference on Electric Power Equipment - Switching Technology (ICEPE-ST) Oct. 25-28, Busan, Korea*, pp. 332–336, 2015.

[9] K.-H. Park, H.-Y. Lee, M. Asif, B.-W. Lee, T.-Y. Shin, and C.-W. Gu, "Assessment of various kinds of AC black-box arc models for DC circuit breaker," *ICEPE-ST - 4th International Conference on Electric Power Equipment- Switching Technology*, pp. 465–469, 2017.

[10] K.-H. Park, H.-Y. Lee, M. Asif, and B.-W. Lee, "Parameter identification of dc black-box arc model using non-linear least squares," *The Journal of Engineering*, no. 16, pp. 2202–2206, 2019.

[11] Cigré Working Group 13.01, "State of the art of circuit-breaker modelling." 1998.

[12] A. M. Cassie, "Arc rupture and circuit severity: a new theory," *CIGRE report*, 1939.

[13] L. C. Zanetta JR., *Transitórios Eletromagnéticos em Sistemas de Potência*. EdUSP, 2003.

[14] O. Mayr, "Beiträge zur theorie des statischen und des dynamischen lichtbogens," *Archiv für Elektrotechnik*, vol. 37, no. 12, pp. 588–608, dec 1943.

[15] J. Schwarz, "Dynamisches verhalten eines gasbeblasenen, turbulenzbestimmten schaltlichtbogens," *ETZ-A*, vol. 92, pp. 389–391, 1971.

[16] U. Habedank, "Application of a New Arc Model for the Evaluation of Short-Circuit Breaking Tests," *IEEE Transactions on Power Delivery*, vol. 8, no. 4, pp. 1921–1925, 1993.

[17] A. Rojek and M. Skrzyniarz, "Contact arc time–important parameter of dc high-speed circuit-breakers," in *MATEC Web of Conferences*, vol. 294. EDP Sciences, 2019.

[18] J. Doke, "Grabit," *The MathWorks MatLab Central Website*, 2020.

[19] A. Rojek, "Switching-off time of electromagnetic blow-out high-speed dc circuit breaker," *Railway Reports*, vol. 169, pp. 53–60, 2015.

[20] G. Zhang, Y. Liu, L. Qi, Y. Xu, and M. Kurrat, "Parameter Estimation of Black Box Arc Model based on Heuristic Optimization Algorithms," *Electrical Contacts, Proceedings of the Annual Holm Conference on Electrical Contacts*, pp. 66–70, 2018.

[21] V. Rashtchi, A. Lotfi, and A. Mousavi, "Identification of KEMA arc model parameters in high voltage circuit breaker by using of genetic algorithm," *2nd IEEE International Conference on Power and Energy*, pp. 1515–1517, 2008.

[22] P. H. Schavemaker and L. Van Der Sluis, "The arc model blockset," in *Proc. of the Second IASTED International Conference Power and Energy Systems (EuroPES)*, 2002, pp. 644–648.

[23] L. Ghezzi and A. Balestrero, "Modeling and Simulation of Low Voltage Arcs," Doctoral Thesis, Delft University of Technology, 2010.