An Experimentally Verified Hybrid Cassie–Mayr Electric Arc Model for Power Electronics Simulations

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***Abstract*—This paper presents an electric arc model that can approximately represent both static and dynamic characteristics of an arc load controlled by a power electronic circuit. The proposed model was developed from the combination and modifications of the classical Cassie and Mayr equations. The model equations have been expressed in a form suitable for incorporation into circuit simulators employing the nodal-analysis method of equation solving. The model has been test-implemented in the Saber circuit simulator. Simulated and experimental results appear to be in good agreement.**

***Index Terms*— Arc modeling, arc plasma, power electronic simulation.**

I. Introduction

COMPUTER-AIDED design (CAD) and simulation tools are increasingly important in the development of new power electronic systems. CAD techniques can help to achieve an optimum system design with a reduced engineering labor cost compared with the traditional trial-and-error design procedure once suitable models for the system are chosen [1].

To facilitate the simulation of the operation of a power electronic circuit controlling an electric arc load, such as an arc-discharge lamp or arc–plasma reactor, an appropriate model for the arc load is necessary. Owing to the very complex arc phenomena, the relationship between the arc voltage and arc current is highly nonlinear. Initially, the nonconducting gas has a very high resistance. This is followed by a negative resistance phase during gas breakdown and followed, finally, by a small positive resistance phase once a stable arc is formed. Therefore, modeling an arc load as a pure resistance does not provide sufficient accuracy. Circuits such as SPICE and Saber simulators, which are widely used in the industry and academic research centers, do not incorporate any arc model. Therefore, it is necessary to consider a practical arc model capable of representing both the static and dynamic behavior of the electric arc and suitable for use in circuit simulators.

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A literature survey of arc modeling work done so far indicated that most models published were not intended for transient analysis in circuit simulation. These models were postulated to explain certain aspects of the arc phenomena, particularly in high-voltage circuit breakers, and they usually require numerical solution of the arc conservation equations in full differential form [2]–[5]. Solutions of these equations are extremely difficult and costly in terms of computing effort and time, and the required parameters are not easy to obtain. A SPICE circuit model has been proposed recently to simulate a simplified voltage–current characteristic of an arc discharge during the ignition phase. This model is based on a two-transistor subcircuit that is therefore divorced from any considerations of arc physics. It is limited to modeling only the ignition phase of an arc and is hence not entirely representative of the dynamic characteristics of an actual arc [6].

To develop a realistic arc model, it is necessary to adopt the micromodeling approach, where a model is based on the physical processes constituting the phenomena. The model should consist of mathematical equations formulated from considerations of these processes so that the model performance is likely to be more accurate over a wide range of operating conditions. It may require the direct implementation of the model equations into the source code of the simulator. In recent years, new versions of some circuit simulators have been offering flexible ways of incorporating new models. PSpice, a commercial version of SPICE, permits the insertion of mathematical equations as generalized controlled sources in the circuit under its Analog Behavioral option [7]. Saber offers its own proprietary analog hardware description language called MAST to facilitate the incorporation of new device models in the form of templates [8].

This paper presents a model of the electric arc that is formulated from the classical Cassie and Mayr models used extensively in the past to study the arc phenomena in the high-voltage circuit breakers. The proposed model describes the arc load as a two-terminal device whose variables are the arc current and voltage. The model is thus amenable to computer-aided circuit analysis as most modern circuit simulators employ the nodal-analysis method of solution. The structure of this paper is as follows. Section II discusses the arc phenomena. Section III describes the development of the arc model. The implementation of the arc model in the Saber simulator is described in Section IV. Parameter estimation for

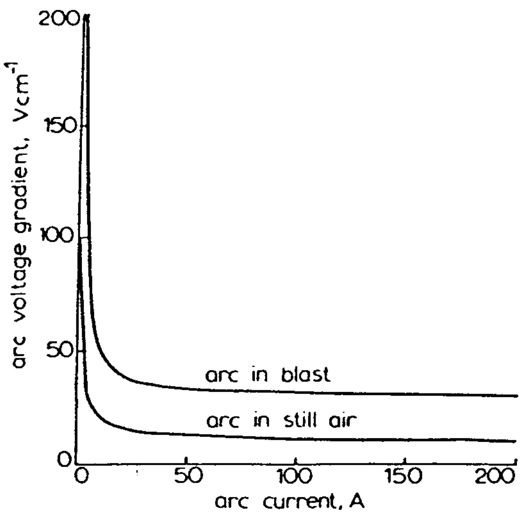


Fig. 1. Static v–i characteristics of arcs in forced and free convection.

the model is discussed in Section V. Experimental verification of the model is given in Section VI. Future work is briefly discussed in Section VII.

II. Arc Characteristics

Fig. 1 shows typical arc characteristics in a quasi-steady-state condition. Our literature survey shows that much experimental research has been done in the past on the static characteristics. There are numerous factors affecting the characteristics, among which are the type of gas, gas pressure, electrode separation distance, electrode material, and geometry and position of the electrodes. Nottingham found that an atmospheric arc of constant length could be represented by an equation of form [9]

$$v = A + \frac{B}{i^n} \tag{1}$$

for a large number of electrode materials, where $v =$ arc voltage and $i =$ arc current. The exponent n in this equation was found to depend upon the absolute boiling temperature T of the anode and also on the type of gas in which the arc burns. However, its value cannot be determined with any great degree of accuracy because of the variable nature of the phenomenon being studied.

The shape of the v–i curve may also be explained by considering the mode of heat loss from the arc [10]. Consider a very simple arc model, with a constant current density and constant heat loss per unit area of the cylindrical surface of the arc. The circumference of the arc column and, therefore, the heat loss vi is then proportional to the arc radius. For a constant current density, the arc radius is proportional to the square root of the arc current. Hence, the relationship between v, i, and the arc conductance G is

$$v \propto \frac{1}{\sqrt{i}} \text{ and } G \propto vi^2. \tag{2}$$

This model gives a shape not unlike the typical characteristics in the low-current range, but not for the high-current range.

In the high-current range, we can let the current density constant, but assume that the loss is proportional to the cross-sectional area of the arc, such as might occur with gas flowing through the arc and removing heat from the entire volume of the arc. In this case, v remains constant, the arc conductance behaves as

$$G \propto i \tag{3}$$

and the model presents an acceptable reproduction of the curve in the high-current region.

The simple heat-loss processes considered so far can satisfactorily account for the static characteristics. To understand the dynamic characteristics, the heat-loss processes have to be considered in greater detail. The temperature of the arc column at high pressure is sufficiently high for thermal ionization to become an important factor in the maintenance of ionization, as evidenced from the well-known Saha's equation. The thermal ionization that maintains the arc is established by virtue of the high gas temperature, which, in turn, is established and maintained by the energy given up by the ions and electrons in collision with the gas particles. If the arc current changes abruptly, the arc exhibits a hysteresis effect, i.e., a time lag in the change in voltage compared to a change in current. This is because the arc–plasma conductivity is a function of the gas temperature. Hence, when the current undergoes a positive rate of change, the conductance does not change instantaneously since the temperature change has a time lag due to the heat capacity of the gas. The result is a lower conductivity and higher voltage drop than the steady-state voltage for a given current.

III. Proposed Arc Model

Careful studies, both theoretical and experimental, have shown that the dynamic arc–plasma phenomena are extremely complex in detail so that complete mathematical models of the arc comparable in simplicity and accuracy with engineering models of the connected power electronic circuit are not possible. However, it has been recognized for many years that the relatively simple Cassie and Mayr differential equation models, based on simplifications of principal power-loss mechanisms and energy storage in the arc column, are useful for at least a qualitative understanding of the phenomena determining arc striking or extinction of the energy-balance type [11]. An attempt is thus made here to modify and combine the Cassie and Mayr models to a form suitable for transient-circuit simulation.

Cassie postulated an arc model that has a constant current density, so that its cross-sectional area varied directly with the current [12]. It also has a constant resistivity and stored energy per unit volume. The air (or other materials) flow penetrated the whole cross section of the arc, carrying away heat, and thus made the dissipation per unit volume constant as well. With the arc resistance R as the dependent variable, the Cassie equation is given by

$$\frac{1}{R}\frac{dR}{dt} = \frac{1}{\theta}\left(1 - \frac{v^2}{E_0^2}\right) \tag{4}$$

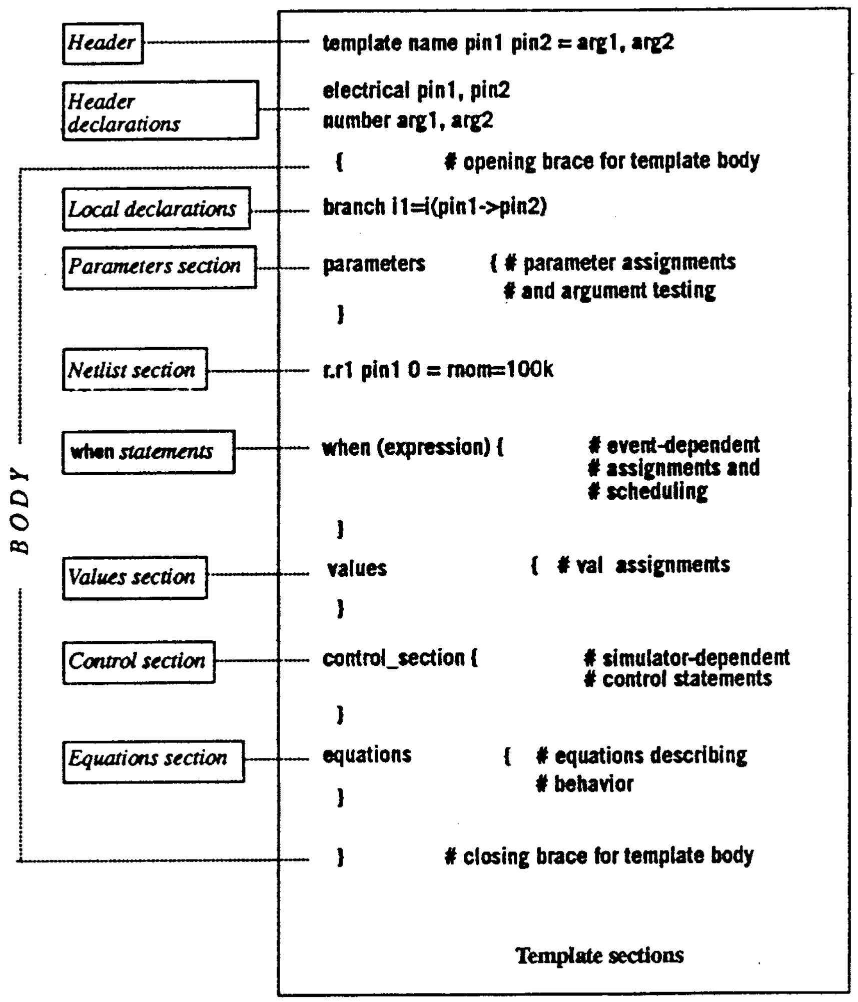


Fig. 2. Skeleton template of arc model implemented using MAST language.

where E_0 is the constant steady-state arc voltage and θ is the arc time constant = energy stored per unit volume/energy loss rate per unit volume. This model has a drawback in that the modeled arc could not be interrupted. It, in fact, describes the behavior of the arc when the current is large.

In Mayr's model, the heat loss is assumed to occur from the periphery of the arc only, and the conductance of the arc varied with the energy stored in it [13]. The Mayr equation is

$$\frac{1}{R}\frac{dR}{dt} = \frac{1}{\theta}\left(1 - \frac{vi}{P_0}\right) \tag{5}$$

where P_0 is the constant power loss. In the steady-state condition, when currents and voltages are changing very slowly, $vi = P_0$. Thus, the steady-state characteristics are hyperbolic, which is a moderately good representation of the curves in the low-current range (Fig. 1). This equation does allow the arc to interrupt since, with R high, vi/P_0 can still be less than unity, so that dR/dt is positive and the resistance continues to increase until the arc is extinguished.

In our experience with transient-circuit simulations using the iterative Newton–Raphson algorithm, convergence problems are frequently encountered whenever the value of resistance of any circuit element converges to a very small value during any of the iterations. Therefore, we proposed to use the arc conductance G as the dependent variable instead of R. It can be shown that the original Cassie equation can be transformed to

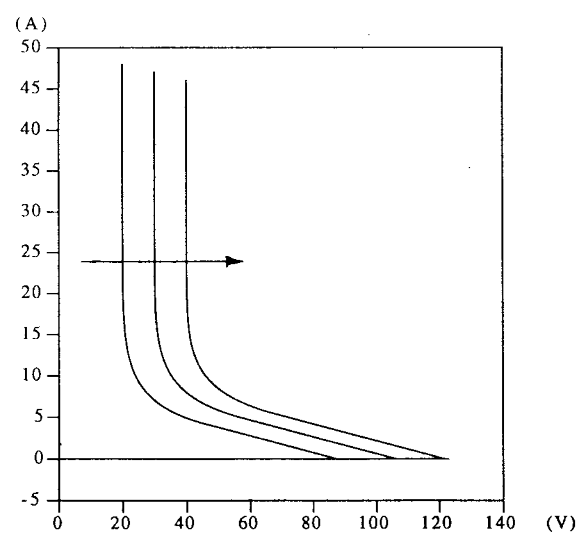


Fig. 3. Effect of increasing the value of parameter E_0.

$$G = \frac{vi}{E_0^2} - \theta\frac{dG}{dt} \tag{6}$$

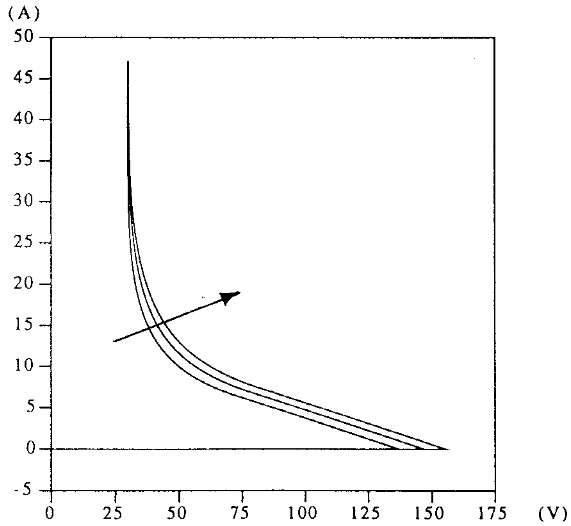


Fig. 4. Effect of increasing the value of parameter P_0.

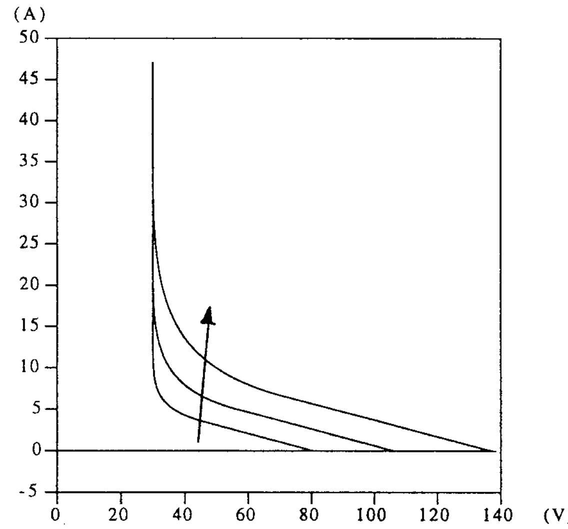


Fig. 5. Effect of increasing the value of parameter I_0.

and the original Mayr equation transformed to

$$G = \frac{i^2}{P_0} - \theta\,\frac{dG}{dt}. \tag{7}$$

It can be seen that (6) and (7) are consistent with the corresponding static relationships given by (3) and (2), respectively. As the Mayr equation is more valid for zero and low-current regions while the Cassie equation is more representative of higher current regions, it is proposed here that an arc may be simulated by the combination of (6) and (7). It is assumed here that the value of θ, now termed as the arc-damping function, is common to both equations. It is defined as the ratio of instantaneous energy stored per unit volume to the instantaneous energy loss per unit volume. Its effect on the transient-arc behavior is analogous to that of the damping factor used to characterize the mechanical system behavior.

One way of combining (6) and (7) into a single model is to define a transition current I_0 such that the arc conductance is given by

$$\begin{aligned} G &= \frac{vi}{E_0^2} - \theta\,\frac{dG}{dt}, &\quad \text{if } i > I_0 \\ G &= \frac{i^2}{P_0} - \theta\,\frac{dG}{dt}, &\quad \text{if } i < I_0. \end{aligned} \tag{8}$$

However, this leads to a lack of a defined derivative at the transition point between the two equations, which can give rise to a host of convergence problems in circuit-transient simulation. To allow smooth transition between (6) and (7), it is possible to define a transition factor $\sigma(i)$, which is a function of the arc current such that the arc conductance is given by

$$G = [1 - \sigma(i)]G_C + \sigma(i)G_M \tag{9}$$

where G_C and G_M are the conductances given by (6) and (7), respectively. The transition factor $\sigma(i)$ varies between zero and unity and should be a monotonic decreasing function when arc current i increases. A satisfactory form of $\sigma(i)$ used in our model is given by

$$\sigma = \exp\left(-\frac{i^2}{I_0^2}\right) \tag{10}$$

where I_o is the transition current. When current i is small, the value of σ is closed to unity and G is dominated by Mayr conductance G_M. When i is large, σ is negligible and, therefore, G is now dominated by Cassie conductance G_C.

In addition, there has to be a finite though very small amount of conductance between any two electrodes when the arc is absent. The value of this constant, $G_{\min}$, would depend on the distance between the electrodes, geometry of the electrodes, type of gas, and temperature. The complete model is thus given by

$$\begin{aligned} G = G_{\min} &+ \left[1 - \exp\left(-\frac{i^2}{I_0^2}\right)\right]\frac{vi}{E_0^2} \\ &+ \left[\exp\left(-\frac{i^2}{I_0^2}\right)\right]\frac{i^2}{P_0} - \theta\,\frac{dG}{dt} \end{aligned} \tag{11}$$

and

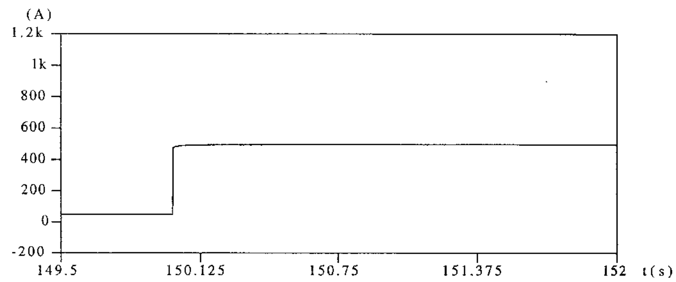
$$i = Gv. \tag{12}$$

Equations (11) and (12) are amenable to implementation in industrial standard-circuit simulators such as SPICE and Saber.

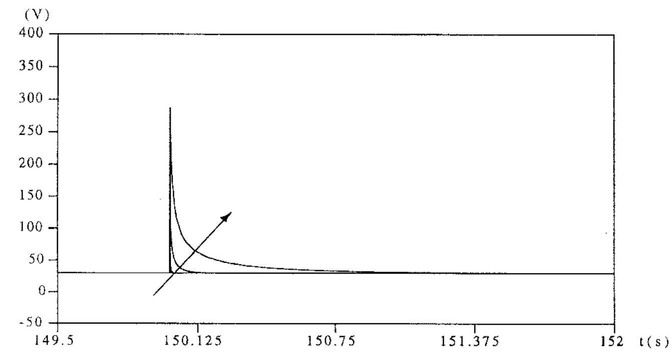
In the most general form, θ should be a function of arc current i. This is because when an arc is striking or extinguishing, the energy stored per unit volume would be large compared with the energy loss per unit volume. However, when the arc stabilizes, θ would be small. Therefore, the arc-damping function θ is assumed to have the following form in our present investigation:

$$\theta = \theta_0 + \theta_1\,\exp(-\alpha|i|) \tag{13}$$

where $\alpha > 0$ and $\theta_1 \gg \theta_0$. When the arc is igniting and extinguishing, i is small and $\theta \approx \theta_1$. When i is large, $\theta \approx \theta_0$. Together with $G_{\min}$, E_0, I_0, and P_0, these seven parameters characterize our arc model.



(a)



(b)

Fig. 6. Effect of increasing the arc-damping parameter θ_0: (a) arc current and (b) arc voltage.

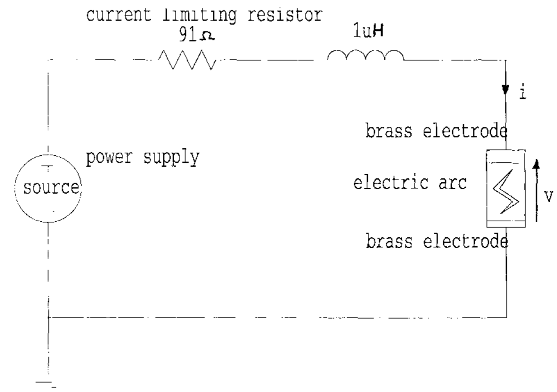


Fig. 7. Test circuit for verification of arc model.

IV. Model Implementation in Saber

To test the validity of the arc model, we have implemented it in the Saber simulator, one of the more widely used circuit simulators in the industry. To describe the behavior of a system, such as a power electronic circuit using Saber, the interconnections of the different components of the system are described using a netlist. The netlist contains a statement for each component of the system that defines the name of the model template used to describe that component and its terminal connection points. The netlist also provides the simulator with the values of the model parameters that are to be changed from the default values defined in the template. The models that describe each of the components of the simulated system can be accessed from the Saber libraries of standard model templates or from user-defined templates, where the equations that describe the physical behavior of the device are implemented [14]. The arc model has been implemented as a user-defined template.

Saber templates are written in the MAST modeling language, which is similar to the C programming language with the addition of specially designed modeling constructs that facilitate the implementation of Kirchhoff's laws and aid convergence [8]. Electrical component models are usually implemented into templates by expressing the current through each element of the component in terms of the system variables of the component. System variables for electrical component models normally comprise: 1) terminal node voltages; 2) internal node voltages; and 3) an explicitly defined system of variables. The Saber simulator solves for the system variables of the entire network such that the net current into each node of the system sums to zero (i.e., Kirchhoff's current law is satisfied) and such that the equations defining any explicitly defined system variables are satisfied. As the electric arc can be regarded as a two-terminal device, the system variables are the terminal voltages v_{anode} and v_{cathode}, whose difference ($v = v_{\mathrm{anode}} - v_{\mathrm{cathode}}$) is the arc voltage that has to satisfy (12) as well as Kirchhoff's current law for the entire network. Two explicitly defined system variables are also required for the model: the arc conductance G, as defined by (11), and its first derivative G', which has to satisfy

$$G' = d\_by\_dt(G) \tag{14}$$

where d_by_dt is the Saber time derivative operator.

A skeleton template of the arc model is shown in Fig. 2, where each section performs the following functions. The template header defines the anode and cathode terminal connection points as well as the names and default values for model parameters such as E_0. The local declaration defines constants and explicitly defines the additional system variables. The parameters section is used to calculate quantities that need to be calculated only once at the beginning of the simulation. Quantities that are functions of the system variables are implemented in the values section. The control section contains information about the nonlinear model relationships and commands to aid convergence. Finally, the equations section describes how the quantities calculated in the values section are assembled to solve for the system variables. The netlist section is presently not required for the arc model. It may be used in future versions, e.g., to describe the temperature-dependent resistive behavior of the electrodes.

V. Model Parameters Estimation

It is important that the relative influence of the model parameters on the simulated characteristics is well understood as this would help in the estimation of model parameters. This section discusses the contributions of each parameter to the simulated characteristics, using analytical analysis as well as observations of trial simulations. From the discussed results, a procedure for the estimation of model parameters is proposed.

Figs. 3–5 each show a family of simulated static characteristics obtained from Saber simulations using the implemented arc-model template. The simulated circuit consists of a voltage source in series with a resistance and an arc. The arc is

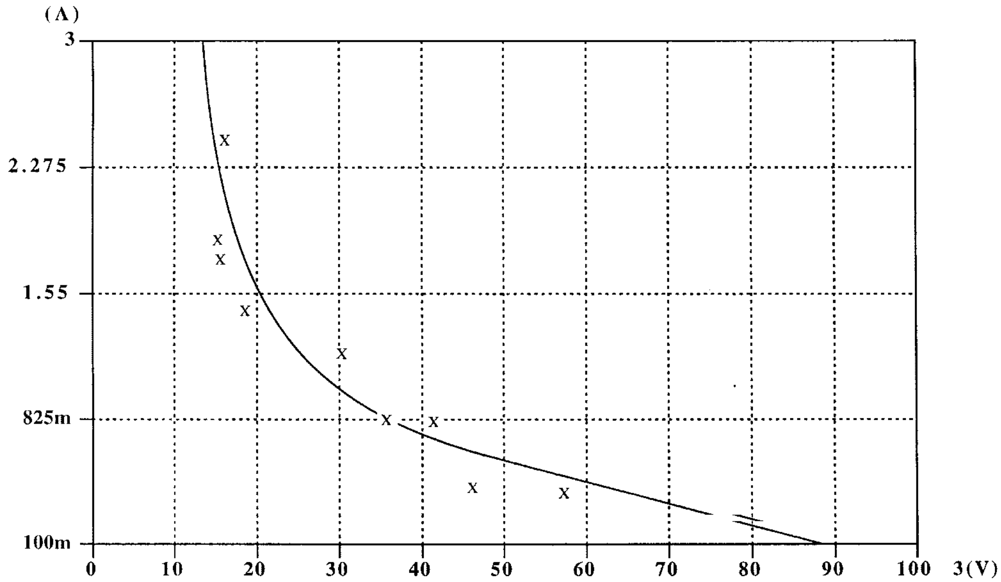


Fig. 8. Comparison of simulated and experimental static characteristics.

ignited by setting the voltage source to a high value. Using the dc transfer function of the simulator, the voltage source is progressively stepped down to zero in true dc operating conditions to obtain the static characteristics. The above procedure is carried out repeatedly each time the value of one chosen parameter, say E_0, is changed to a different value. In this way, a family of static characteristics is obtained that clearly illustrates the influences of that parameter as it changes.

At high steady-state currents, it can be seen from (11) that the arc conductance is approximately

$$G \approx \frac{vi}{E_0^2}. \tag{15}$$

Therefore

$$v^2 \approx E_0^2. \tag{16}$$

Hence, E_0 strongly governs the level of arc voltage at high currents. This can be observed in Fig. 3. At low steady-state currents, (11) can be simplified to

$$G \approx \frac{i^2}{P_0}. \tag{17}$$

Therefore

$$v \approx \frac{P_0}{i}. \tag{18}$$

Hence, the static characteristic has a hyperbolic shape at low currents and is dependent on the value of parameter P_0, as can be seen in Fig. 4. For the same arc current, the arc voltage is higher for larger values of P_0. For very small values of P_0, the characteristics display a markedly positive differential resistance in the transition region.

From Fig. 5, it can be observed that the parameter I_0 has an important bearing on the current value at which the curve becomes dominated by the Cassie term. The value of arc voltage at high currents is virtually unaffected by P_0 and I_0. All three parameters, E_0, P_0, and I_0, determine to some extent the voltage at which the arc is extinguished. On the other hand, the striking voltage is dictated mainly by $G_{\min}$.

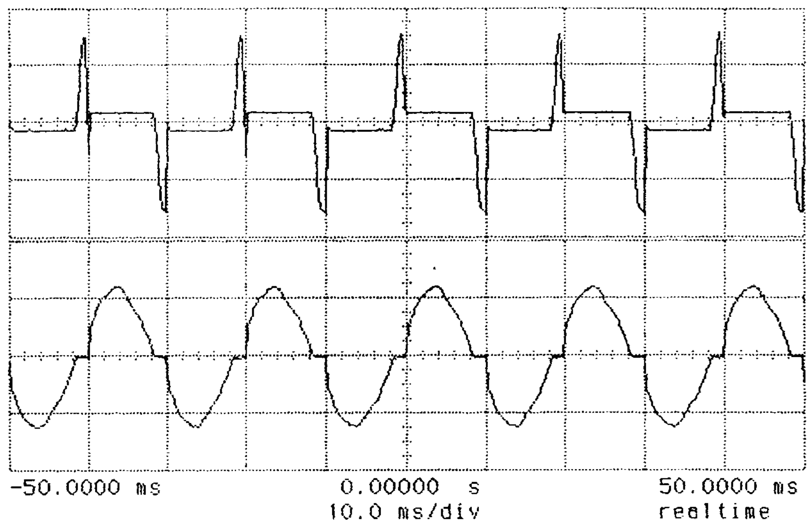
Fig. 6 shows the effect of the arc-damping function $\theta = \theta_0$ on the simulated dynamic characteristics. This series of simulations is obtained using the transient simulation function of Saber. The step change in the arc current imposed by the external circuit is shown in Fig. 6(a), while the corresponding arc voltage responses are shown in Fig. 6(b). The damping effect on the transient response can be clearly seen. A large arc voltage occurs, which then gradually decreases to the steady-state value. The rate of decay is observed to increase with the value of θ_0.

From the above simulation studies and analysis, a simple multistep parameter estimation procedure is proposed. For a given pair of electrodes and gas medium, experimental static characteristics should first be obtained. Simulations of the test conditions are then carried out to calibrate the model using the following guidelines.

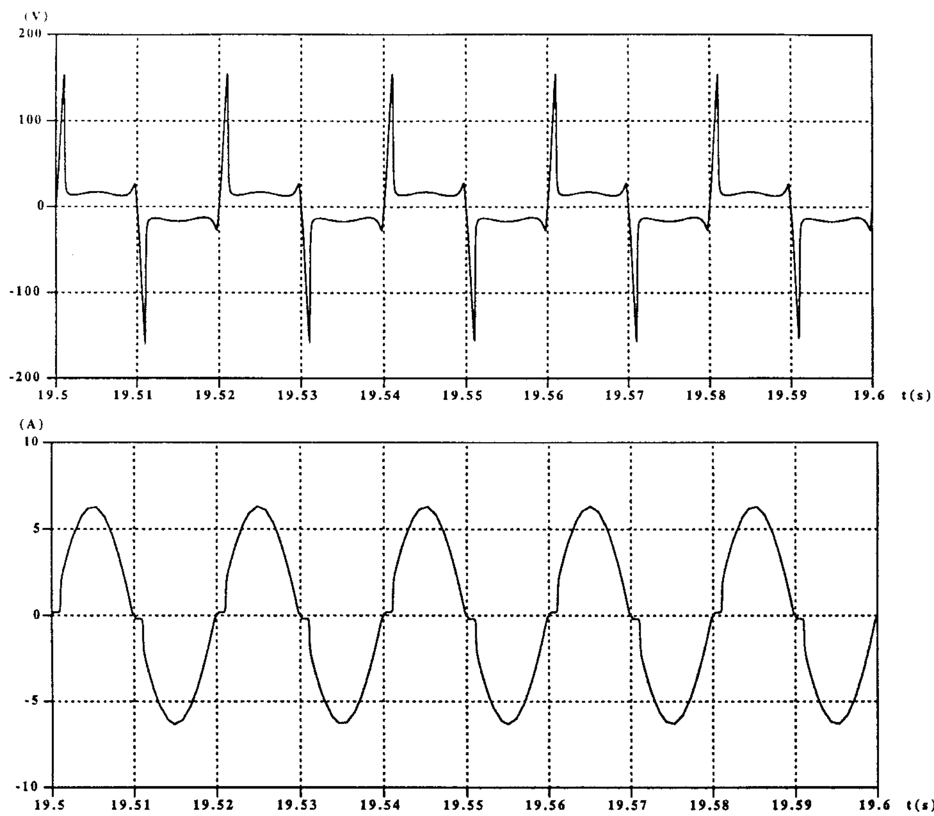
1) Choose E_0 such that the steady-state voltage at high-current levels is correctly simulated.
2) Choose I_0 such that the low-current curve is realistically reproduced.
3) Choose P_0 such that the extinguishing voltage is correctly simulated. The adjustment of P_0 and I_0 may have to be done iteratively until an optimum pair of values is obtained.
4) Choose $G_{\min}$ such that the simulated striking voltage is comparable to the observed experimental value.
5) Assume $\alpha = I_0$ and choose $\theta_0 = 0.01$ and $\theta_1 = 1000$. If transient experimental results are available, then adjust θ_0 and θ_1 so that the simulated transient-arc voltage and current matches the sample experimental results.

VI. Experimental Verification

The arc model was evaluated using the test circuit shown in Fig 7. Two brass electrodes with a diameter of 3 mm were used to create the arc. The arc was ignited by bringing the electrodes together and then slowly separating them to form



(a)



(b)

Fig. 9. Comparison of simulated and experimental transient-arc voltage and current: (a) experimental oscillogram and (b) simulation obtained using Saber.

an arc length of 5 mm. To obtain the experimental data of the static characteristics, a variable dc power supply was used. The dc supply voltage was gradually reduced while recording the arc voltage and current until the arc was extinguished.

Using the parameters-estimation procedure described in Section V, the model parameters for this particular arc setup have been determined as $E_o = 28$, $I_o = \alpha = 4.8$, $P_o = 30$, $G_{\min} = 1 \times 10^{-8}$, $\theta_0 = 1 \times 10^{-4}$, and $\theta_1 = 100$. Fig. 8 shows the simulated static characteristics obtained using the proposed hybrid model and experimental values. It should be noted here that it is not possible to compare the hybrid model with the original Cassie and Mayr models using our simulation method. The equations in the original Cassie and Mayr models were not meant for nodal-circuit analysis. It is not just that their predicted values would be unrealistic under certain operating conditions, but also that their invalidities cause severe convergence problems that prevent any meaningful simulations. The hybrid model not only combines the original Cassie and

Mayr models, but also incorporates important modifications that enable the electric arc to be simulated for all operating conditions, both static and dynamic.

For the investigation of dynamic characteristics, a 50-Hz ac power supply of voltage 415 $V_{\rm rms}$ was used so that the instantaneous relationship between the arc voltage and current can be observed and captured on a digital oscilloscope. Fig. 9 shows the comparison of the simulated and experimental instantaneous voltage and current waveforms when the arc is excited by the ac supply. It can be seen that for each half cycle (10 ms) of the ac supply voltage, the arc is momentarily extinguished and then reignited. The figures show good correlation between the simulated and experimental results.

VII. Further Work

The developed model is currently being used by the authors to design a power electronics circuit to generate an electric arc plasma that is pulsed at a high frequency of 100 kHz. The circuit would eventually be developed into a 10-kW power converter for a plasma reactor to be used for waste treatment. This experimental work will also provide verification for the arc model at high frequencies.

Plans are also underway to explore the possibility of applying the arc model for low-pressure arcs, such as fluorescent or neon lamps. The authors are also working on better techniques for estimation of parameters for the arc model.

VIII. Conclusion

An electric arc model is proposed here that facilitates the transient simulation of power electronic circuits controlling electric arc loads. The model has its roots in the classical Cassie and Mayr equations that were used extensively in the past to explain how the arc extinguishes in high-voltage circuit breakers. The equations of the proposed model have been cast in a form suitable for implementation in standard industrial circuit simulators. Experimental results obtained so far indicate that the model is able to predict the static and dynamic characteristics of the electric arc with reasonable accuracy for a given example.

References

[1] B. K. Bose, "Power electronics—An emerging technology," in *Proc. IEEE Industrial Elec. Conf.*, Singapore, 1988, pp. 501–508.

[2] L. Van der Sluis, "Comparison of test circuits for high voltage circuit breakers by numerical calculations with arc models," *IEEE Trans. Power Delivery*, vol. 7, no. 4, pp. 2037–2045, 1992.

[3] "Practical application of arc physics in circuit breakers—Survey of calculation method and application guide," *Electra (France)*, no. 118, pp. 66–79, May 1988.

[4] CIGRE Working Group 13-01, "Applications of black-box modeling to circuit breakers," *Electra (France)*, no. 149, pp. 40–71, Aug. 1993.

[5] K. Ibuki, "An arc model used in analysis of interruption test of GCBC," in *Proc. 9th Int. Conf. Gas Discharges and Their Appl.*, Venice, Italy, 1988, pp. 87–90.

[6] M. Narui and F. P. Dawson, "A SPICE model for simulating arc discharge loads," in *IEEE Ind. Applicat. Soc. Annu. Meet.*, Dearborn, MI, 1991, pp. 1476–1481.

[7] *Pspice Circuit Analysis Reference Manual, Ver 6.2*, Microsim Corp., CA, Apr. 1995.

[8] *MAST Reference Manual, Saber Simulator, Release 3.4*, Analogy, Inc., Beaverton, OR, 1995.

[9] J. D. Cobine, *Gaseous Conductors—Theory and Engineering Applications.* New York: McGraw-Hill, 1941.

[10] J. M. Meek and J. D. Craggs, *Electrical Breakdown of Gases.* London, U.K.: Oxford Univ. Press, 1953.

[11] T. E. Browne, "Practical modeling of the circuit breaker arc as a short line interrupt," *IEEE Trans. Power Apparatus Syst.*, vol. PAS-97, no. 3, pp. 838–847, 1978.

[12] A. M. Cassie, "Arc rupture and circuit serverity: A new theory," Paris, France, CIGRE Rep. 102, 1939.

[13] O. Mayr, "Beitrage zur theorie des statischen und des dynamischen lichbogens," *Archiv fur Elektrotechnik*, Berlin, Germany, vol. 37, no. 12, pp. 588–608, 1943.

[14] K. J. Tseng, "Saber templates for the design of inverters and motion controller," in *Int. Power Electron. Motion Control Conf.*, Beijing, China, 1994, pp. 732–736.

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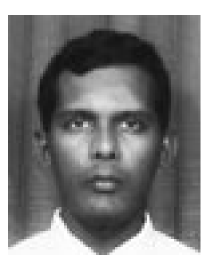

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