

Comparison of Universal Circuit Breaker Arc Representation with EMTP Built-in Model

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Abstract– A preliminary description of a new arc representation has been introduced in [1]. In which, the Modified Mayr (P - τ model) arc equations are solved in the Transient Analysis Control System (TACS) field of the Electromagnetic Transient Program (EMTP) and represented in the power network by TACS controlled voltage source. In this paper, substantial improvements of this representation are carried out to insure its universality. Details of implementation of the universal representation are given. A performance comparison with the EMTP built-in Avdonin model is incorporated to validate the proposed representation effectiveness. An SF6 circuit breaker rated at 40kA, 123kV with experimentally defined $P(g)$ and $\tau(g)$ functions are used as a test sample. The thermal limiting curve is computed by the proposed and the built-in models and compared with the measured characteristic. Test results validated the proposed representation regarding universality and accuracy.

Keywords– Modified Mayr Equation, EMTP Simulation, Arc Interaction, Arc Models, Switchgear

I. INTRODUCTION

Design of circuit breaker interrupting unit has been emphasized by several studies over the past years. Most of these studies have experimental nature, as the early breaker arc models have not produced satisfactory results for the manufacturers. Therefore, interrupter design was usually processed and optimized via series of laboratory tests in spite of the associated technical and economical sophistication. In order to overcome the experimental sophistication, efficient arc models should be developed to facilitate the evaluation of the interruption performance of the breaker. Modern breaker arc models have shown distinguished performance and numerous models are considered an important design aid particularly with the initial design of the interrupting units [2-6].

Breaker arc models can be classified into three categories. Thermal and dielectric recovery models that describe the arc dynamical behavior considering the impact of different interrupter parameters such as nozzle size and geometry, type of quenching medium and speed of flow, pressure, ... etc [2-3]. Other models are based on empirical form(s) [4]. Both categories are efficient in determining the internal dimensions and quenching medium parameters of the interrupter. However, the third category of models is concerned with the arc external characteristics such as Cassie, Mayr, and modified Mayr models [5-6]. This category is recommended, as far as evaluating breaker-interrupting performance in the power system is only concerned. This may explain why such models have been only

included in the EMTP software package [7].

Unfortunately, breaker arc card and card structure of ver 2.0 of the EMTP were inadequate to fulfil different applications. Therefore numerous papers have proposed new models/representations that can be implemented in the EMTP environment [8-11]. These models involves representation of the arc using variable resistance or the application of KEMA model. These representations would have better performance than that of the built-in ones. However, variable resistance model is not easily implemented in the EMTP environment and therefore it has been realized in the Alternative Transient Program (ATP). In addition, KEMA model requires manufacturing data, which may not be available to most of the users. Recently, the shortcomings of ver. 2 have been partially rectified with ver. 3.x of the EMTP [7]. In which, breaker arc model can be freely elected between three models; Avdonin or Modified Mayr, Urbanek, and Kopplin. Although these models show better accuracy, they do not have enough flexibility to account for universal applications. For example empirical arc models, arc furnace, possible innovations in arc models ... etc. can not be directly implemented. This can be remedied with the proposed arc representation [1]. Although this primary representation accounted for P - τ model only, additional efforts can be directed for further enhancement towards universality.

In this paper, a universal breaker arc representation in the form of controlled voltage source in the EMTP is presented. A comparison of the proposed representation with the EMTP built-in Avdonin model is performed. Thermal limiting curve derivation and breaker performance evaluation in a direct test circuit and transmission system are carried out. Possibility of implementing different arc models using the novel representation is investigated.

II. PROPOSED ARC REPRESENTATION

The proposed representation of the arc model can be explained with the help of Fig. 1. The generator is used to provide the breaker with the short circuit current level and the R_c - C_c branch is used to control the rate of rise of the recovery voltage (RRRV). The breaker arc is represented by TACS controlled voltage source type 60. The value of the voltage is computed in the TACS field by multiplying the computed arc resistance by the arc current measured by sensor 91. This resistance is derived from the dynamic arc equation(s) exploiting the TACS tools. At the next step, the corresponding arc voltage can be fed back into power network via controlled voltage source type 60. In this

manner, arc interaction with the power system elements is fully considered. Note that during pre-zero current periods, the controlled voltage source is connected to the system, as the switch SW is normally closed until current zero crossing. While for testing the breaker RRRV withstanding during post current-zero interval, the switch is opened and the breaker voltage is transported into TACS field by sensors 90. Then, the RRRV against the zero current conductivity states interruption/re-ignition conditions according to post zero dynamic arc equation(s). Control signals are generated in order to distinguish between the pre and post zero current periods. Details of the P - τ model implemented using this universal representation is given in [1] and summarized in the Appendix.

Some efforts have been directed to improve this model performance. These efforts include elimination of numerical instability that may be produced due to the wide difference between the power system and arc time constants. Also, representation of contact parting interval is considered. The most important enhancement is the adaptation of this representation to implement different arc models considering EMTP ver. 2.0 or higher. The later is investigated with example in section V.

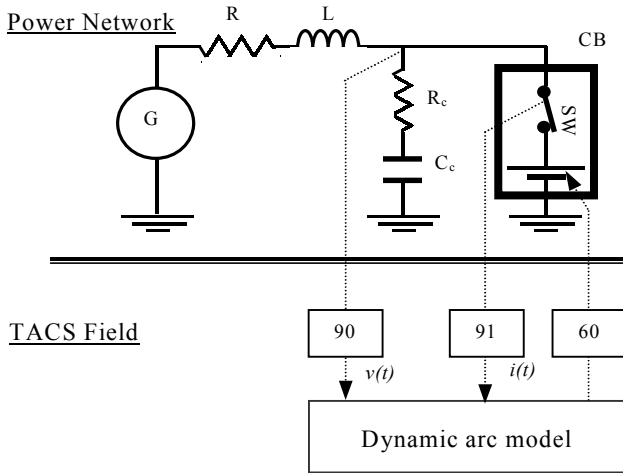


Fig. 1 EMTP network of synthesizer generator and breaker.

III. THERMAL LIMITING CURVE

An SF6 breaker rated at 123kV and 40kA breaking current is used as a test sample. The characteristic arc time constant $\tau(g)$ and power loss $P(g)$ functions were obtained experimentally via series of short circuit tests as traced by Fig. 2 [6]. It is obvious from Fig. 2 that, $P(g)$ and $\tau(g)$ functions are divided into three functions considering the magnitude of the conductivity. This would represent an obstacle to EMTP Avdonin model as the model accounts only for a single function of $P(g)$ and $\tau(g)$.

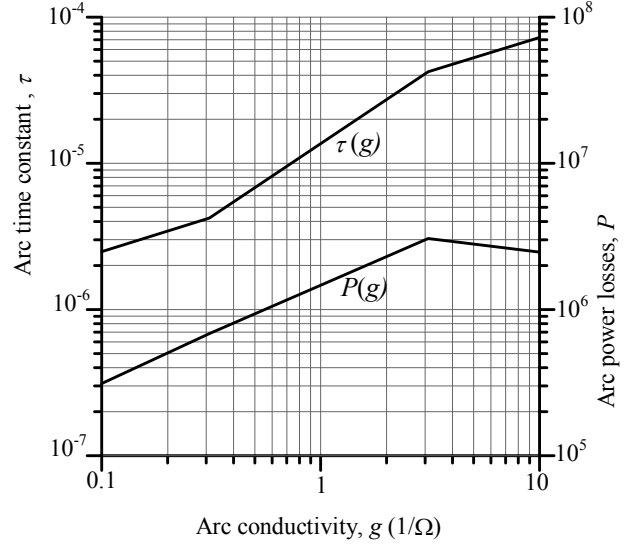


Fig. 2 Reported P - τ functions of the circuit breaker [6]

A. Limiting Curve Using the Universal Representation:

The thermal limiting curves are usually extracted using the synthesizer generator tester shown in Fig. 1. The tester is usually considered as stiff current and voltage sources for pre and post-zero crossings, respectively. Thus, EMTP network given by Fig.1 can be easily reduced to a simpler network as shown in Fig. 3. The network current and voltage are used as inputs to the first order differential equations of modified Mayr equation as:

$$g = \int \left(\frac{i^2(t)}{P(R)\tau(R)} - \frac{g}{\tau(R)} \right) dt \quad (1)$$

$$R = \int \left(\frac{R}{\tau(R)} - \frac{v^2(t)}{P(R)\tau(R)} \right) dt \quad (2)$$

where $i(t)$, $v(t)$, g , R , $\tau(R)$, and $P(R)$ are the arc current, voltage, conductivity, resistance, time constant, and power loss, respectively. Given that $g=1/R$, $\tau(R)=\tau_o R^\alpha$, and $P(R)=P_o R^\beta$, and α & β are constants. Note that, modified Mayr model is demonstrated here to explain the procedure only.

The three $P(g)$ and $\tau(g)$ functions of Fig. 2 are realized in the EMTP considering the flexibility of TACS FORTRAN expressions. The measured current is used as input to Eqn. (1) during the pre-zero crossing while the arc voltage is considered as an input to Eqn. (2) during post-zero crossing, as shown in Fig 3. In Fig. 3.a, the arc conductivity can be computed at zero crossing against the interrupting current (I) by applying different values of the current from the power network fed the integral form of Eqn. (1) in the TACS field. Thereafter, the value of g at the zero crossing is utilized as an initial condition for arc dielectric recovery described by a different DAT file. This file is developed for carrying out the RRRV limits during post-zero crossing as shown in Fig. 3.b. The stiff voltage source is represented by a source card with constant ramp value and excites the integral form of Eqn. (2). This equa-

tion is tested for different values of the RRRV for estimating the critical RRRV limit. By combining both results of pre and post-zero crossings, the RRRV–I limiting curve can be deduced to explore the breaker thermal failure limits as shown in Fig. 4. It is evident from Fig. 4 that a good matching between the computed and the reported thermal limiting curve traced by Fig. 5 for zero time delay of voltage application on the arc channel post current zero [6].

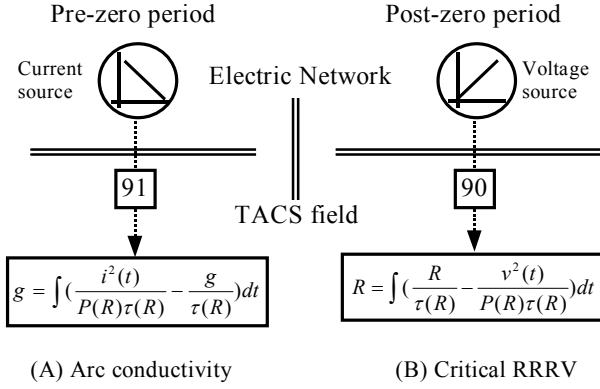


Fig. 3 Proposed technique for computing thermal limiting curve

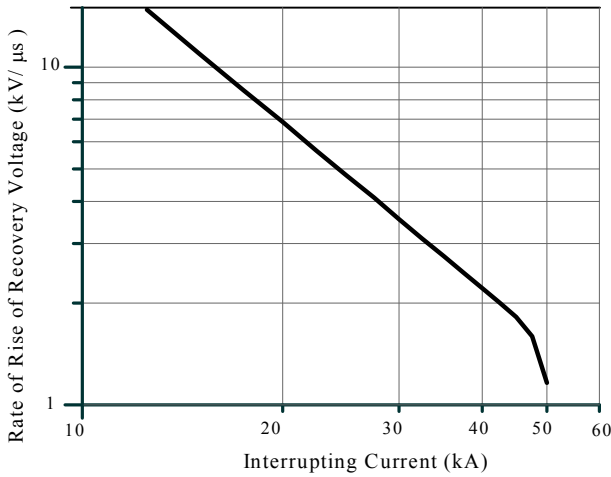


Fig. 4 Limiting curve using the universal arc representation.

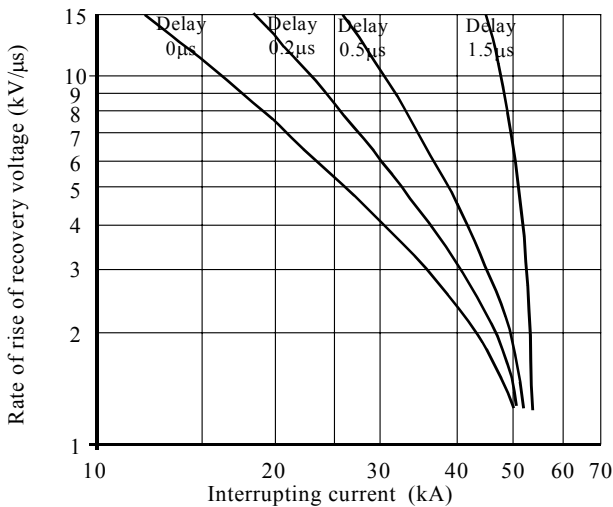


Fig. 5 Reported thermal limiting curves [6]

B. Limiting Curve Using EMTP Avdonin Model

Avdonin arc model is one of the breaker models of the EMTP and it is defined by arc voltage, arc time, parting time, node names, and the arc model parameters considering the following equation. [7]:

$$\frac{1}{R} \frac{dR}{dt} = \frac{1}{\tau(R)} \left(1 - \frac{v(t) \times i(t)}{P(R)} \right) \quad (3)$$

Deducing the limiting curves using Avdonin model is not an easy task. This is because it is not possible to measure the arc conductivity at zero crossing in order to test it with different RRRV until obtaining the critical level. The test circuit shown by Fig. 6 is proposed to overcome this issue. The circuit consists of current source with negative di/dt during the pre-zero crossing, while for post-zero region, a variable voltage source with constant ramp value (RRRV) is applied. The values of R_c - C_c are selected such that minimal deformations, as possible, on the breaker di/dt and RRRV nearby the zero crossing point are produced. These values are: $R_c=10k\Omega$ and $C_c=10^{-5}\mu F$. Note that reducing capacitor size and increasing the resistor would reduce the deformation in di/dt and RRRV. Also, the instant of closing the ASW is set equal to the starting time of the voltage source. This instant should be declared in the source card. In order to reduce the associated error, the computation time step should be selected as small as possible.

Another issue raised with the application of this particular breaker test sample. The breaker has three functions for the $P(R)$ and $\tau(R)$ considering arc resistance value. Declaring these functions is impossible considering EMTP Avdonin model cards. In order to sort out this issue, two solutions are proposed. The first one is to use $P(R)$ and $\tau(R)$ corresponding to the lowest value of g and use them in the arc parameter card. The other solution is to use some regression forms in order to reduce the three functions into single function. The first solution is applied and the limiting curve is computed as shown in Fig. 7. It is evident from Fig. 7 that the derived curve by the built-in model has a lower accuracy than that of the universal representation. The inaccuracy is progressively increased with the increasing of the interrupted current towards levels higher than $46kA$. This is attributed to the flexibility of the proposed representation in considering the three functions of $P(g)$ and $\tau(g)$ compared with only one function is declared in the built in Avdonin model.

In order to confirm the aforementioned conclusion, a single function of $P(g)$ and $\tau(g)$ is considered for the proposed representation and Avdonin built-in models. Then, the thermal limiting curves are computed, as shown in Fig. 8. The results of both models are fairly close, however both curves are relatively deviated from the reported limiting curve of Fig. 5. This would reveal that the proposed representation has the same accuracy of the built in models as far as single function of $P(g)$ and $\tau(g)$ is considered. However, the proposed representation has the flexibility to consider more than one function of $P(g)$ and $\tau(g)$.

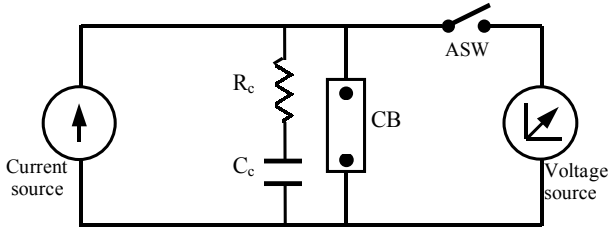


Fig. 6 Circuit breaker test circuit for carrying out the built-in thermal characteristic curve

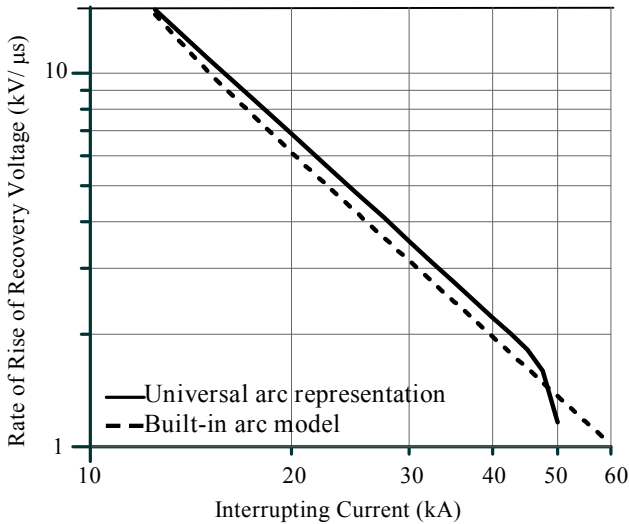


Fig. 7 Comparison of the computed limiting curves.

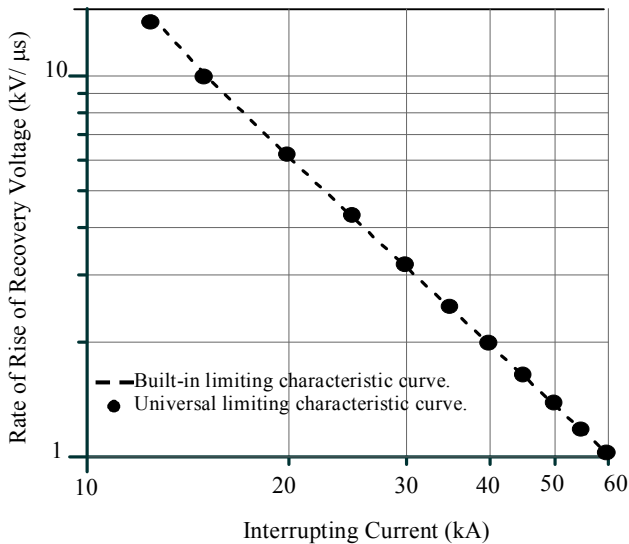


Fig. 8 Thermal limiting curves of the two models for the same arc parameters obtained for lowest g region.

IV. COMPARISON USING DIRECT TEST SYSTEMS

Testing of hvac circuit breakers using the laboratory direct test circuit is extremely difficult. Where, one source delivers the required current under the specified voltage as shown in Fig. 1. The EMTP network equivalent to the synthesizer generator of Fig. 1 can be deduced without the consideration of the aforementioned simplifications (stiff

current and voltage sources for pre and post-zero crossing, respectively). In this case, one DAT file program should handle both periods. For carrying out the computation study, the voltage source of Fig. 1 is selected with $106.14kV$ peak, 0° angle, and $60Hz$ frequency. While the R_c - C_c branch is 57.38Ω and $1.055\mu F$, respectively. The values R and L are 0.0Ω and $9.8mH$, respectively.

The breaker is represented at first with Avdonin model. In which, the circuit breaker starts parting its contacts at $5.0ms$, starting time of arc voltage T_{max} is $5.5ms$ with V_{max} of $800V$, and the arcing time is declared by $6.0ms$, from the program starting time. However for the universal representation, the same EMTP network with Avdonin cards is considered but with the replacement of Avdonin model by the proposed one. After the breaker is tripped, the dynamic arc equations are solved, arc voltage is computed and passed into the network. This will produce sudden change in voltage and may lead to numerical instability. In order to overcome this drawback, the arc controlled voltage source is set similar to the built-in model with constant ramp value representing the contact parting. Thereafter, the arc voltage is computed by solving the integral forms of the dynamic arc equations with consideration of the arc interaction. Fig. 9 shows the measured arc voltage using Avdonin and the universal arc representation. It is evident from Fig. 9 that, both time responses have exact-matching in the vicinity of the current zero. However, a slightly different behavior in the representation of contact parting as the proposed representation considers arc voltage building up with constant rate of $2.0kV/ms$ until reaching the estimated value by the dynamic arc equation.

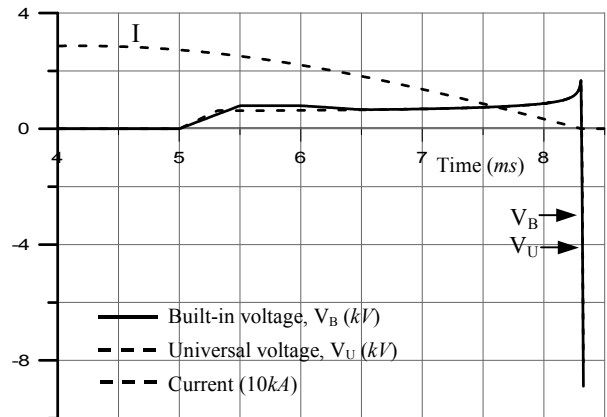


Fig. 9 Arc voltage comparison using direct test circuit.

On the other hand, testing the two models are also performed considering the power transmission system shown in Fig. 10. Parameters of this transmission system are given in [12] and used in this paper but for $110.0kV$ bus voltage. The following scenario is considered, at $32ms$ a line-to-ground fault is occurred at the end of the $15miles$ -transmission line. Consequently, the protection relays trip breaker CB1, which is represented by the SF6 breaker test sample. At $42ms$, the contacts of the breaker are separated and the arc is created. From this instant and until the arc extinction, the potential difference between BUS1 and

BRK1 is forced from the TACS field via the controlled voltage source. This represents a challenge in the EMTP, as the voltage source must be connected to one node name only according to the EMTP rulebook [7]. In order to sort out this problem, the controlled voltage source is replaced by two controlled current sources injecting current (I) and (-I) in a small resistance connected in series with the network. The produced voltage drop across this resistor is equal to the voltage of the controlled voltage source. Fig. 11 shows the performance of the proposed and the Avdonin representation of the modified Mayr arc model. It is evident from Fig. 11 that excellent matching between both responses is obtained.

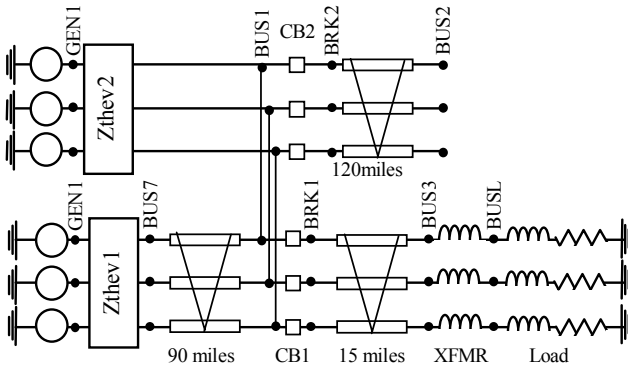


Fig. 10 Transmission line network.

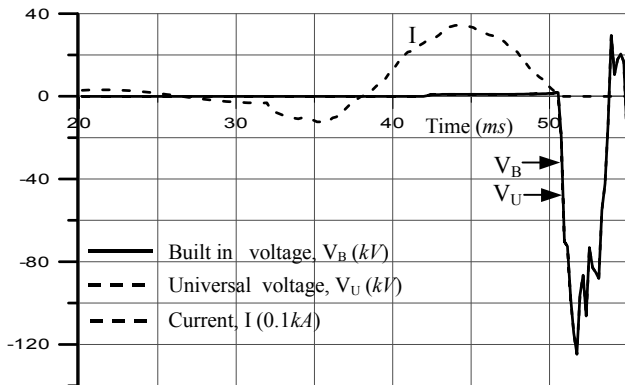


Fig. 11 Arc voltage comparison in transmission line.

V. PROPOSED REPRESENTATION UNIVERSALITY

One of the innovations in arc models is the introduced one by KEMA High Power Laboratory Group [11]. Although, this model can not be realized considering the built-in models, it can be implemented with the help of the proposed representation by adapting the arc model to:

$$\frac{1}{g} \frac{dg}{dt} = \frac{1}{\tau} \left(\frac{v \cdot i}{\max(U_{arc} |i|, P_o + P_1 v \cdot i)} - 1 \right) \quad (4)$$

where P_l and P_o are constants of cooling power and τ is the arc time constant. However, U_{arc} is the constant arc voltage in the high current area. If this value is zero, KEMA is transformed into Mayr model. In order implement this model, the considered parameters of an SF6 breaker rated at 245kV/50kA/50Hz are $\tau=0.27\mu s$, $P_o=15917$, and $P_l=0.994$. These values have been determined

from a least square fit of KEMA experimental results [11]. This arc model represents Cassie model during the high current, while nearby zero current the modified Mayr is dominant. This feature is provided by the **max** statement of Eqn. (4).

The real time operation of the breaker can be evaluated with the help of the transmission system given in Fig. 10. However, the system bus voltage is adjusted to 230kV. The arc voltage is declared with approximately 1100V in high current area. The time response of the breaker is given by Fig. 12 for the same scenario described in Section IV. It is found that the arc voltage in the high current area is close to the specified one by the model data which reflects the conformity with Cassie model, while near zero point the improved Mayr model with its three free parameter is ruling the arc performance. This result insures the universality of the proposed arc representation as it can be easily altered to suit other arc models.

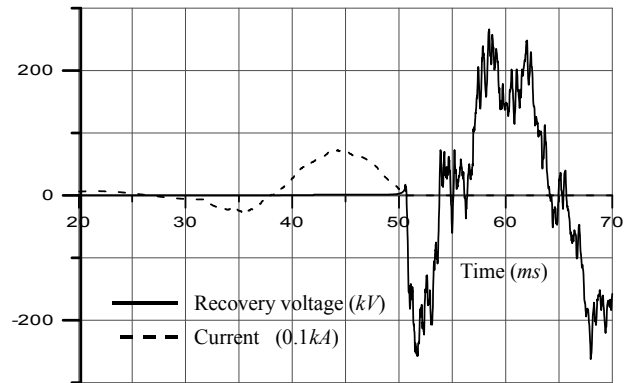


Fig. 12 Real time operation of ac breaker

VI. CONCLUSIONS

A universal arc representation in the EMTP environment has been validated via comparing the results with the Avdonin built-in model. The thermal limiting curves have been computed and models' performances are deeply investigated. The investigation has been extended to cover breaker operation in a direct test circuit and in a typical power transmission system. Possibility of implementing alternative arc models such as the KEMA model has been proven and therefore, the simplicity of altering the proposed representation to suit different models is confirmed. This result insures representation universality.

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APPENDIX

The proposed arc representation is depicted in Fig. A.1 [1]. The two integral forms of the modified Mayr model is combined in one arrangement. After breaker tripping, the arc is created. In order to distinguish the current pre and post-zero crossing periods, the control signals CTRA and CTRV are generated by the assistance of the Logical FORTRAN expressions. In pre-zero intervals, the signal CTRA is relatively high until current zero. However in the post-zero periods, the CTRV signal turns to high and CTRA is low. This is achieved using a conditional statement (device type 60) for comparing the arc current with zero value. The result of this device and the generated signal SIG0 are used as inputs for the AND gate which is represented by a supplemental variable using logical operators in the FORTRAN statement. The produced signals CTRA and CTRV are used as control signals for the two controlled integrators. When CTRA is high, Eqn. (1) is solved for computing the arc conductivity during pre-zero periods. Consequently, the arc resistance is magnified by the arc current value to compute the arc voltage, which is fed back into the power network in the next time step. Also, the arc resistance is used in calculating $\tau(R)$ and $P(R)$. When the control signal CTRV is high, the value of the arc resistance at zero crossing is used as an initial condition for Eqn. (2) during post-zero current. Consequently, the arc resistance can be computed and interruption/re-ignition of the breaker is decided.

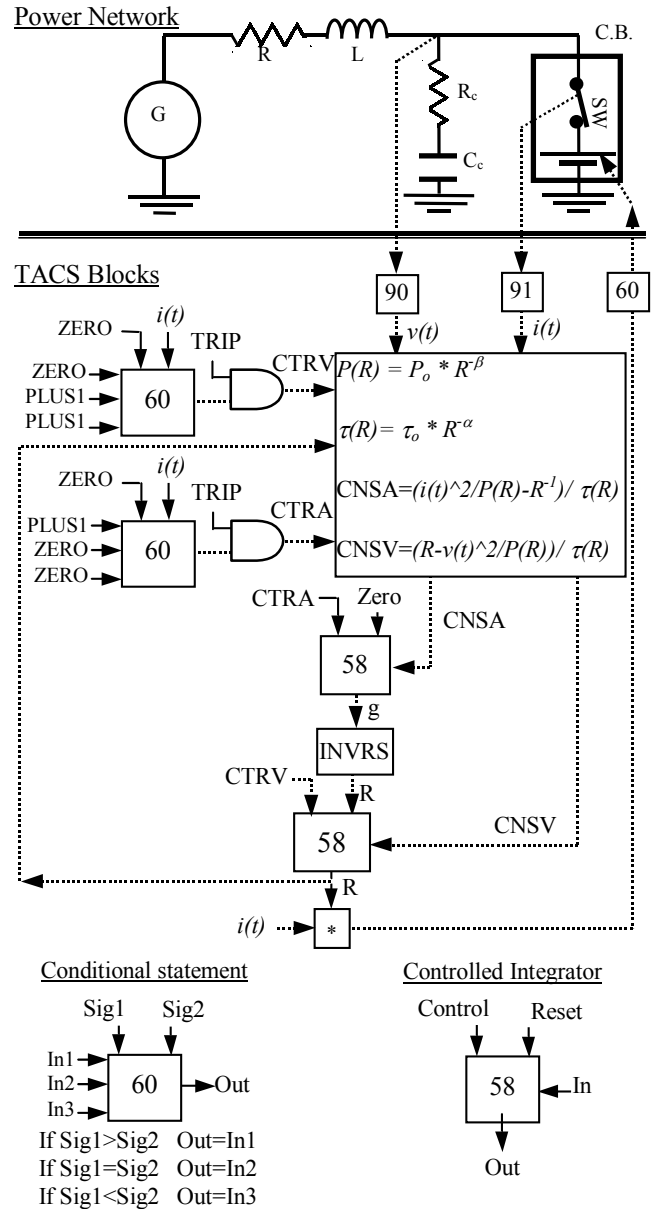


Fig. A1 Universal arc representation of modified Mayr model

BIOGRAPHIES

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