Investigation of Arc Parameters in Serially-Connected 3 Arc Model

T. Koshizuka, K. Udagawa, T. Iijima, T. Uchii, T. Shinkai, T. Mori

***Abstract*-- This paper shows the simulations of SLF interruption performance for SF_6 gas circuit breaker by serially connected 3 arc models. The arc model is constructed by serially connecting one Cassie model and two Mayr models. A 550kV model circuit breaker was used to measure and simulate the SLF interruption performances. Simulations were good agreed with the measurements. Mayr arc time constant of 550kV model circuit breaker and the 300kV model circuit breaker was identical. But, Cassie arc time constant was different from the 300kV model circuit breaker. It was investigated the Cassie arc time constant and showed the relation with nozzle throat diameter.**

***Keywords*: Arc model, SLF interrupting performance, SF6 gas, Arc parameter.**

I. Introduction

Because a circuit breaker interrupts a current by blowing compressed SF_6 gas or alternative gas to arc for extinction, the gas flow during the current interruption process is often observed and analyzed. However, it is difficult to directly calculate the success or failure of current interruption by analyzing gas flow.

On the other hand, arc models such as the Cassie [1] and Mayr [2] models can be easily combined with a circuit to determine the success or failure of current interruption. Avdonin [3], Urbanek [3] and Kopplin [4] models are used in EMTP. And, serially connecting Cassie and Mayr model [5][6] were known. Serially connecting three modified Mayr models was used to evaluate interruption performances for the circuit breakers [7]. However, it is difficult to derive relations among arc parameters (such as arc time constant and arc power loss of an arc model), the structure of a circuit breaker, and how the gas flows.

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We established serially connected 3 arc models to analyze the short line fault (SLF) interruption performances with an SF_6 gas circuit breaker [8][9]. The arc model was constructed by serially connecting one classical Cassie model and two classical Mayr models. The Cassie model simulates the large current region. The two Mayr models have different arc parameters. One of them was used as a model for simulating the vicinity of the arc voltage extinction peak (defined as Mayr model 1) and the other was used as a model for simulating the vicinity of the current zero (defined as Mayr model 2). At the rated voltage of 300kV, the interruption performances of two types of model circuit breaker were reproduced with a calculation using EMTP-ATP Models.

In this paper, a 550kV model circuit breaker was used to measure the SLF interruption performances. Using serially connected 3 arc models, the interrupting performances and arc voltage were reproduced. Based on the results, we investigated arc parameters and showed that it is possible to set the same values for the arc time constants of a Mayr model 1. We also showed that the ratio of the arc time constant and arc power loss of the Mayr model 2 versus those of the Mayr model 1 are the same for each circuit breakers. In addition, we investigated the arc time constant with the Cassie model and showed the relation with nozzle throat diameter.

We also combined a simplified circuit with arc models, and calculated the SLF interruption performances using the finite difference method instead of using EMTP-ATP.

II. Serially Connected 3 Arc Models for a SF_6 Gas Circuit Breaker [8][9]

Equation (1) is for the Cassie model and (2) is for the Mayr model. In general, it is said that the Cassie model can simulate an arc in a large current region and the Mayr model can simulate an arc in the vicinity of the current zero. The calculation of SLF interrupting performance used to focus only on the region in the vicinity of the current zero and a single Mayr model or serially connected 2 Mayr model were often used. The arc models used here were serially connected 3 arc models to reproduce the arc voltage from a large current region, and furthermore to evaluate the SLF interrupting performance of the circuit breaker.

Figure 1 explains serially connected 3 arc models. The arc voltage of a circuit breaker is the cumulative arc voltages of three arc models. That is, a large current region is shown using the Cassie model; the region in the vicinity of the extinction peak is shown using the Mayr model; and, the region in the vicinity of the zero is shown using another Mayr model, thereby simulating the arc voltage covering the entire range from a large current region to the current zero.

Cassie model:

$$\frac{1}{g}\left(\frac{dg}{dt}\right)=\frac{1}{\theta_c}\left(\frac{v^2}{v_0^2}-1\right) \quad (1)$$

Mayr model

$$\frac{1}{g}\left(\frac{dg}{dt}\right)=\frac{1}{\theta_m}\left(\frac{vi}{P}-1\right) \quad (2)$$

g : arc conductance, v: arc voltage, i: current,
θc: Cassie model arc time constant, v_0: Cassie model arc voltage, θm: Mayr model arc time constant, P: Mayr model arc power loss

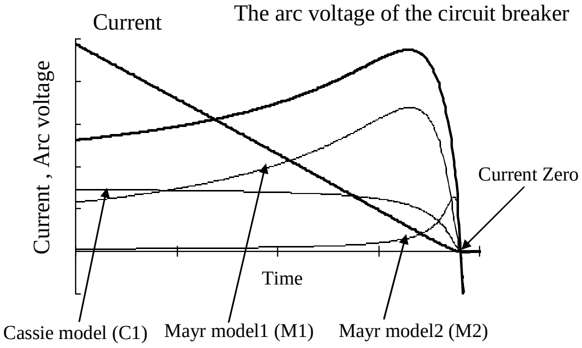


Fig. 1. Explanation of serially connected three arc models

III. 300kV MODEL CIRCUIT BREAKER

Figure 2 compares measured and simulated current and voltage waveforms for a 300kV double flow-type model circuit breaker under the 63kA-50Hz-90% SLF interruption condition. It shows that the interruption was successful and the post arc current was observed after the current zero. Good agreement is seen between measured and simulated falling current, post arc current, and arc voltage. The success or failure of interruption is also reproduced well. In Figure 2, the following arc parameters were used for the calculation.

Cassie model: $\theta c=2.5$ μs, $v_0=1500$ V
Mayr model 1: $\theta m_1=1.6$ μs, $P_1=680$ kW
Mayr model 2: $\theta m_2=0.16$ μs, $P_2=13.6$ kW
($\theta m_2=\theta m_1\times 10\%$, $P_2=P_1\times 2\%$)

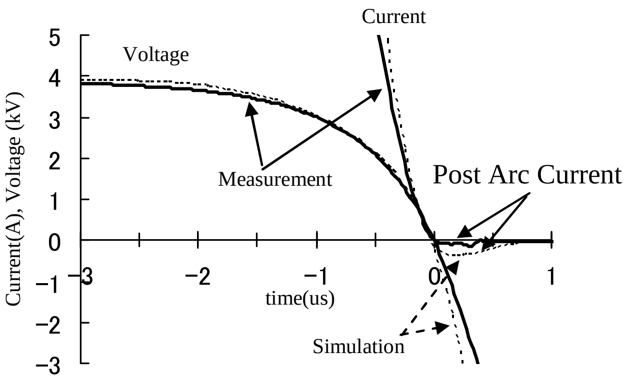


Fig. 2. Comparison between measured and simulated waveforms for 300kV SF_6 gas model circuit breaker

The value of each arc parameter in the Figure 2 was set so that measured and simulated arc voltage waveforms were identical.

The same simulation was conducted for the model circuit breakers of different types at the same rated voltage.

Table I shows the arc time constant for the arc model used for calculating the interrupting performance of the aforementioned 300kV double flow-type model circuit breaker (Model CB-1) and a 300kV tandem puffer-type model circuit breaker (Model CB-2). The Mayr model 1 arc time constants for both CB-1 and CB-2 model circuit breakers are identical because the extinction peaks of both model circuit breakers are the same, which is approximately a current of 100A. In addition, the Mayr model 2 arc time constants for both model circuit breakers were made identical. As a result, the Cassie model arc's time constants were different.

TABLE I
ARC TIME CONSTANT FOR 300KV CB USED IN SIMULATION

Arc time constant	Cassie	Mayr-1	Mayr-2
Model CB-1	2.5μs	1.6μs	0.16μs
Model CB-2	1.5μs	1.6μs	0.16μs

IV. 550kV MODEL CIRCUIT BREAKER

A. Arc voltage

Figure 3 shows the measurement results of arc voltage and current for the 550 kV model circuit breaker (hybrid puffer type). The measurement conditions were interruption current of 63 kA-50 Hz–90% with arc time varied. The current and arc voltage were measured using a Rogowski coil and a voltage divider installed near the model circuit breaker, and each value was converted into a digital signal by sampling at 40 MHz and a resolution of 12 bits [10].

The figure shows the following.

1) In the region of a large current of 10kA or more, arc voltage values are almost constant-approximately 1700V.
2) Arc voltage is highest around the time when current is 100A, which is the extinction peak. This current value is identical to that of the 300kV model circuit breakers in Chapter III [8][9].

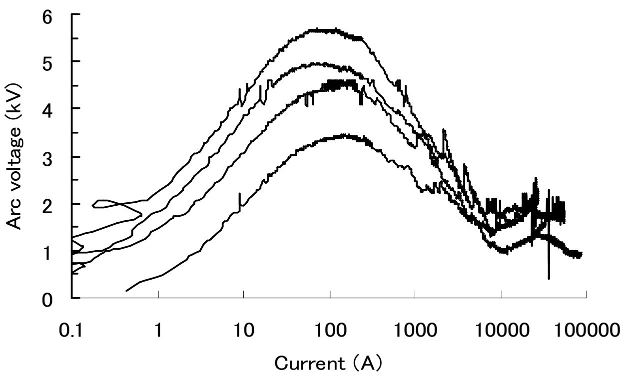


Fig. 3. Measurement result, the relation between current and arc voltage of 550kV model circuit breaker

B. Interruption performances with serially connected 3 arc model

Figures 4 and 5 show comparisons of measured waveforms of current and arc voltage for waveforms simulated with serially connected 3 arc models. Both Figure 4 and Figure 5 show a good agreement between measured and simulated waveforms and reproduced success or failure of interruption with the calculation. Table II summarizes arc parameters used for this calculation.

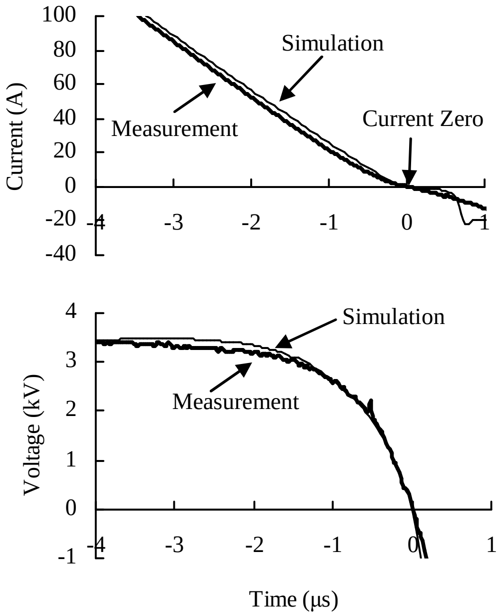


Fig. 4. Comparison between measured and simulated waveforms for 550kV SF_6 gas model circuit breaker, case of interruption failure

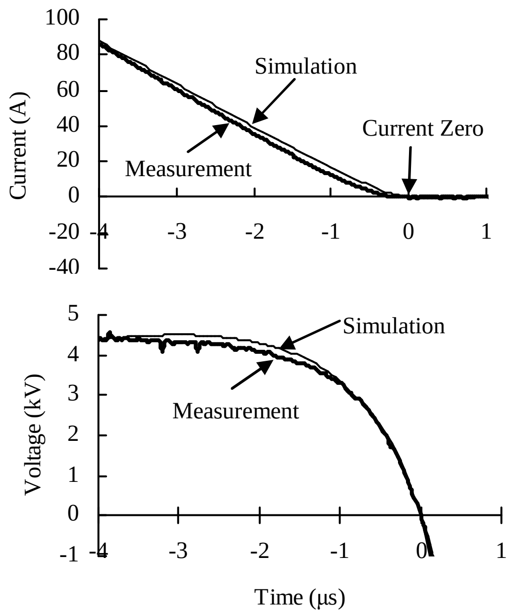


Fig. 5. Comparison between measured and simulated waveforms for 550kV SF_6 gas model circuit breaker, case of interruption successful

TABLE II

ARC PARAMETERS USED IN FIGURE 4 AND FIGURE 5

	Cassie	Mayr-1	Mayr-2
Arc time constant	1.95μs	1.6μs	0.16μs (10%×Mayr-1)
Arc voltage / Arc power loss	1700V	A	2%×Mayr-1

(A: Set to agree with the voltage value at the extinction peak.)

V. ARC PARAMETERS FOR SF_6 GAS CIRCUIT BREAKER

A. Mayr arc time constant

This is a known method to calculate Mayr model arc parameters by processing measured current and arc voltage waveforms. Figure 6 shows the calculation method.

The horizontal axis shows the values obtained by multiplying values of current and arc voltage. The vertical axis shows the left side of the equation (2). The points in the above figure show the calculation values at each sampling time for measurement. By drawing a tangent line on the calculation values as shown in Figure 6, arc time constant and arc power loss are obtained from the point intersecting each axis.

Figure 7 shows the calculation results of Mayr arc time constant for the 300kV model circuit breaker 1 and the 550kV model circuit breaker within the current range of 100A to zero using this calculation method.

Figure 7 shows the following:

a) In the range of measured current of 100A or less, the arc time constant for the 300kV model circuit breaker 1 and that for the 550kV model circuit breaker are almost identical.

b) The arc time constant of a current of 100A around the arc voltage extinction peak agrees with the value used for calculations in the previous sections.

c) Arc time constant falls from the extinction peak toward current zero.

d) The arc time constant directly before the current zero is approximately 0.1μs, which agrees with the Mayr model arc time constant set for simulating the vicinity of the current zero.

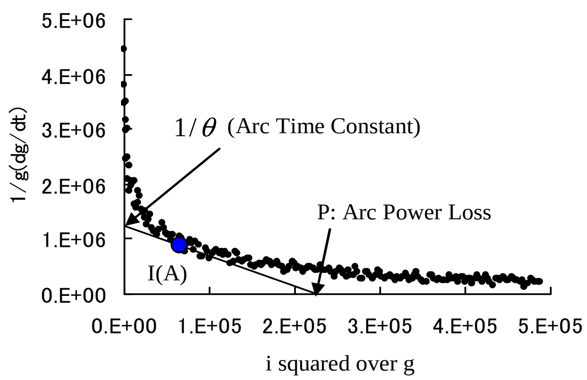


Fig. 6. Explanation for calculation of Mayr arc time constant in i^2/g -1/g dg/dt

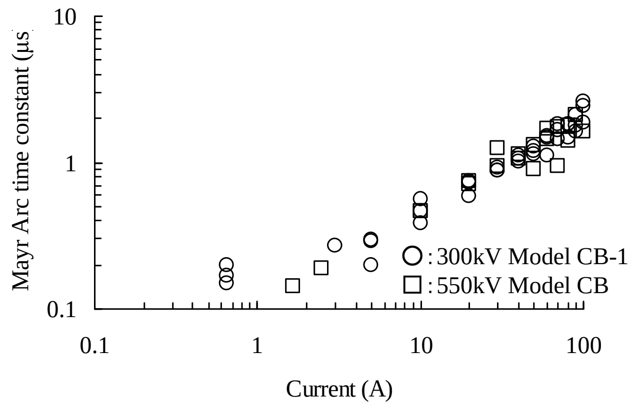


Fig. 7. Mayr arc time constants of 300kV model CB-1 and 550kV model CB

Reference [11] shows there are two arc time constants in molecular gas-arc time constant corresponding to the core and the cooler outer zone. The arc time constant of the arc in SF_6 gas continues to fall even with a current of 1 A or less. Reference [11] shows that the arc in SF_6 gas consists only of the core and the core diameter's changes correspond to small arc time constants. Arc time constants of SF_6 in Figure 7 change just as stated in [11].

B. Cassie arc time constant

Figure 8 shows the relation between Cassie model arc time constants and diameter of nozzle throat used for calculation with 300 kV model circuit breakers 1 and 2 as well as a 550 kV model circuit breaker. The arc time constant was, as stated above, set as shown in Figure 8 by repeating calculations so that arc voltage and the interruption performances correspond to measurements. The line connecting the three points in Figure 8 is an approximated curve produced by spread-sheet software, Excel ®. The line best expressed the relation among three points when approximated by a quadratic expression, which shows that Cassie arc time constants are expressed by a square function of the circuit breaker's nozzle throat diameter.

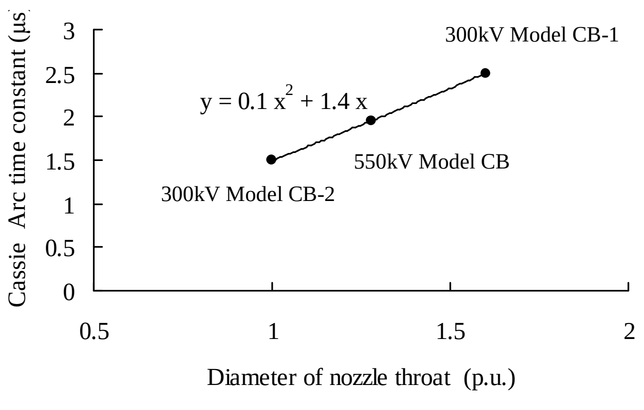


Fig. 8. Relation between Cassie arc time constants and diameter of nozzle throat

The equation (3) expresses the Cassie model expressed by equation (1) with regard to arc time constant θ:

$$\theta = \left(\frac{v^2}{v_0^2} - 1 \right) \cdot g \cdot \frac{dt}{dg} \tag{3}$$

Given that the arc voltage expressed by the Cassie model is constant up to the vicinity of current zero, with current consistently decreasing toward the current zero, dg/dt=constant will be the case.

With arc radius *r*, current flowing in arc *I* and arc voltage *E*, the Ohm's law for an arc column is shown in equation (4). In general, electrical conductivity σ spreads in the direction of arc radius along with the temperature distribution in the direction of arc radius. However, due to the Cassie model's assumption of high temperature and small change of the electrical conductivity, we can simplify and assume the electrical conductivity to be constant, thereby transforming equation (4) into (5) and obtaining the relation between conductance *g* and arc radius *r*. If equation (5) and dg/dt=constant substitute in equation (3), arc time constant is expressed by equation (6), resulting in an arc radius function.

Figure 8 shows the relation between the diameter of the nozzle throat and arc time constant. When the diameter of the nozzle throat is small, arc radius is also small, which makes Cassie arc time constant small.

$$I = 2\pi \int_0^r \sigma E r dr \tag{4}$$

r: arc radius, σ: electrical conductivity, *E*: arc voltage

$$\frac{I}{E} = g = \pi r^2 \sigma \tag{5}$$

$$\theta = \left(\frac{v^2}{v_0^2} - 1 \right) \cdot g \cdot \frac{dt}{dg} = \left(\frac{v^2}{v_0^2} - 1 \right) \cdot \frac{\pi r^2 \sigma}{C} \tag{6}$$

C: constant

VI. Practical Applications

Because EMTP was used to evaluate SLF interrupting performance by serially connected 3 arc models, the circuit and its constant can be set freely and detailed analyses are possible. It has become easy to set up arc parameters, which makes evaluating interrupting performance with a simplified circuit effective as well. So, we tried to evaluate interrupting performance by applying the finite difference method to arc models expressed by a differential equation and combining it with a simplified SLF interruption circuit. We did the calculation using the macro function of spread-sheet software instead of using EMTP-ATP.

Figure 9 shows a simplified circuit for short line fault interruption [12].

r, L and C are source-side impedance and r_b is a damping resistor for source-side TRV. Z simulates surge impedance for transmission line connected to the end of a circuit breaker. In actuality, after interruption, voltage oscillation occurs in the transmission line and triangular voltage wave appears at line-side terminal of the circuit breaker. Although, on the circuit in

Figure 9, a rate of rise of the triangular voltage wave on transmission line can be simulated, we cannot simulate whole triangular waveforms. However, in an actual interruption, success or failure is often determined by the time between current zero and first triangular voltage wave peak. Therefore, simulating the success or failure of interruption is possible using the circuit in Figure 9 as well.

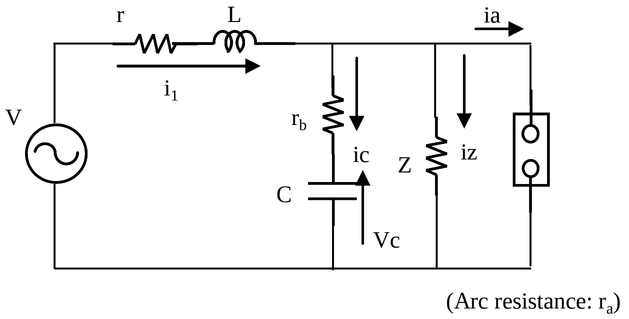


Fig. 9. SLF simplified calculation circuit

Equations for the circuit in Figure 9 are (7),(8) and (9).

$$V = r \cdot i_1 + L\frac{di_1}{dt} + r_a \cdot i_a \tag{7}$$

$$C\frac{dV_c}{dt} = i_1 - i_a - i_z \tag{8}$$

$$r_a \cdot i_a = Z \cdot i_z = r_c(i_1 - i_a - i_z) + V_c \tag{9}$$

Equations (10) and (11) are obtained by transforming equation (9), which is then substituted in equations (7) and (8), and the finite difference method is applied.

$$i_1\big|_{t=t+\Delta t} = i_1 + \frac{(V - r_1 \cdot i_1 - r_a \cdot i_a)\cdot \Delta t}{L} \tag{10}$$

$$V_c\big|_{t=t+\Delta t} = V_c + \frac{(i_1 - i_a - i_z)\cdot \Delta t}{C} = V_c + \frac{(i_1 - i_a - \frac{r_a}{Z}\cdot i_a)\cdot \Delta t}{C} \tag{11}$$

Cassie model and Mayr arc model are expressed by arc conductance in equations (1) and (2), in which conductance is expressed as resistance (R_C: Cassie Model resistance, R_M: Mayr model resistance) to make the calculation easier. Applying the finite difference method to each, equations (12) and (13) were obtained.

$$R_C\big|_{t=t+\Delta t} = R_C + \frac{R_C}{\theta_C}\left(1 - \frac{i^2 \cdot R_C^2}{v_0^2}\right)\cdot \Delta t \tag{12}$$

$$R_M\big|_{t=t+\Delta t} = R_M + \frac{R_M}{\theta_m}\left(1 - \frac{v \cdot i}{P}\right)\cdot \Delta t \tag{13}$$

With Cassie and Mayr model finite difference equations, for the serially connected 3 arc models, we should simply add the resistance values obtained from these equations and substitute r_a with the resistance value in equations (10) and (11).

Figure 10 shows an example of the calculation result. Equations (10),(11),(12) and (13) were programmed by macro function of spread-sheet software instead of using EMTP-ATP. Calculation conditions and arc parameters were set as follows.

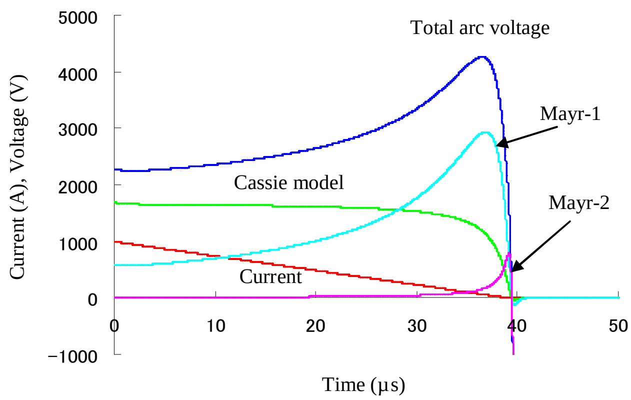
550kV-63kA-90%, 50Hz and 60Hz

Cassie model: θc=1.95 µs, V_0=1700 V

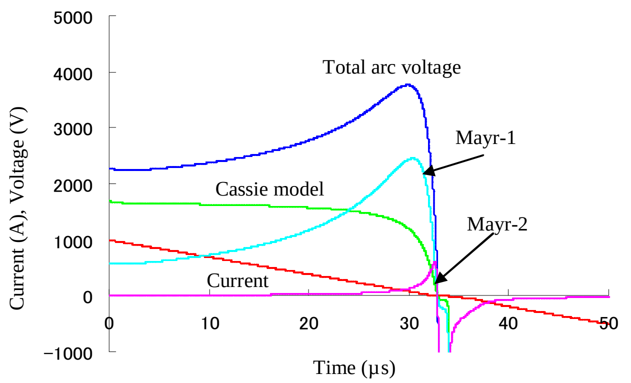
Mayr model 1: θm_1=1.6 µs, P_1= 0.58 MW

Mayr model 2: $\theta m_2 = \theta m_1 \times 10\%$, $P_2 = P_1 \times 2\%$

In Figure 10 (a), interruption succeeded with the condition 63kA-90%-50Hz. In Figure 10 (b), however, interruption failed with the condition 63kA-90%-60Hz. It was found that with the simplified simulation circuit in Figure 9 the SLF interruption performances can be calculated by using spread-sheet software.



(a) 550kV - 63kA - 90%, 50Hz, interruption succeeded



(b) 550kV - 63kA - 90%, 60Hz, interruption failed

Fig. 10. Example of calculation result under a condition of 550kV - 63kA - 90%, 50Hz and 60Hz by finite deference method instead of using EMTP-ATP

VII. Conclusion

By applying serially connected 3 arc models that were developed to evaluate a circuit breaker's short line fault (SLF) interruption interrupting performance for the rated voltage of a 550kV model circuit breaker, the following results were obtained:

1) In addition to previously made serially connected 3 arc

models using a model circuit breaker with a rated voltage of 300kV, we showed that the model is applicable to a 550kV model circuit breaker with a different rated voltage.

2) We showed that the value of the Mayr model arc time constant for simulating the vicinity of the point zero from around extinction peak is the same even with a different rated voltage.

3) The value of the arc time constant of 2), which was estimated from the waveform of arc voltage, corresponds to the value obtained with a different arc time constant calculation method.

4) The relation between Cassie model arc time constant and nozzle throat diameter was discovered.

5) We presented an interrupting performance calculation method by combining a simplified SLF circuit and arc model and using the finite difference method. With this method, it is possible to calculate the success or failure of interruption using a programming language such as the macro function of spread-sheet software as well.

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