Circuit Breaker Model using Serially Connected 3 Arc Models for EMTP Simulation

T. Koshizuka , T. Shinkai , K. Udagawa , H. Kawano

Abstract--**This paper shows the simulation of SLF interrupting performance for SF6 gas circuit breaker. From the measurements on 300kV-SF6 gas model circuit breaker, it was shown that the extinction peak voltages were varying with arcing times. But, the current values at the extinction peak were the identical. To simulate the SLF interrupting performance for the circuit breaker, serially connected 3 arc models with different arc parameters were used. There was good agreement between the measurements and simulations.**

***Keywords*: Circuit Breaker, Cassie model, Mayr model, EMTP, MODELS.**

I. INTRODUCTION

The Short-line-fault (SLF) interruption performance of a circuit breaker is evaluated by calculation in which serially connected multiple arc models are combined within a circuit [1] [2] [3]. When using arc models for calculation, it is important to set the arc parameters such as the arc time constant and arc power loss. A method of extracting arc parameters from measurement data has been proposed [4], but it necessitates complicated data processing such as differentiation of arc resistance or arc conductance and linear approximation.

This paper describes an evaluation method in which the parameters of the arc models are estimated from the waveform of the arc voltage with respect to the current, and the results are used to calculate the SLF interruption performance of an SF6 gas circuit breaker. The arc model for calculating the interruption performance was constructed by serially connecting one Cassie model and two 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).

Interruption tests were carried out using a 300 kV SF6 gas model circuit breaker (hereafter called “model circuit breaker”) under 63 kA – 50 Hz – 90% SLF interruption conditions, and the success or failure of interruption and the arc voltage were measured. It was confirmed that the voltage in the large current region remained roughly constant regardless of the arcing time, and also that the value of the arc voltage at the extinction peak varied according to the arcing time, but the value of the current at the extinction peak remained constant regardless of the arcing time.

The arc voltage waveform in the large current region can be simulated by making the parameters of the Cassie model constant, and the value of the extinction peak voltage can be simulated by adjusting the arc power loss of Mayr model 1. The fact that the value of the current at the extinction peak is constant could be simulated by making the identical value of the Mayr model 1 arc time constant. The arc voltage waveform from the extinction peak to the current zero could be simulated by Mayr model 2. In addition, good agreement between measurement and calculation of the success or failure of interruption was obtained by setting the arc time constant of Mayr model 2 to 10% of that of model 1, and the arc power loss to 2% of that of model 1.

In the EMTP simulations, these arc models were defined using MODELS, and combined with the SLF synthetic test circuit [1].

II. MEASUREMENT OF SLF INTERRUPTION PERFORMANCE OF THE MODEL CIRCUIT BREAKER

Figure 1 shows the results of a 63 kA – 50 Hz – 90% SLF interruption test performed on the model circuit breaker. In the interruption tests, the interrupting current was maintained constant, and the arcing time was varied. Figure 1 shows the value of the extinction peak of the arc voltage, and also the success or failure of interruption, versus the arcing time. Interruption fails when the arcing time is approximately 13 ms, and is successful when the arcing time is approximately 14 ms. The value of the extinction peak is low when the arcing time is short, and progressively increases to a maximum when the arcing time becomes approximately 18 ms. At D where the arcing time becomes increasingly long, the value of the extinction peak becomes low once again.

Figure 2 shows the arc voltage versus the arc current. It indicates the period from a point approximately 4 ms prior to the current zero. The horizontal axis is a logarithmic scale.

T. Koshizuka is with Power & Industrial Systems Research & Development Center, Toshiba Co., Kawasaki, JAPAN (e-mail of corresponding author: tadashi.koshiduka@toshiba.co.jp).
T. Shinkai is with Power & Industrial Systems Research & Development Center, Toshiba Co. Kawasaki, JAPAN
K. Udagawa is with Power & Industrial Systems Research & Development Center, Toshiba Co., Kawasaki, JAPAN
H. Kawano is with Power & Industrial Systems Research & Development Center, Toshiba Co., Kawasaki, JAPAN

Paper submitted to the International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009

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 [2]. The symbols A to D in Fig.1 correspond to those in Fig.2.

In Fig.2, in the region of large current exceeding 10 kA, the arc voltage differs slightly with the arcing time, but is more or less constant at approximately 1500 V. Under the conditions of A and B where the arcing time is short, in the large current region the contacts are not sufficiently open, so the arc voltage is slightly low.

All of the arc voltages start to increase at a current of approximately 10000A or below, and the extinction peak is reached when the current is approximately 100 A. Subsequently, the arc voltage falls as the current zero is approached.

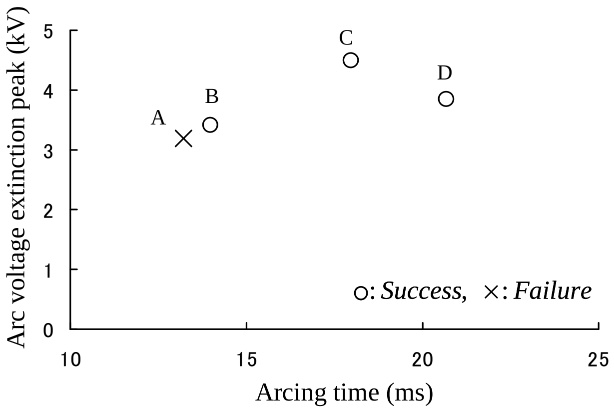

Fig. 1. Measured results of 300kV model circuit breaker for 63kA-50Hz-90% SLF interruption

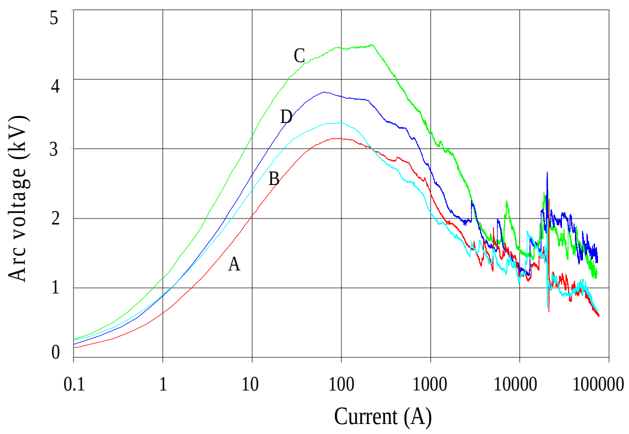

Fig. 2. Measured arc voltages of 300kV model circuit breaker

As shown in Fig.1, the value of the arc voltage at the extinction peak varies depending upon the arcing time. However, as shown in Fig.2, the value of the current corresponding to the extinction peak is constant at roughly 100 A, regardless of the arcing time. Because the interruption current is maintained constant, it can be said that the time from the point at the extinction peak of the arc voltage to the current zero remains constant regardless of the arcing time.

III. Calculation of Interruption Performance Using the Three Serially connected Arc Models

A. Calculation of Arc Voltage

Equations (1) and (2) are the equations for the Cassie model and the Mayr model.

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

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

Where, 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

Generally, it is said that the Cassie model can simulate an arc in the large current region, and the Mayr model can simulate an arc in the vicinity of the current zero. In order to use these arc models to indicate the arc voltage in Fig.2, one Cassie model and two Mayr models were serially connected. In other words, from Fig.2, the arc voltage in the large current region is represented using the Cassie model. The vicinity of the extinction peak is represented bv Mayr mode 1. In addition, the region where the current is 10 A or below is represented by Mayr model 2.

Figure 3 shows the waveform obtained as a result of calculating the arc voltage using the three serially connected models. It reproduces the arc voltage of C shown in Fig.2. The arc parameters used in the calculation are as follows.

Cassie model: θ c = 2.5 μs, v0 = 1500 V
Mayr model 1:θ m1 = 1.6 μs, PI = 680 kW
Mayr model 2:θ m2 = 0.16 μs, P2 = 13.6 kW
(θ m2 = θ m1 × 10%, P2 = P1 × 2%)

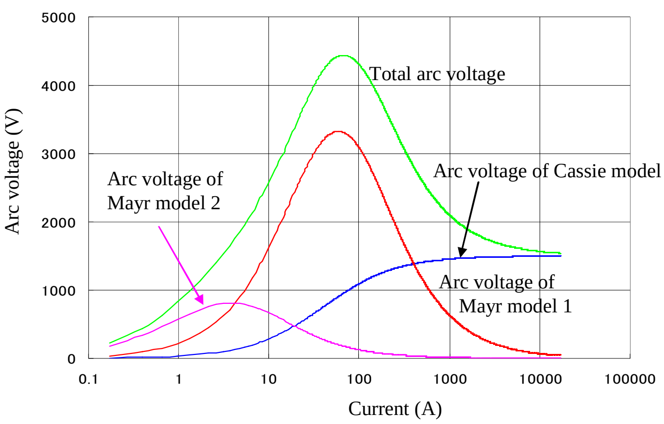

Fig. 3. Computed arc voltage waveform by 3 arc models

The total arc voltage shown in Fig.3 is the sum of the three arc voltages. The aspects of the arc voltages closely match those of C in Fig.2. In other words, in the large current region the arc voltage of the Cassie model is dominant, and is approximately 1500 V. The extinction peak occurs at a current of approximately 100 A. In addition, as a result of the use of Mayr model 2, the aspect of the attenuation of the arc voltage agrees closely with Fig.2.

B. Calculation of Interruption Performance

An attempt was made to reproduce the SLF interruption test results using the three serially connected arc models described in the previous paragraph. Figure 4 shows a comparison of the measured results and the calculated results. The measured results are the same as those of Fig.1, and are expressed in terms of the relationship between the arcing time and the value of the extinction peak. In the calculation of each of A to D, the arc time constant of the Cassie model, the arc voltage, and the arc time constant of the Mayr model agreed with the calculated values shown in Fig.3. The arc power loss of Mayr model 1 was adjusted so that the extinction peak of the arc voltage agreed with the measured value. The measured success or failure of interruption could be reproduced by calculation. The parameters of the arc model are explained in Section 4.

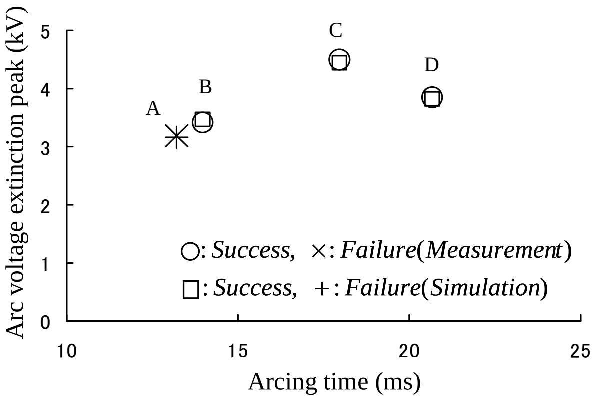

Fig. 4. Comparison between measurement and simulation

IV. ARC PARAMETERS

A. Time Constant of Mayr Model 1 near the Extinction peak

The method of obtaining the arc parameters of the Mayr model 1 by linearly approximating the relationship $i^2/g(=vi)$ – $1/g(dg/dt)$ is known [4]. Figure 5 shows these parameters expressed using i^2/g (=vi) along the horizontal axis, and $1/g(dg/dt)$ along the vertical axis, using the current and arc voltage during the period from the vicinity of the extinction peak to the current zero in the results for C in Fig.1. The conductance decreases as the current zero is approached, so dg/dt is a negative value. However, in Fig.5 dg/dt is indicated as an absolute value.

In Fig.5, a straight line is shown. This is because the arc voltage is assumed to be in the vicinity of the point in time corresponding to the extinction peak, and the data corresponding to the period between 5 μs and 2 μs before the current zero is linearly approximated by means of the least squares method. The inverse of the value at the point of intersection between this straight line and the vertical axis is the arc time constant. In Fig.5, the arc time constant was 1.5 μs. In the other results of Fig.1 as well, the results of calculating the arc time constant are likewise shown in Fig.6. The arc time constant was more or less constant regardless of the arcing time, and was 1.6 μs on average. It agreed with the value calculated using the method shown in Fig.3 and Fig.4.

Figure 7 shows the change in the arc voltage extinction peak when each of the arc time constant and the arc power loss is changed in the Mayr model alone.

1 and 2 correspond to the case where the arc time constant remains unchanged at 2.7 μs, and only the arc power loss is changed. 1 and 3 correspond to the case where the arc power loss remains unchanged, and the arc time constant is changed.

In 1 and 2, because the arc power loss is changed, the extinction peak also changes. However, because the arc time constant remains unchanged, the period from the current zero to the extinction peak value does not change.

In 1 and 3, both the extinction peak value and the period from the current zero to the extinction peak have changed.

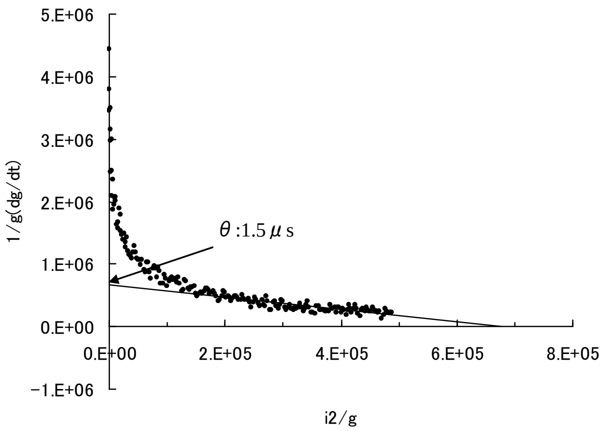

Fig. 5. Example of measured arc time constant of the Mayr model 1

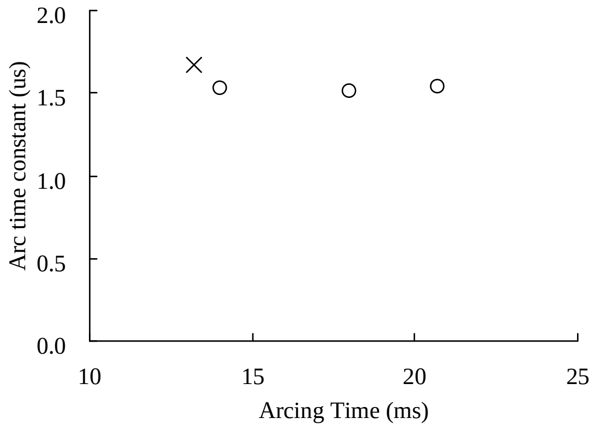

Fig. 6. Measurement results of Mayr model 1 arc time constant in the vicinity of the extinction peak of the arc voltage

The following can be said from the results of Fig.6 and Fig.7.

1) The result in which the current at the extinction peak of Fig.2 is constant can be simulated by making the identical value of the Mayr model 1 arc time constant.
2) By changing only the arc power loss of the Mayr model 1, the aspect of the arc voltage extinction peak of Fig.2 can be simulated.

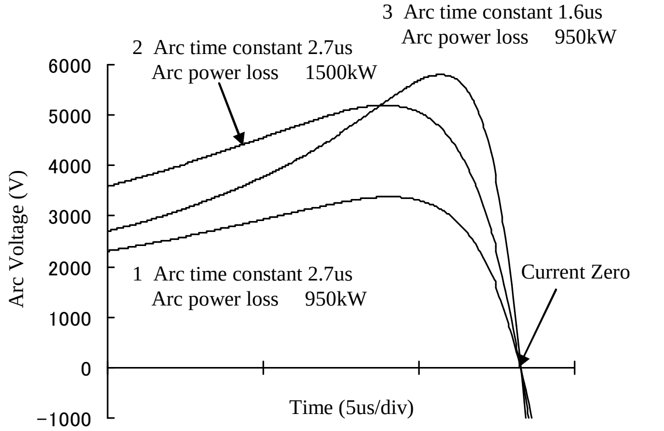

Fig. 7. Computed arc voltage waveforms with different Mayr model 1 arc parameters

B. Mayr Model 2 Arc Time Constant near the Current zero

Figure 8 shows an example of the waveform resulting from calculation of the arc voltage when the Cassie model is connected to Mayr model 1 alone. The Cassie model arc parameters and the arc time constant of Mayr model 1 were the same as the values used for Fig.3, but the arc power loss of the Mayr model 1 was adjusted so that the extinction peak value agreed with C in Fig.1.

In Fig.8, there is no significant difference from Fig.3 from the large current region to the vicinity of the extinction peak. However, the aspect of the attenuation of the arc voltage from the extinction peak to the vicinity of the current zero differs greatly from Fig.3, particularly when the current is approximately 10 A or less. In other words, the attenuation occurs quickly in the case of Fig.8. Also, the calculation of Fig.8 indicated an interruption failure.

When the arc time constant of the Cassie model is reduced, the attenuation of the arc voltage of the Cassie model slows down, and the aspect of the attenuation of the total arc voltage from the extinction peak to the current zero agrees with Fig.1. However, even in this case, the interruption success or failure did not agree with the result of measurement. This indicates that during the period from the extinction peak to the current zero, the circuit breaker cannot be simulated using one Cassie model and one Mayr model connected serially. Consequently, in Section 3, Mayr model 2 was added in order to simulate the vicinity of the current zero.

Figure 9 is an enlarged view of Fig.5. It shows the results of calculating the arc time constant of Mayr model 2 by performing linear approximation in the same way as Fig.5 using the data between 50 ns and 500 ns prior to the current zero. As a result, the arc time constant was 0.2 µs. During this period, the amount of data is small, so it is expected that there will be an error in the arc time constant calculated by an approximation. However, the value was approximately 10% of the value in the vicinity of the extinction peak shown in Fig. 5, and agreed with the arc time constant used for Mayr model 2 in Section 3.

The foregoing agrees with the fact that it is said that in this model the interruption success or failure is determined by the Mayr model 2, and the SLF interruption performance of an SF6 gas circuit breaker is determined by several µs in the vicinity of the current zero.

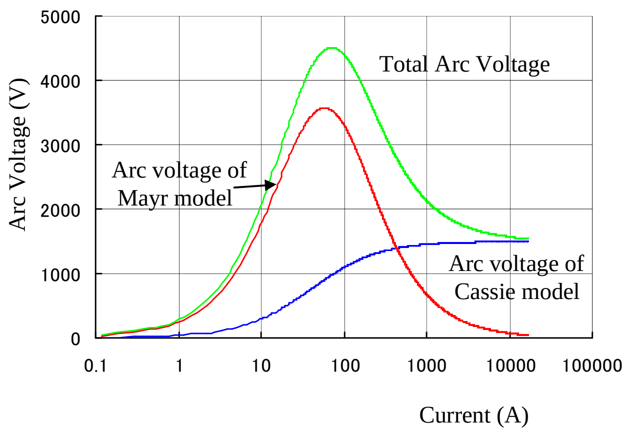

Fig. 8. Computed arc voltage waveform by 2 arc models

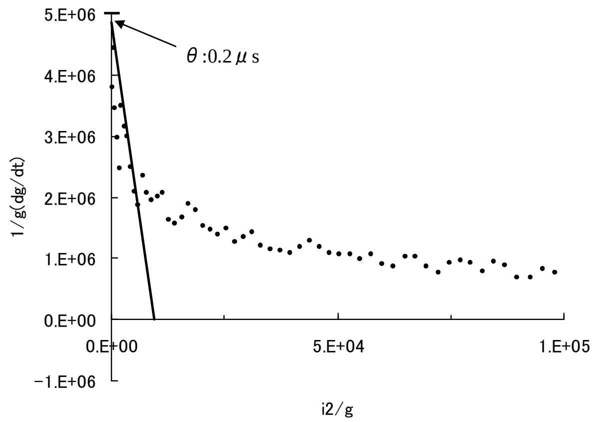

Fig. 9. Example of measured arc time constant of Mayr model 2 between 50ns to 500ns before current zero

C. Cassie Model Arc Time Constant

At the current zero, (3) is derived from (1) [5].

$$\frac{dv}{dt} = \frac{V_0}{\theta_C} \quad (3)$$

Figure 10 is an enlarged view of the vicinity of the current zero of the total arc voltage of Fig.3 and the Cassie model arc voltage. It can be seen that the point of intersection of dv/dt and V_0 (1500 V) at the current zero of the Cassie model arc voltage corresponds roughly to the point in time at which the extinction peak of the total arc voltage occurs. In other words, the period between this point of intersection and the current zero is the arc time constant.

The only known method of calculating the arc time constant of the Cassie model is one in which, when the Cassie model and Mayr model 2 are serially connected, the Cassie model arc time constant is changed and calculations are repeated until that the total arc conductance agrees with the measured value [3]. In this case, a large number of repetitions may be necessary depending upon the setting of the initial value.

As shown in Fig.10, it is considered that the defining of the period from the extinction peak to the current zero as the Cassie model arc time constant is one method of calculation. The question of whether or not this applies to circuit breakers that have other voltage ratings is an issue for the future.

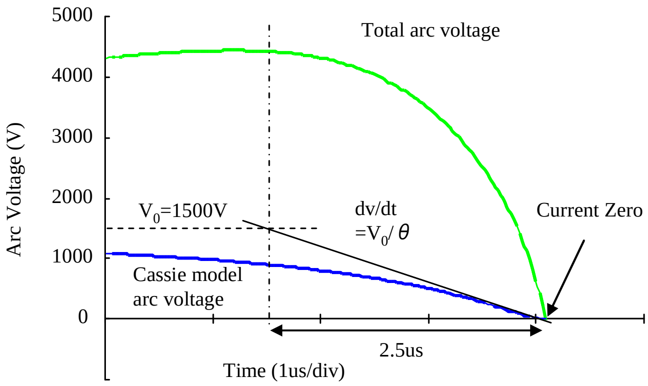

Fig. 10. Arc time constant of Cassie model

V. Conclusions

An arc model for evaluating the 63 kA – 50 Hz – 90% SLF interruption performance of a 300 kV-SF6 gas model circuit breaker using calculations was studied.

a) An interruption test was performed by leaving the interruption current constant and changing the arc time, and the arc voltage was measured. The extinction peak value of the arc voltage varies according to the arc time. However, the value of the current corresponding to the extinction peak did not depend upon the arc time, and remained roughly 100 A.

b) In order to simulate the arc voltage waveform during the period from the vicinity of the peak value of the current to the zero point, an arc model was constructed by serially connecting three models, namely a Cassie model for simulating the large current region, a Mayr model 1 for simulating the vicinity of the arc voltage extinction peak, and also a Mayr model 2 for simulating the vicinity of the current zero.

c) The arc parameters of the Cassie model and the arc time constant of the Mayr model 1 which represents the vicinity of the extinction peak were made constant, and the arc power loss was varied. As a result, good agreement between the measured and calculated values of the current corresponding to the extinction peak and the arc voltage corresponding to the extinction peak could be obtained.

d) In Mayr model 2 which indicates the region in the vicinity of the current zero subsequent to the extinction peak, the arc time constant and the arc power loss were made 10% and 2%, respectively, of the Mayr model 1 values, thus enabling the aspect of the arc voltage waveform during the period from the extinction peak to the zero point to be reproduced by calculation. In addition, the measured and calculated results of the success or failure of interruption agreed with each other.

e) When using this arc model, only the arc voltage in the large current region and the arc voltage at the extinction peak are necessary. These values can be easily obtained from measurement of the arc voltage, thus obviating the need for complicated arc parameter calculations.

VI. References

[1] T.Koshizuka, et al., ”EMTP Simulation of SLF Interrupting Performance for Serially Connected Two Arcs with Different Arc Parameters” IEE-J Trans. B, Vol.121-B、No.7、July、2001、pp845-852 (in Japanese)

[2] Smeets, et al., “ Short-Line Fault Interruption Assessment of High-Voltage Circuit Breakers by means of Current Zero Analysis” CIGRE A3 Colloquium, 2003

[3] G.Bizjak, et al,. “Circuit Breaker Model for Digital Simulation based on Mayr’s and Cassie’s Differential Arc Equations” IEEE Trans. Power Delivery, Vol.10, No.3, July 1995

[4] T.Sawada, et al., “ Evaluation Method of Interruption Performance using Two Series Mathematical Arc Models(No.1) IEEJ Power and Energy Conference 2003 (in Japanese)

[5] T.E.Browne, Jr., “ Practical modeling of the Circuit breaker Arc as a Short Line Fault Interrupter” IEEE PES Summer Meeting F77 625-5