CO_2 Circuit Breaker Arc Model for EMTP Simulation of SLF Interrupting Performance

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

***Abstract*-- This paper presents a CO_2 circuit breaker arc model for an Electro Magnetic Transients Program (EMTP) simulation of SLF interrupting performance. One Cassie arc model and two Mayr arc models were serially connected. A large post arc current was measured. The simulated post arc current using the arc model agreed well with measurements. The temperature profile of the arc was calculated, and it was shown that the CO_2 arc has an arc core and an outer zone of arc column. Using EMTP simulations, the most severe SLF condition of the CO_2 circuit breaker was found to be 75% or 80%.**

***Keywords*: CO_2 circuit breaker, Arc model, EMTP, SLF interruption.**

I. Introduction

Research on substitute gases for SF_6 gas, which is used in switchgear, is currently underway. Using CO_2 gas as an arc-extinguishing medium for circuit breakers has attracted the attention of researchers [1]. A flow of a large post arc current of several amperes has been obtained for a short line fault (SLF) interruption of a CO_2 circuit breaker, suggesting that many aspects differ considerably from those of a SF_6 gas circuit breaker [1].

To evaluate the SLF interrupting performance of a SF_6 gas circuit breaker with arc model calculations, we developed serially-connected three arc models consisting of one Cassie arc model and two Mayr arc models [2], [3]. Using the arc models, we obtained measured results that allow us to quantitatively evaluate the SLF interrupting performance of a SF_6 gas circuit breaker.

In this paper, we applied the serially-connected three arc models to evaluate the interrupting performance of a CO_2 circuit breaker. Consequently, using arc model calculations, we could reproduce aspects of arc voltages, an aspect of a large post arc current and the interrupting success or failure for the circuit breaker. The calculations showed that the parameters differed between the SF_6 gas circuit breaker arc model and the CO_2 circuit breaker arc model. Accordingly, we clarified the differences in arc parameters between the CO_2 circuit breaker and the SF_6 gas circuit breaker by calculating arc radius and temperature profile. Moreover, using the serially-connected three arc models, we examined the most severe SLF condition for the CO_2 circuit breaker.

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II. SLF Interrupting Performance with a CO_2 Circuit Breaker

A. Post Arc Current

Fig. 1 shows the waveforms of the post arc current measured at 31.5 kA-50 Hz-90% SLF conditions for a 72 kV CO_2 circuit breaker [1]. For the measurements, the short circuit current was kept constant at 31.5 kA-90% and the di/dt of the injected current from the synthetic test circuit was varied. The arcing time was set to be constant at 13 ms.

When the gradient of the current-zero (di/dt) was small, almost no post arc current flowed. As di/dt increased, post arc current increased. The post arc current increased most at di/dt=130% (given the rated condition of 100%), indicating approximately 3 amperes. Meanwhile, wave peak value of the post arc current occurred at approximately 2 μs after the current-zero and the post arc current flowed for approximately 5 μs. In this test, interruption of current failed at di/dt=134%.

The post arc current with a high wave peak value and a long duration, which is shown in Fig. 1, was not measured for a SF_6 gas circuit breaker. Therefore, the high wave peak value and long duration may be considered to be major features of SLF interruption for a CO_2 circuit breaker.

Current was measured through Rogowski coils installed near the circuit breaker. The measured signals were digitized at a sampling frequency of 40 MHz and a resolution of 12 bits.

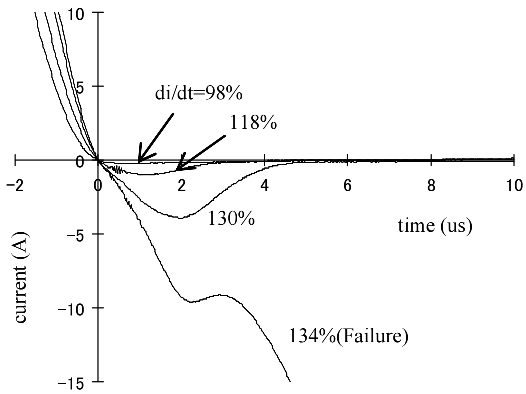


Fig.1 Measured post arc current waveforms of CO_2 gas circuit breaker

B. Arc voltage

Fig. 2 shows measured arc voltages. The arc voltages were measured with a voltage divider. While di/dt was small, the extinction peak increased to approximately 4 kV. As di/dt increased, however, the extinction peak decreased. The extinction peak gradually declined to about 3 kV at a di/dt of 130% and further decreased at a di/dt of 134%, thereby recording a failed interruption. Meanwhile, the extinction peak for a SF_6 gas circuit breaker also showed a similar trend of declining arc voltage values as the interrupting conditions became increasingly severe. It will be necessary in particular to analyze the arc voltage to determine whether the arc model used to evaluate the SLF interrupting performance of a SF_6 gas circuit breaker is applicable to a CO_2 circuit breaker.

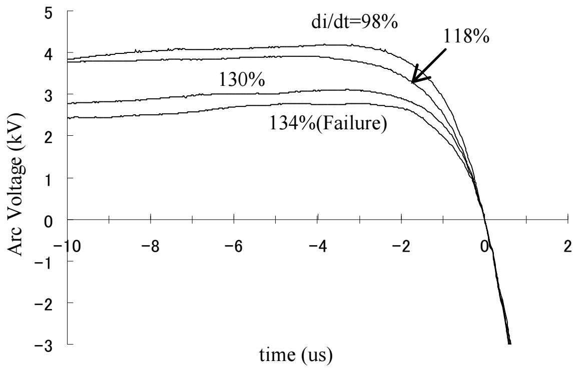


Fig.2 Measured arc voltages of CO_2 gas circuit breaker (relation to time)

III. Evaluation of Arc Model Using Serially Connected One Cassie and Two Mayr Models

A. Application of Arc Model in CO_2 Circuit Breaker

To evaluate the SLF interrupting performance of a SF_6 gas circuit breaker we developed serially-connected three arc models [2]. They consist of one serially-connected Cassie arc model simulating a large-current area, a serially-connected Mayr arc model simulating the area near the extinction peak, and a serially-connected Mayr arc model simulating the area near the current-zero. It was revealed that (i) the arc voltage for a SF_6 gas circuit breaker is almost constant in the current domain above several thousand amperes regardless of interrupting conditions, (ii) current values at the extinction peak are almost constant, and (iii) the extinction peak value varies depending on interrupting conditions.

Consequently, we set the serially-connected three arc models for a SF_6 gas circuit breaker as described below.

a) The arc parameter was assumed for the Cassie arc model based on (i) above and was set to be constant;
b) The arc time constant was assumed for the Mayr arc model simulating the area near the extinction peak based on (ii) above, and was set to be constant regardless of interrupting conditions. Arc power loss was assumed in view of the extinction peak value based on (iii) above, and was varied depending on the interrupting conditions; and,
c) The arc time constant of the Mayr arc model simulating the area near the current-zero was set to 10% of that of the Mayr arc model simulating the area near the extinction peak. The arc power loss for the former was set to 2% of the latter. With these settings, it is not necessary to calculate complicated arc parameters.

We applied the above arc models for a SF_6 gas circuit breaker to a CO_2 circuit breaker. Fig. 3 shows the relationship between the arc voltages of the CO_2 circuit breaker in Fig. 2 and current. The values on the horizontal axis are logarithms. The time in the figure is that from the vicinity of the wave peak value of the interrupting current to the area near the current-zero. Fig. 3 reveals the following points.

(iv) The arc voltage shows almost constant values even if di/dt varies in the large-current area above approximately 3,000 amperes;
(v) The current value at the extinction peak is almost constant at approximately 50 amperes; and,
(vi) The extinction peak value varies if di/dt, or an interrupting condition, varies.

When applying the serially-connected three arc models to a CO_2 circuit breaker, the parameter for the Cassie arc model can be set to a constant value based on (iv) above. The arc time constant for the Mayr arc model simulating the area near the extinction peak can be assumed based on (v) above. The arc power loss can be assumed based on (vi) above. As a result, the concept of the serially-connected three arc models may seem applicable to the CO_2 circuit breaker, although specific parameter values for the Cassie and the Mayr arc models and the ratios of the parameters for the Mayr arc model simulating the area near the current-zero are predicted to differ from the corresponding values of the SF_6 gas circuit breaker.

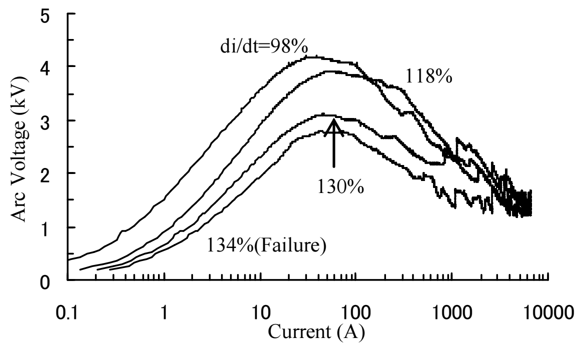


Fig.3 Measured arc voltages of CO_2 gas circuit breaker (relation to current)

B. Calculation of Interrupting Success or Failure

Fig. 4 shows a comparison of the measured arc voltage waveforms for a CO_2 circuit breaker and those obtained using calculations for arc models. Fig. 4 presents variations in arc voltage against current before the zero point under the condition di/dt=130% shown in Fig. 3. In the calculations, a 31.5 kA-50 Hz-90%SLF test circuit used for actual measurements was simulated with the EMTP, and the arc models were described using the “Models” function of the

EMTP. The calculations were performed for a total time of 8 ms from the wave peak point to the post-zero point of the current. The parameters used for the respective arc models were as follows:

a) Cassie arc model: Arc time constant of 0.4 μs and arc voltage of 1.2 kV
b) Mayr arc model (Simulation for area near extinction peak): Arc time constant of 3.3 μs and arc power loss of 500 kW
c) Mayr arc model (Simulation for area near current-zero): Arc time constant of 0.66 μs and arc power loss of 25 kW

In Fig. 4, aspects of the arc voltages were reproduced well by calculations from the large-current area to the current-zero. In particular, the voltage decay of the arc voltage from the extinction peak to the current-zero agreed well between calculations and measurements. In the figure, the C1 waveform shows the arc voltage for the Cassie model, the M1 waveform shows the arc voltage for the Mayr model simulating the area near the extinction peak, and M2 waveform shows the arc voltage for the Mayr model simulating the area near the current-zero. The arc voltage of the circuit breaker in the calculations is the sum of these three arc voltages.

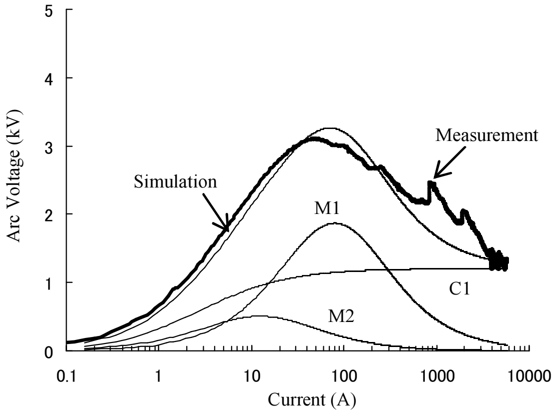


Fig.4 Simulated arc voltage waveform (di/dt=130%)

Fig. 5 shows a comparison of calculations and measurements for the post arc current after the zero point with regard to the calculations in Fig. 4. The aspect and magnitude of the post arc current were reproduced well by calculations using the arc models. Above all, it seems that the aspect of increasing current was reproduced well for time periods after the current-zero to approximately 0.5 μs and to the subsequent wave peak value of the current. The aspect of post arc current after the zero point agreed well with measurements by matching the aspect of arc voltage before the current-zero with that obtained from measurements.

Furthermore, although it is not shown in the figure, interrupting success or failure could be reproduced under all di/dt conditions in Fig. 1. Consequently, it is revealed that SLF interrupting success or failure can be evaluated using the serially-connected three arc models for a CO_2 circuit breaker.

As described previously, the arc time constant and the arc power loss values for the Mayr arc model simulating the area near the current-zero were 20% and 5% of the corresponding arc time constant and the arc power loss values for the Mayr arc model simulating the area near the extinction peak. Although other ratios were also used in the calculations, the values above most appropriately reproduced the aspects of arc voltages, the aspect of post arc current and the interrupting success or failure.

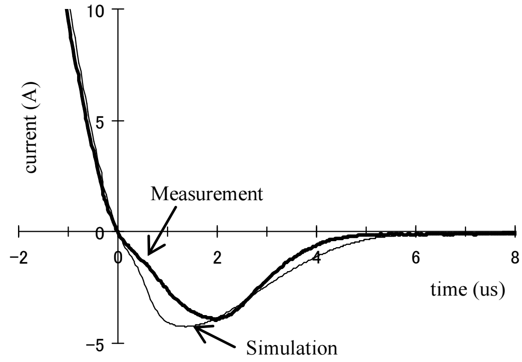


Fig.5 Simulated post arc current (di/dt=130%)

IV. Considering Parameters of Arc Model

A. Cassie Arc Parameters for CO_2 Circuit Breaker that Differ from those of SF_6 gas Circuit Breaker

Although it became clear that interrupting success or failure can be evaluated using the serially-connected three arc models even for a CO_2 circuit breaker, the arc model parameters differed from those used of the SF_6 gas circuit breaker. Fig. 6 shows a scheme that presents the arc voltages of the respective arc models and the total arc voltage for the circuit breaker as the sum of the three arc voltages. The arc time constants for the respective arc models, which were used for both SF_6 gas and CO_2 circuit breakers, are also input in the figure. C1, M1, and M2 are same as Fig.4. Comparing both types of circuit breaker, the difference in the arc time constant for the Cassie arc model was significantly large at 2.5 μs for the SF_6 gas circuit breaker against 0.4 μs for the CO_2 circuit breaker. We examined the differences by focusing on changes in arc radius in the area near the current-zero.

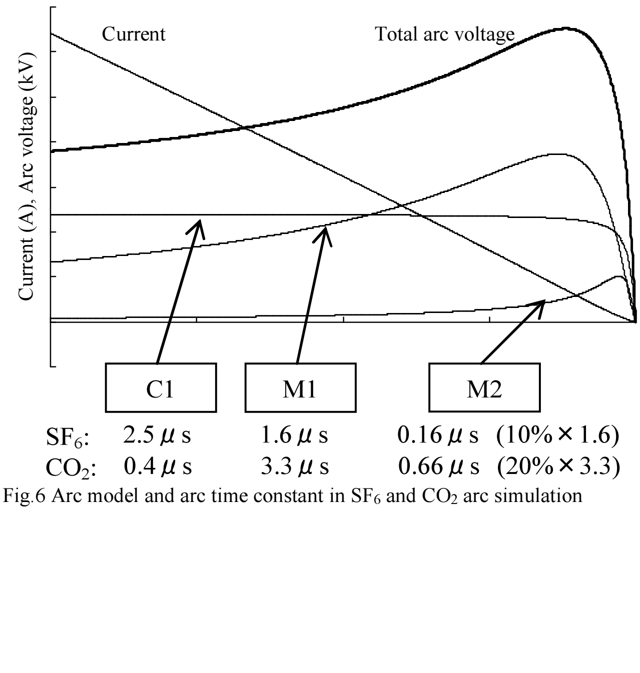


Fig.6 Arc model and arc time constant in SF_6 and CO_2 arc simulation

B. Method of Deriving Temperature Profile in CO_2 Arc

To calculate changes in temperature profile and arc radius of a CO_2 arc, we used the Law of Conservation of Energy, which is used for calculating the temperature profile of a wall-stabilized arc [4], [5].

The equation (1) below is a conservation energy equation where the Joule heating of the arc balances with energy loss from thermal conduction and forced convective flow in the axial direction.

$$\sigma E^2 + \frac{1}{r}\frac{d}{dr}\left(r\kappa\frac{dT}{dr}\right) - \frac{V_0}{l}\left(1-\frac{r}{R}\right)^{1/7}\rho(h-h_{300}) = 0 \qquad (1)$$

$$\sigma E^2 = \sigma\left(\frac{I}{G}\right)^2$$: Joule heating of the arc

$$G = \int_0^R 2\pi r\sigma dr$$

$$\frac{1}{r}\frac{d}{dr}\left(r\kappa\frac{dT}{dr}\right)$$: Energy loss from thermal conduction

$$\frac{V_0}{l}\left(1-\frac{r}{R}\right)^{1/7}\rho(h-h_{300})$$

: Energy loss from forced convective flow

Where r: Radius, T: Temperature, α: Electric conductivity, E: Electric field, K: Thermal conductivity, p: Density, h: Enthalpy, V_0: Flow velocity, l: Arc length

The above equation contains three hypotheses.

· The arc is axisymmetric;
· Local thermal equilibrium is a premise and the current domain where energy loss via radiation can be neglected is covered; and,
· Gas flows at 300 K toward the arc in the axial direction.

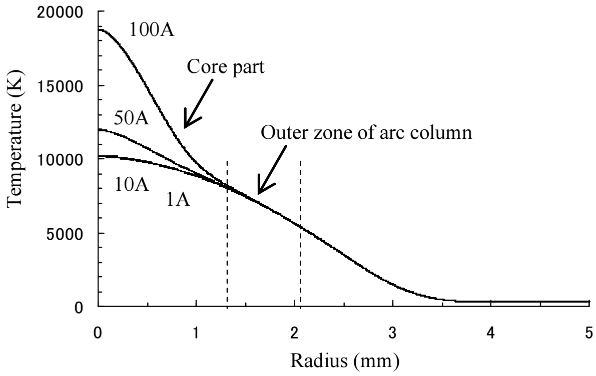
To solve equation (1), the physical properties values of CO_2 gas in Reference [6] were used. In addition, the following three points were hypothecated and the Runge-Kutta Method was used for the relevant calculations.

· The container wall had a nozzle throat with a radius of 5 mm. The temperature at the 5 mm radius was 300 K.
· Current was varied at 100 A, 50 A, 10 A, and 1 A.
· The energy loss from forced convection was always the same value.

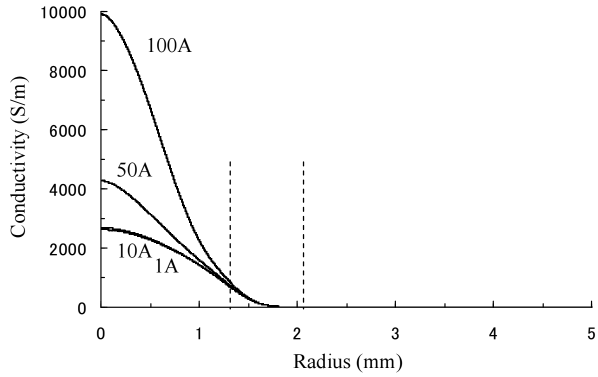
C. Temperature Profile in CO_2 Arc

Fig. 7 shows the calculated result of the temperature profile of a CO_2 arc in the radial direction. As for CO_2 gas, the domain with high electric conductivity includes an area where temperature is almost unchanged, despite the change in current. There is another area where temperature rises along with an increase in current at the outer zone closer to the center. The former is assumed to be the outer zone of arc column while the latter is assumed to be the arc core.

The change in temperature was insignificant with regard to electric conductivity in the arc for the Cassie model, which leads to the hypothesis that the change in arc conductance depends on the change in the cross-sectional area of the arc core and not to the change in electric conductivity. Meanwhile, electric conductivity in the arc of the Mayr model was significant depending on temperature, which leads to the hypothesis that the change in arc conductance is controlled by the change in electric conductivity rather than the change in the cross-sectional area of the arc core.



a) Radial temperature profile in CO_2 arc



b) Electric conductivity in CO_2 arc

Fig.7 Simulated radial temperature and conductivity profile in and CO_2 arc

Fig. 7 also shows the relationship between electric conductivity and temperature profile, and the following points can be deduced therefrom.

a) In the area corresponding to the arc core, electric conductivity diminishes along with the change in current.
b) At the outer zone of the arc column, electric conductivity is almost unchanged.
c) Consequently, some models presenting the arc core and the outer zone of arc column would be necessary for the area near the current-zero of CO_2 gas: one is the Mayr model that presents the arc core and the other is the Cassie model that presents the outer zone of arc column.
d) c) above agrees with the facts that the arc time constant for the Cassie model is small and the impact of the Cassie model is significant up to the area near the current-zero with regard to the serially-connected three arc models.
e) Meanwhile, it is said that only the arc core exists for the SF_6 gas circuit breaker near the area of the current-zero. Accordingly, the Cassie model presenting the outer zone

of arc column does not have a great impact at the area near the current-zero. The preceding description can also be explained by the large arc time constant of the Cassie model in Fig. 6.

D. Arc Model to Decide Interrupting Success or Failure

It has been clarified that whether interruption succeeds or fails for the SF_6 gas circuit breaker depends on the Mayr arc model simulating the area near the current-zero in calculations for the serially-connected three arc models [2], [3]. This concept agrees with the fact that interrupting success or failure for the SF_6 gas circuit breaker is decided within several μs after the current-zero. Hereafter, we examine arc models that are associated with interrupting success or failure for the CO_2 circuit breaker.

Fig. 8 shows the waveforms of the arc voltage using serially-connected two arc models (Cassie model and Mayr model simulating the area near the extinction peak) after eliminating one Mayr arc model (M2) simulating the area near the current-zero from the calculations in Fig. 4.

In Fig. 8, the aspect of the arc voltage from the large-current area to the extinction peak is not so different from that in Fig. 4. However, regarding the time from the extinction peak to the current-zero, the difference between measurements and calculations increased compared to Fig. 4, showing that the decay of the calculated waveform has become more rapid than the measured decay.

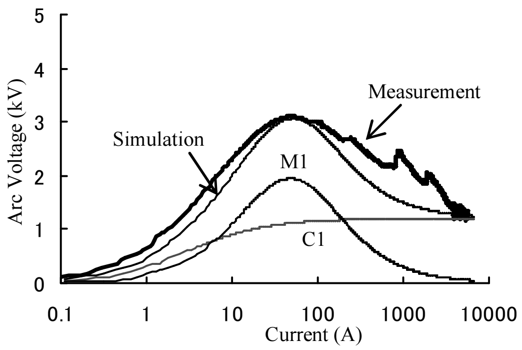


Fig.8 Comparison between measured arc voltage and simulation using 2 arc models, (di/dt=130%)

Fig. 9 shows a comparison of the calculated waveforms between the post arc current in Fig. 5 and the waveform using the serially-connected two arc models, for which the magnitude of the post arc current almost doubled and the duration of the post arc current more than doubled. However, it shows that interruption succeeded for the serially-connected two arc models.

The following points can be deduced from the results above.

a) SLF interrupting success or failure can be evaluated even for a CO_2 circuit breaker based on the serially-connected three arc models:
b) SLF interrupting success or failure for a CO_2 circuit breaker using the serially-connected three arc models depends on the Mayr model simulating the area near the extinction peak: and,
c) The Mayr arc model simulating the area near the current-zero only has the effect of limiting the magnitude of the post arc current.

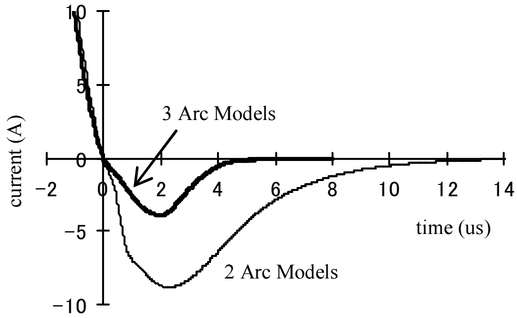


Fig.9 Comparison between measured arc voltage and simulation using 2 arc models, (di/dt=130%)

V. MOST SEVER SLF CONDITON FOR CO_2 CIRCUIT BREAKER

It is said that the 90% condition is the most severe among all of the SLF conditions for a SF_6 gas circuit breaker. As shown in Fig. 6, the preceding paragraph can also be explained by the fact that, for the serially-connected three arc models, interrupting success or failure depends on the Mayr arc model simulating the area near the current-zero, at which the arc time constant is small at 0.16 μs.

The arc time constant for the Mayr model simulating the area near the extinction peak as the determinant factor of interrupting success or failure for a CO_2 circuit breaker is approximately 3 μs, as described previously. It may therefore be considered that the most severe SLF condition for a CO_2 circuit breaker differs from that of a SF_6 gas circuit breaker. We, therefore, examined the most severe SLF condition for a CO_2 circuit breaker by calculating whether interruption succeeds or fails in the case of changing SLF conditions based on the serially-connected three arc models.

TABLE 1 shows values of interrupting current and transient recovery voltage (TRV) under 90%, 85%, and 75% SLF conditions, which were calculated for the IEC-62271-100 high-voltage alternating-current circuit breakers [7].

Fig. 10 shows samples of the calculated TRV waveforms under 90% (L90), 85% (L85), and 75% (L75) SLF conditions. In the calculations, the circuit breaker was considered to be an ideal switch with the following connections: a single-phase line of 450 Ω surge impedance is connected to one terminal of the circuit breaker while the other terminal is connected to a 72 kV power supply through inductance and capacitance so that TRV frequency at the power supply side becomes 2.4 kHz at the rated interrupting current of 31.5 kA. The length of the line was set to allow the interrupting current to meet L90, L85, and L75 conditions.

Based on Table 1 and Fig. 10, compared to the L90 SLF condition, the interrupting current (di/dt) and the dv/dt of SLF-TRV decrease under L85 and L75 SLF conditions, whereas the wave peak value of SLF-TRV increases.

TABLE I
CURRENT AND VOLTAGE VALUE AT SLF INTERRUPTION

Rate Condition 72kV-31.5kA-50Hz		L90	L85	L75
Rate short-circuit breaking current	I_{SC} (kArms)	31.5	31.5	31.5
Short-line breaking current	I_L (kArms)	28.4	26.8	23.6
	di/dt	12.6	11.9	10.5
Voltage at the instant of current interruption	$u_0=U_m*(1-I_L/I_{SC})$ (kV)	5.9	8.8	14.7
Peak value of first peak of line side TRV	u_L* (kV)	9.4	14.1	23.5
Peak factor	$k=u_L*/u_0$	1.6	1.6	1.6
Rise time	t_L (us)	1.7	2.6	5.0
Rated-of-rise of line side TRV	u_L*/t_L (kV/us)	5.7	5.4	4.7
Peak value of recovery voltage	$U_m=\sqrt{2}U_r/\sqrt{3}$ (=u_1)(kV)	58.8	58.8	58.8
Transient Peak voltage	$u_m=U_m(1+0.4I_L/I_{SC})$ (kV)	80.0	78.8	76.4

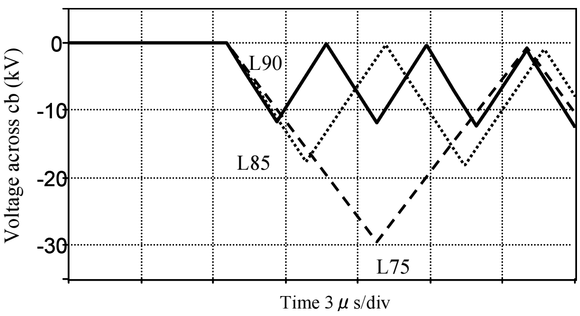


Fig.10 SLF-TRV wave shapes at L90, L85 and L75

Next, Fig. 11 shows the calculated results for interrupting success or failure in the case of setting the circuit breaker for the above circuit with serially-connected three arc models, given the aforementioned current and TRV conditions. The area near the interrupting current-zero is emphasized in the figure. In Fig. 11, the L80 and L70 SLF conditions are also added. All the parameters for the serially-connected three arc models are deemed to be identical.

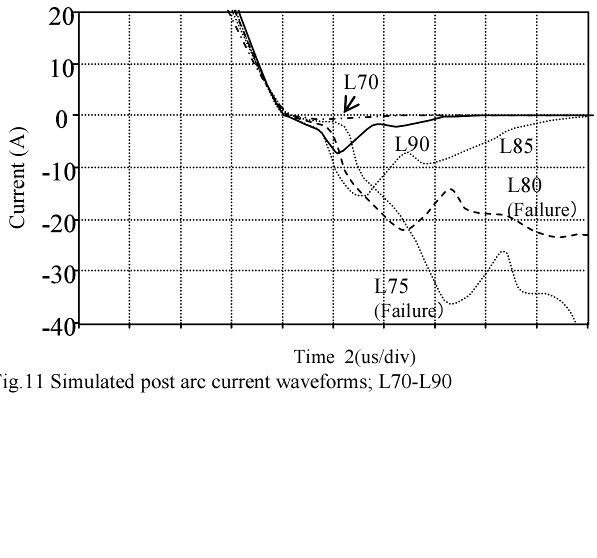


Fig.11 Simulated post arc current waveforms; L70-L90

In Fig. 11, interruption failed under L80 and L75 conditions. Although a large post arc current was recorded under the L85 condition, interruption succeeded. Under the L70 condition, interruption succeeded with the least post arc current among these conditions. Based on these results, the 75-80% SLF conditions are more severe than the 90% condition in the case of an interrupting current under SLF conditions for a CO_2 circuit breaker.

VI. CONCLUSION

We examined the possibility of applying serially-connected three arc models to the interrupting performance of a CO_2 circuit breaker. Our conclusions are as follows:

a) We applied the serially-connected three arc models, which were developed to evaluate the SLF interrupting performance of a SF_6 gas circuit breaker, to a CO_2 circuit breaker. Consequently, it was shown that they can be used to evaluate the interrupting performance of a CO_2 circuit breaker.
b) The flow of a large post arc current was measured under the 90% SLF condition after current was interrupted. The aspect and magnitude of the post arc current were reproduced by calculations using the arc models.
c) The arc parameters were estimated for Mayr arc model and Cassie arc model based on measuring arc voltage waveforms. More work can be done to extract the arc parameters from measurements using a numerical analysis, for example a fitting procedure in matlab.

Moreover, we examined differences in the arc time constant for the Cassie arc model between the CO_2 circuit breaker and the SF_6 gas circuit breaker based on the temperature profile of arc. The following conclusions were obtained.

d) Radial temperature profile of the axisymmetric arc was calculated by resolving the relevant conservation energy equation where the Joule heating of the arc brings a balance with the energy loss from thermal conduction and forced convective flow in the axial direction.
e) It was found that the CO_2 arc has an arc core and an outer zone of arc column.
f) It could be explained that, unlike the SF_6 gas circuit breaker, the Cassie arc model has a significant impact even in the area near the current-zero for the CO_2 circuit breaker, with regard to the serially-connected three arc models.

Furthermore, the following conclusions regarding the most severe SLF conditions were obtained by drawing on the determinant factor on whether interruption succeeds or fails for the CO_2 circuit breaker.

g) It was shown that 75-80% SLF conditions may be more severe than the 90% SLF condition for a CO_2 circuit breaker, based on arc model calculations.
h) It was shown that interrupting success or failure for a CO_2 circuit breaker is decided at the area near the extinction

peak based on the arc model calculations. The fact that the most severe SLF condition, which was presented in c) above, is not 90% because the arc time constant for the Mayr model simulating the area near the extinction peak is long was explained

VII. Acknowledgment

We used the physical properties values of the CO_2 gas, which were calculated by Yasunori Tanaka, Professor at Kanazawa University, for the temperature profile calculations of the arc radius in this paper. We thank him for his collaboration in the appropriation of data.

VIII. Appendix

Fig.12 shows an experimental setup for measuring current and arc voltage at SLF condition. Current was measured through Rogowski coils, and arc voltage was measured a voltage divider. These measured signals were digitized at a sampling frequency of 40MHz and a resolution of 12 bits by converter device called Front End. After that, the signals were transmitted to control units through optical fibers.

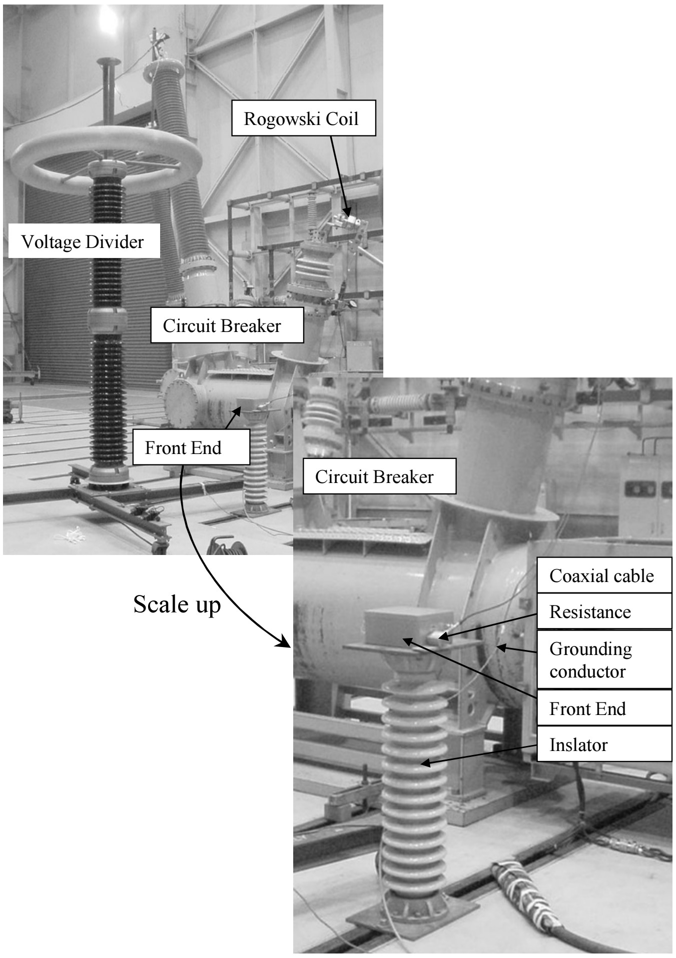


Fig.12 Experimental setup for measuring current and arc voltage

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X. Biographeis

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