Comparison of Evaluation Methods of the Small Current Breaking Performance for SF_6 Gas Circuit Breakers

Ki-Dong Song, Byeong-Yoon Lee, Kyong-Yop Park and Jung-Hoo Park

Abstract - In order to evaluate the dielectric recovery strength for GCBs, two equations have been usually utilized. One is the empirical formula obtained from a series of tests and the other is the theoretical formula obtained from the streamer theory. In this paper, both methods were applied to predict the small capacitive current interruption capability of model circuit breakers and were investigated in terms of the reliability by comparing the simulation results with test ones.
Keywords - SF_6 Gas circuit breaker, Dielectric recovery, Small current interruption, Shock wave, Arcing contacts

1. Introduction

With the increasing reliability of the analysis schemes and the dramatically increased computing speed, the computer simulation has become an indispensable process to predict the interruption capacity of circuit breakers.

In general, circuit breakers have to possess both the small current and large current interruption abilities and the circuit breaker designers need to evaluate its capacities to save the time and the expense. The analyses of small current and the large current interruption performances have been considered separately because the phenomena occurring in a interrupter are quite different. To analyze the dielectric recovery after large current interruption many physical phenomena such as heat transfer, convection and arc radiation, the nozzle ablation, the ionization of high temperature SF_6 gas, the electric and the magnetic forces and so forth must be considered. However, in the analysis of small current interruption performance only the cold gas flow analysis needs to be carried out because the capacitive current is so small that the influence from the current can be neglected.

Many authors have used theoretical and semi-experimental approaches to evaluate the transient breakdown voltages after the current interruption [1, 2, 3, 4]. Moreover, an empirical equation, which is obtained from a series of tests, has been used to estimate the dielectric recovery strength [5].

In this paper, two methods that have different approaches each other to evaluate the dielectric recovery strength have been applied to real circuit breakers. The results of analyses have been compared with the test results and the reliability on each method has been investigated.

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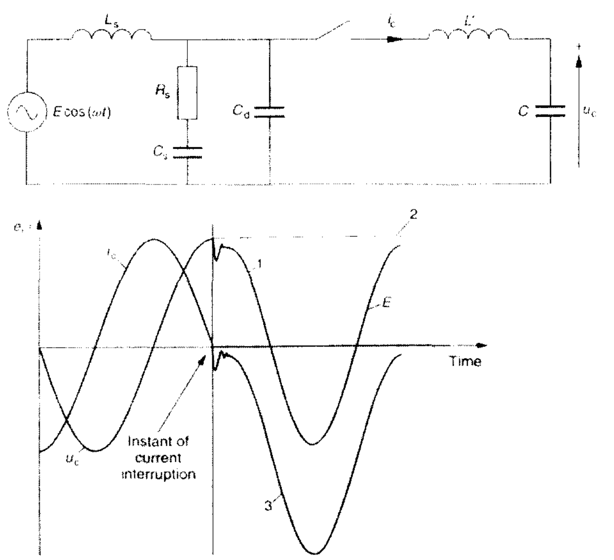
2. Small capacitive current interruption

There are two types of small current interruption. One is to interrupt the small inductive current such as the no-load or the magnetizing current of a transformer, or the disconnecting current of a shunt reactor. The other is to interrupt the small capacitive current such as the disconnecting of capacitor banks and the dropping of unloaded overhead lines or cables

When a circuit breaker interrupts the small inductive current, sometimes the over zealous action of arc suppression devices in the circuit breaker bring the current to zero abruptly and prematurely ahead of the normal current zero. This phenomenon is referred to as current chopping. It can give rise to an abnormal overvoltage as a consequence of the release of trapped magnetic energy associated with the current. The resultant stress on the power devices is similar to that due to a switching impulse. But in case of gas circuit breakers, the interruption of small inductive current is not considered particularly. Because in gas circuit breakers the magnitude of chopped current and the rate of rising of the overvoltage are small and the surge is limited by the contact material with low-surge. Therefore in the design of gas circuit breakers only the small capacitive current interruption is being considered[6].

Power systems contain lumped capacitors such as capacitor banks for voltage regulation or power factor improvement and capacitors that are part of filter banks to filter out higher harmonics. In addition, cable networks on the distribution level form a mainly capacitive load for the switching devices. Capacitive switching requires special attention because, after current interruption, the capacitive load contains an electrical charge and can cause a dielectric re-ignition of the switching device.

The capacitive current is small, a few Amperes to several hundreds of Amperes, compared with the rated short-circuit current for which the circuit breaker is designed, and the capacitive current can be interrupted even at short arcing times. At the instant of current interruption, the capacitor is fully charged and the voltage is approximately equal to the peak voltage of the supply. After a half cycle, the supply voltage has reversed its polarity and the voltage across the breaker terminals is twice the peak value of the supply voltage, as can be seen in Fig. 1.



1: supply voltage, 2: voltage on the capacitor, 3: voltage across the circuit breaker

Fig. 1 Transient recovery voltage during the small capacitive current interruption

$$V_c(t) = E(1 - \cos\omega t) \quad (1)$$

where, E is the supply voltage[V], $\omega = 2\pi f$(f: frequency [Hz]).

When the circuit breaker is in a closed position, the voltage behind the breaker is higher than the supply voltage. The voltage difference is $\triangle U = u_c - E$. This is called the Ferranti rise and can also be seen as the effect of the capacitor acting as a source of reactive power; it is subsequently increases the voltage level. As a consequence of the Ferranti rise, a voltage jump occurs in the voltage at the supply side of the breaker[7].

When we realize that the small capacitive current could already be interrupted at a short arcing time and that the arcing contacts therefore have not travelled very far, the gap between the arcing contacts is still narrow and a dielectric breakdown of the extinguishing medium can occur. A dielectric breakdown of the arc channel within 4.2ms(time of 1/4 cycle in case of 60Hz power system) after interruption of the capacitive current is called a re-ignition and a dielectric breakdown of the arc channel after 4.2 ms is called a restrike. High voltage circuit breakers, which have to perform capacitive current switching, should be restrike-free to avoid overvoltage.

Finally, The small current interruption capability of a circuit breaker is utterly dependent on the dielectric recovery between the contacts after the current interruption.

3. Interruption tests

Three puffer type 362kV gas circuit breakers were used for the small capacitive current interruption tests. The rated voltage of the model circuit breakers is 362kV class but in the shapes of the nozzle and the arcing contacts each circuit breaker has some differences respectively. These differences had been counted in the analysis of the small current interruption.

After circuit breakers interrupt the small capacitive current, the voltage across the breaker terminals is calculated by the following equation (2);

$$V(t) = \frac{\sqrt{2}}{\sqrt{3}} \times V_n \times (1 - \cos(\omega t)) \times F_k \times F_p \quad (2)$$

where V_n is the rated voltage of the circuit breakers, F_k is the voltage coefficient(=1.2), F_p is the pole number(in case of 1-pole circuit breakers F_p = 1.0, in case of 2-pole circuit breakers F_p = 0.55).

According to the international test standard (IEC)[8], circuit breakers should be passed the test duty 1, 2, 3 and 4 of the small capacitive current and even one restrike is not permitted in the twelve times interruption each of the test duty.

Fig. 2 shows a typical example of the failed tests case during the dielectric recovery process after the capacitive current interruption in the model A circuit breaker. The current is once interrupted at the point Ⓐ. However, the restrike occurs at 5.5ms after the current interruption. At the instant, the voltage is about 80% of the peak value. From the breakdown point the current flows again between contacts during the period of Ⓑ and at point Ⓒ by increasing the distance of between contacts the current is interrupted again and the voltage reappears between the breaker terminals.

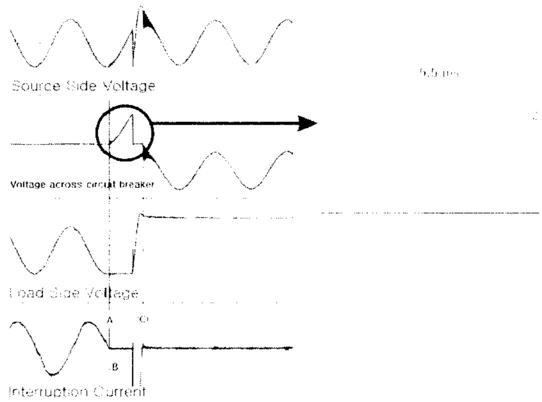


Fig. 2 An example of the failed test case of the small capacitive current. interruption.

In the verification tests for the interruption capability, first only the test duty number 4 which is the severest test duty to the circuit breaker has been performed on the all of the model circuit breakers and then only the circuit breaker passed the test duty number 4 carried out the test duty number 1, 2, and 3.

The test results each of the model circuit breakers are shown in Table 1. There were six times of breakdown in fifteen interruption tests in the case of model A circuit breaker and two times restrike in twenty-eight tests in model B circuit breaker respectively in the test duty number 4. But, the model C circuit breaker satisfied all the required conditions in the international test standard.

Table 1 Test results of the small capacitive current interruption.

Model	performed test number	failed number	arcing time [ms]	Breakdown Voltage [kV]	Test Current [A]
Model A Circuit Breaker	15	6	2.0	569.1	315-10% (Line charging current switching test, Test duty #4)
			3.0	521.0	
			1.5	631.0	
			1.5	579.0	
			2.0	615.0	
			1.0	520.0	
Model B Circuit Breaker	28	2	1.0	572.4	" "
			1.0	595.4	
Model C Circuit Breaker	48	0	1.0~9.0	-	362kV Line charging current switching test, Test duty #1, #2, #3, #4

4. Analysis of Dielectric Recovery Strength

4.1 Equations for the dielectric recovery

Two equations have been used to predict the dielectric recovery strength of the model circuit breakers.

One is the empirical formula as shown in equation (3) using experimental constants, which were determined from the breakdown tests [5].

$$V_{bd} = a\frac{\rho^{b}}{E_{0}} \tag{3}$$

where a, b are constants and E_0 is the local electric stress is the electric stress when the potential difference is 100V between the contacts. Equation (3) was established based on the concept that the breakdown voltage can be described in the static SF_6 gas with the local gas density ρ, the local electric stress E_0 and the breakdown stress E_f.

he other is the theoretical approach based on the streamer theory. Considering the exponential growth of electron avalanches, Pedersen[9] has proposed the electric breakdown equation (4) as

$$\int_0^x (\alpha - \eta)\, dx \geq K \tag{4}$$

where α is the ionization coefficient, η is the electron attachment coefficient and $K \approx 18$. Equation (4) has been simplified to equation (5) by Trepanier[10] using the values of SF_6 gas.

$$E/N > (E/N)^{*} \tag{5}$$

where E is the electric field stress and N is the number of gas particles. When the effective ionization coefficient is equal to zero, the ratio E/N is called the critical E/N and it is noted by $(E/N)^*$. At the condition $E/N = (E/N)^*$, the critical breakdown voltage V_{bd} can be obtained as follow [11]:

$$V_{bd} = \frac{(E/N)^{*}}{E/N} \times TRV \tag{6}$$

where TRV is the potential difference between the contacts. In equation (6), N is substituted by

$$N = \frac{\rho}{W_{SF_6}} N_A \tag{7}$$

where W_{SF_6} is molecular weight and N_A is Avogadro's number.

In the dielectric recovery estimation of a circuit breaker, the tip of fixed arcing contact is employed as the investigative region, as can be seen Fig. 3. Because the highest electric field strength appears in the whole of interrupter and the gas density rapidly decrease due to the formation of shock wave at the region[12]. Therefore, it is extremely important to get the precise values of the gas density and the electric field strength at the investigative region according to the moving of the circuit breakers.

Fig. 3 Investigate region of the fixed arcing contact tip.

4.2 Cold gas flow field analysis

Equations (3) and (6) for the evaluation of the dielectric recovery strength require the distributions of the density and electric field at the necessary instants during the moving action of the gas circuit breaker.

As it is impossible to measure the local gas pressure at all positions inside a interrupter, the local density distribution should be obtained by the computer simulation. To analyze the gas flow field in an interrupter, the moving action of circuit breaker should be simulated without damaging the convergence. A commercial CFD code "PHOENICS" was used the user-coded subroutines the moving action of circuit breaker, the boundary conditions etc., were added by the authors[13].

The compared results between the computational and experimental in the model A circuit breaker are shown in Fig. 4. The calculated values are quite close to the measured values but the peak value of pressure- rise in puffer cylinder is about 8% higher than that of the experimental. This is can be explained that the leakage of puffer-cylinder was not considered in the calculation.

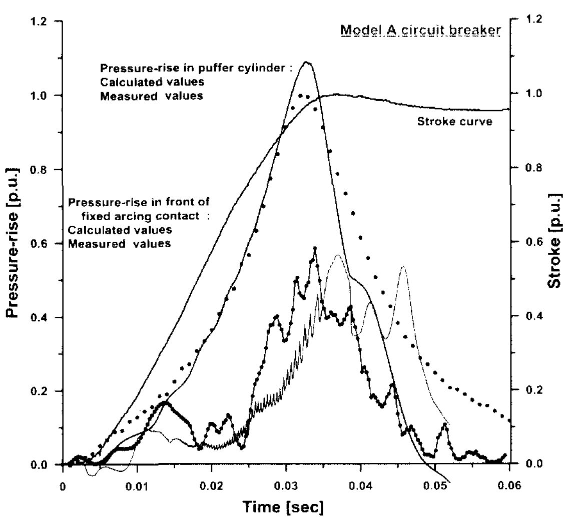


Fig. 4 Comparison of pressure-rise in model A circuit breaker.

4.3 Electric field analysis

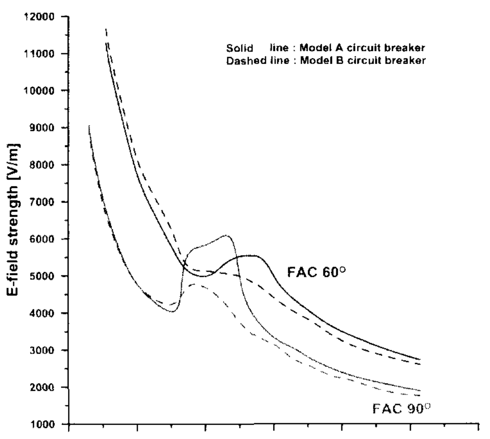
The electric field strength was calculated simultaneously every time step using the same grids for the gas flow analysis. At the first step, the potential values $\phi 1$, $\phi 2$ were given on the moving contact and the fixed contact respectively. And the potential in the interrupter can be obtained by solving the Laplace's equation:

$$\nabla^2 \phi = 0 \tag{8}$$

The electric field E in the interrupter including the tip of fixed arcing contact can be obtained from following equation;

$$E = -\nabla \phi \tag{9}$$

Fig. 5 shows the variation of electric field strength at the tip of fixed arcing contact after the contacts separation to the travelling of the model circuit breakers. As the distance between both contacts increases the electric field strength rapidly decreases, but as the fixed arcing contact approaches to the nozzle throat the strength abruptly increases and slowly decreases as the fixed arcing contact coming out the nozzle throat. This is believed that since the permittivity of the nozzle(ε =2.1) is high compared with that of the SF_6 gas(ε =1.0), the electric field strength varies according to the distance between the nozzle and the tip of fixed arcing contact.



· FAC60 : 60 degree point of the tip(see Fig. 3)
· FAC90 : 90 degree point of the tip(see Fig. 3)

Fig. 5 Electric field strength on the fixed arcing contact.

5. Results and Discussion

Fig. 6 represents the dielectric recovery characteristics of the model A circuit breaker. From the test results, the restrikes happened during the time period 5.45 ~ 6.54 ms after the contact separation. In this time period, the 90° region of the fixed arcing contact as shown in Fig. 3 is positioned at the start region of the nozzle down stream. At that position the gas flow fully develops to the supersonic flow (Mach no. > 1) and it is adequate to make the shock wave between the nozzle wall and the tip of fixed arcing contact as shown in Fig. 7(a). The shock wave rapidly decreases the density on the surface of the fixed arcing contact as can be seen in Fig. 7(b) and it acts as the main factor of the breakdown between contacts.

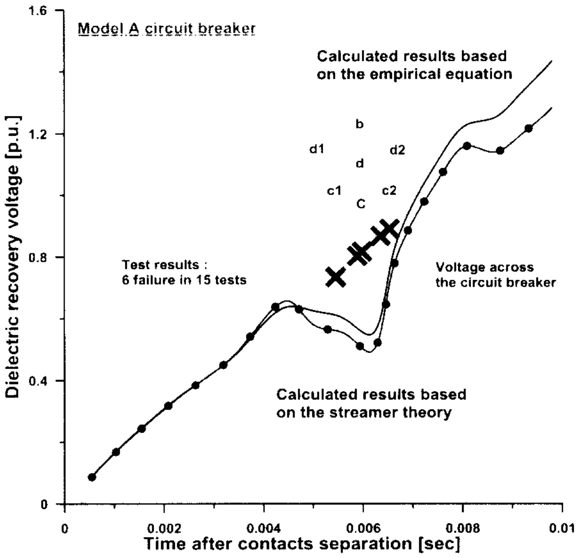
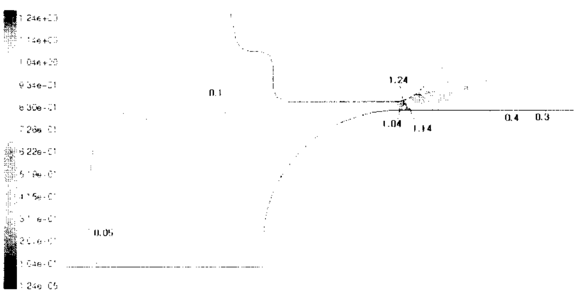
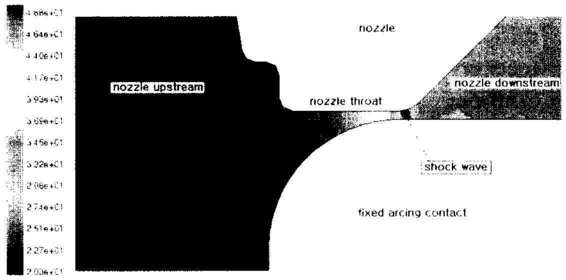


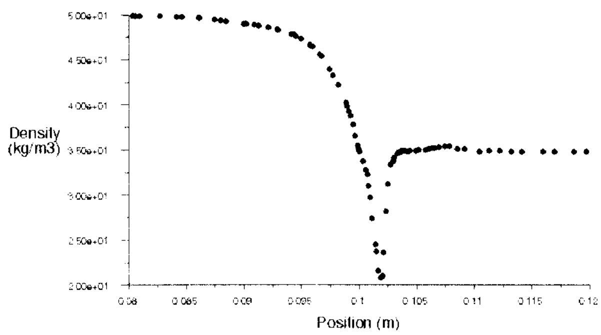
Fig. 6 Dielectric recovery of Model A GCB.



(a) Mach number



(b-1) Gas density distribution at the nozzle throat in kg/m^3



(b-2) Variation of gas density at the point of shock wave formation

Fig. 7 Supersonic flow at the nozzle throat region of Model A.

In Fig. 6, although the estimated results from the application of the streamer theory are somewhat severer than that from the empirical equation, the results also include the weak parts c1 ~ c2.

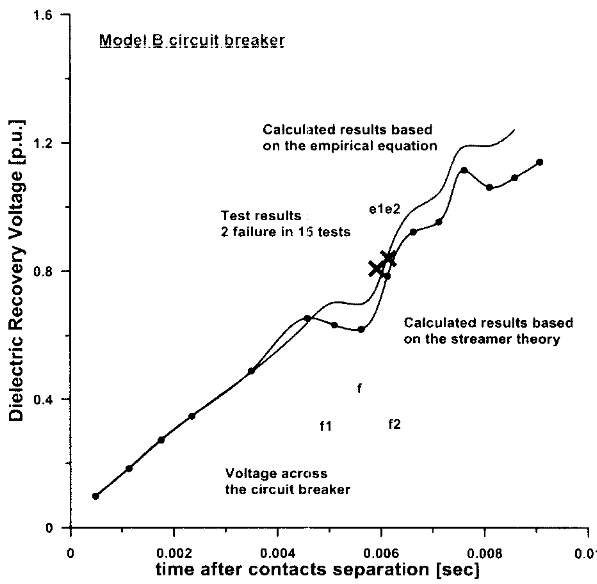
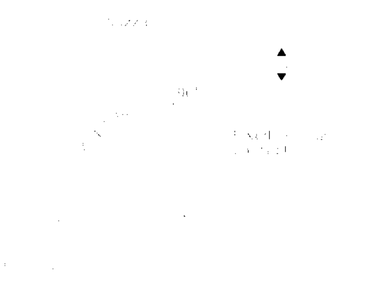


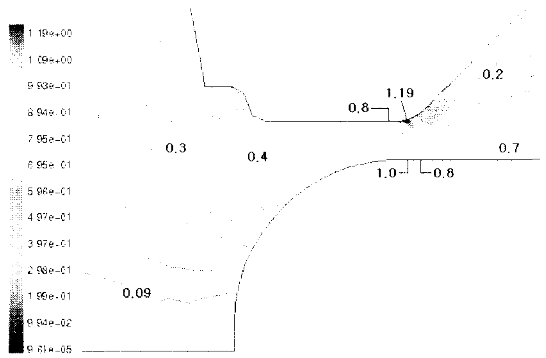
Fig. 8 Dielectric recovery of Model B GCB.

Fig. 8 shows the dielectric recovery characteristics of the model B circuit breaker. Two times breakdown happened in the vicinity of marked "e" in Fig. 9(a) and the calculated results contain the weak point from the test.

From the Fig. 6 and 8, the dielectric recovery characteristics of the model B circuit breaker is slightly better than that of the model A. Considering the same test conditions and the same operating conditions, it is believed that the increased distance between the nozzle and the fixed arcing contacts as marked "d" in Fig. 9(a) elevates the dielectric strength. This is confirmed from the increasing of the electric field strength in the nozzle throat is lower than that of the model A as shown in Fig. 5 and the formation of shock wave is not clear compared with the model A due to the bigger diameter of nozzle throat as given in Fig. 9(b). Therefore, it is believed that the formation of the shock wave in front of the arcing contacts has a major influence on the transient breakdown voltage.



(a) calculated weak region of the model B GCB



(b) Mach number at point f2

Fig. 9 Supersonic flow at the nozzle throat region of Model B GCB.

From the comparison of the computed values with tests results, both the estimation methods predict well the weak regions of the model A and B circuit breakers. However, The predicted results based on the streamer theory are somewhat severer than that of the empirical equation. This difference in the results by the two estimation methods can make confusion in case such as the model C circuit breaker.

The computed results of the model C circuit breaker are given in Fig. 10. Because there was no restrike in the tests, it can be affirmed that its dielectric strength is higher than the breakdown voltage across the circuit breaker. But, both methods presented the contrasted results each other i.e., while the estimation based on the empirical equation predicted the successful interruption like the test results, the prediction based on the streamer theory gave the failure. Therefore, in view of precision, it can be said that the application of empirical equation is more accurate.

On the other hand, at present in the international test standard[14] the small current interruption tests are being permitted to perform under the pure

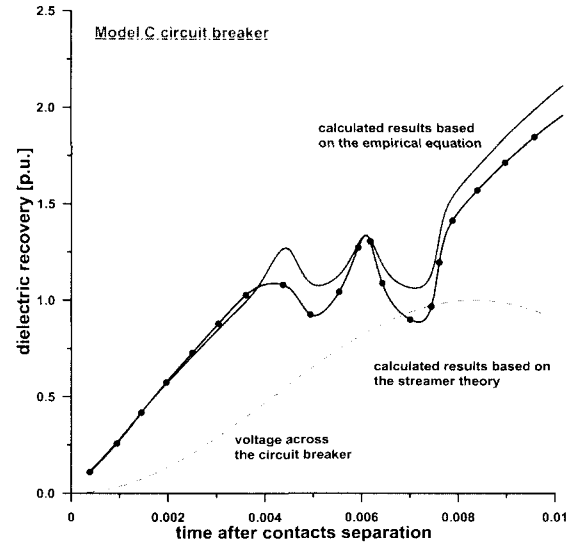


Fig. 10 Dielectric recovery of Model C GCB.

conditions of circuit breaker. But, from next year, the new test standards require the performance of the small current interruption tests immediately after the large current interruption tests without the maintenance such as the refreshment of the contaminated medium and the replacement of the arcing contacts and the insulation nozzle. Consequently, considering the damage of the nozzle and the arcing contacts due to the large current arc, the capacity of the small current interruption ought to have the adequate allowance. From this view point, preferably the estimation method based on the streamer theory can be more useful to the circuit breaker designer.

6. Conclusion

Combining the gas flow field analysis and the electric field analysis, the dielectric recovery characteristics of model circuit breakers were estimated from two equations that have different schemes each other. The results are summarized as follows:

1) In the estimated results from the empirical and the theoretical method for the dielectric recovery of the model circuit breakers, it is shown that the computed results predict well the weak parts, but it is still difficult to predict quantitatively the dielectric recovery strength.
2) Considering the computed results and the tested ones it is believed that the empirical method seems to have less predicted errors than the theoretical approach based on streamer theory.
3) Therefore, to obtain the more accurate results, the above equations are need to be modified and much more test results and further studies are required.
4) To improve the dielectric recovery characteristics of

circuit breakers, it is more effective to control the formation of the shock wave near the arcing contact than to increase the pressure-rise in the puffer cylinder.

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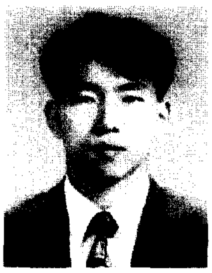

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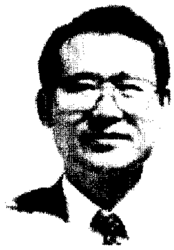

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