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SWITCHING CAPABILITIES OF SF_6 GAS CIRCUIT BREAKER, ISOLATOR AND EARTHING SWITCH

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1 INTRODUCTION

Requirement of electric power energy is tending to increase more and more, and accordingly, importance of switching and protective equipments is increasing. This paper describes switching capabilities of circuit breakers, isolators and earthing switches.

At the development of Fuji gas insulated switchgear, the following technologies are being applied in addition to the technologies and experience accumulated through the past many years.

(1) Analysis of arcing phenomena with characteristics of properties of SF_6, nozzle material, etc. taken into considerations; Diagnosis of arc by means of an optical observation and establishment of theory; Analysis of circuit breaking characteristics including line conditions.

(2) Execution of the optimized design through analysis of electric field and analysis of not only the completely opened conditions but also operating characteristics during switching.

(3) Establishment of rational proving method taking the interaction between the line cahracteristics and arcing characteristics taken into considerations.

(4) Examinations for compatibilities of items improved in the domestic and foreign standards and conditions newly added to the standards.

(5) Executions of analysis of the line conditions required to the circuit breakers, isolators and earthing switches by means of EMTP (Electro-Magnetic Transients Pro-gram), TNS (Transient Network Simulator), etc.

2 COMPACT PUFFER TYPE GAS CIRCUIT BREAKER

To reduce dimensions and weight of puffer type single pressure gas circuit breakers, current breaking performance of the breaking chamber must be improved, the technical problems caused by accomodating triple poles in a common enclosure must be solved, and the results must be thoroughly proved.

The technologies applied to the development of the gas circuit breaker are introduced below from the points of view of short circuit current breaking, small inductive and capacitive current breaking and technologies for three phase encapsulation.

2.1 Improvement of short circuit current breaking performance

Short circuit current breaking of a puffer type single pressure gas circuit breaker is accomplished by blowing the compressed gas (stored in puffer chamber) against the high current arc between breaking contacts.

Because of this operating principle, to break a high current arc, a high puffer pressure is required. The major specifications such as cubic volume of the puffer chamber and operating energy against the breaking capacity of the circuit breaker can be decided by precisely analyzing the characteristics of blown gas pressure at existence of arc.

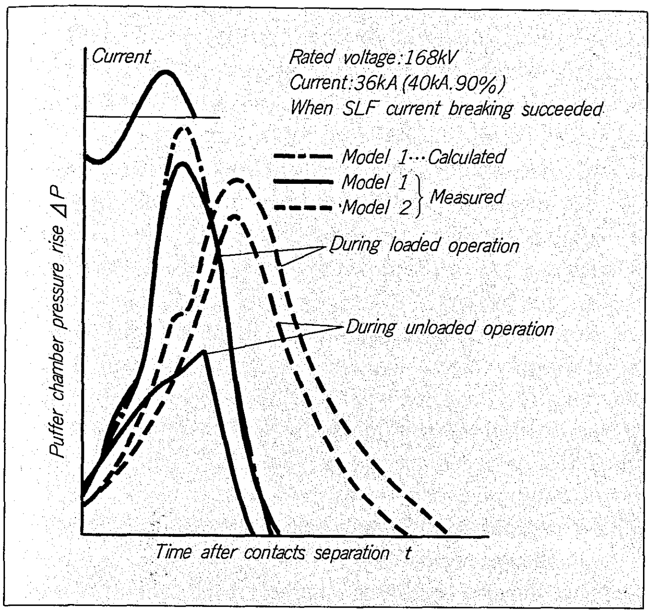
Further, the hot gas due to the high current arc affects the withstand voltage across poles and against the capsule at the down stream side of the nozzle, and this is one of the major subjects to be carefully examined when reducing dimensions and weight.

Furthermore, so called thermal reignition region around vicinity of current zero point must also be analyzed for the severe rate of rise of transient recovery voltage rising rate such as SLF and ITRV.

2.1.1 Analysis of operating characteristics during current breaking

Mainly, the current breaking operation of a circuit breaker is decided by the difference between the energy driving the puffer chamber and reacting energy caused by the pressure rise in the puffer chamber. Out of these factors, the pressure rise of the puffer chamber (hereinafter expressed as ΔP) greatly affects the current breaking performance. *Fig. 1* shows waveforms of ΔP of models having the same arc quenching performance. This figure indicates that the arc quenching performance is same as long as ΔP is equivalent during the current breaking even if ΔP is considerably low during the unloaded operation. In addition, cubic volume of the puffer chamber of Model 1 is 35% of

Fig. 1 Comparison of puffer chamber pressure rise ΔP



that of Model 2, and this indicates that dimensions of the puffer chamber and operating energy can be reduced.

The ΔP during current breaking which greatly affects arc quenching performance is decided by the following factors.

(1) Pressure rise due to mechanical compression of the puffer chamber.

(2) Pressure rise due to arc

 (a) Arc occupies the nozzle. This causes the cross-sectional area through which the arc quenching gas flows out to reduce. Then, pressure rises.

 (b) Arc clogs the nozzle, causing high temperature gas to flow reversely to the puffer chamber. Then, pressure rises.

As described above, during loaded operations, ΔP is considerably affected by the circuit breaker control mechanism and arc quenching process.

For this reason, a simulation program was developed for operations at the time of current breaking by building an analysis program using an enthalpy flow arc model into the calculating program for operations of hydraulic control mechanism of circuit breaker. *Fig. 2* shows the flow chart, and the *Fig. 1* shows the ΔP waveform obtained by the simulation in single dot dash-dot line. With the *Fig. 1*, it can be understood that the calculated value well agrees with the actually measured value.

With this simulation, specifications of the control mechanism and current breaking chamber could be optimized.

2.1.2 Observation of down stream side of nozzle during high current breaking by the use of a high speed camera

Insulations against the capsule or electrode of circuit breakers are designed based on AC withstand voltage, impulse withstand voltage, etc. by using electric field calculations, etc. However, the above mentioned factors apply only when arc does not exist, and dielectric strength after short circuit current breaking is not taken into consideration. When breaking a short circuit current, a high current arc is generated, and a large volume of high temperature gas due to the arc energy is produced. It is considered that density and dielectric strength of this high temperature gas are low, and when high temperature gas exists in the vicinity of the breaking chamber after breaking the current, a restriking is anticipated to occur because the gas cannot withstand against the transient recovery voltage. Therefore, when intending to reduce dimensions a circuit breaker, the behavior of high temperature gas exposed to arc in the down stream side of the nozzle must be examined particularly carefully.

For this purpose, using a model of 168 kV dead tank

Fig. 2 Flow chart for simulation of current breaking operation by circuit breaker

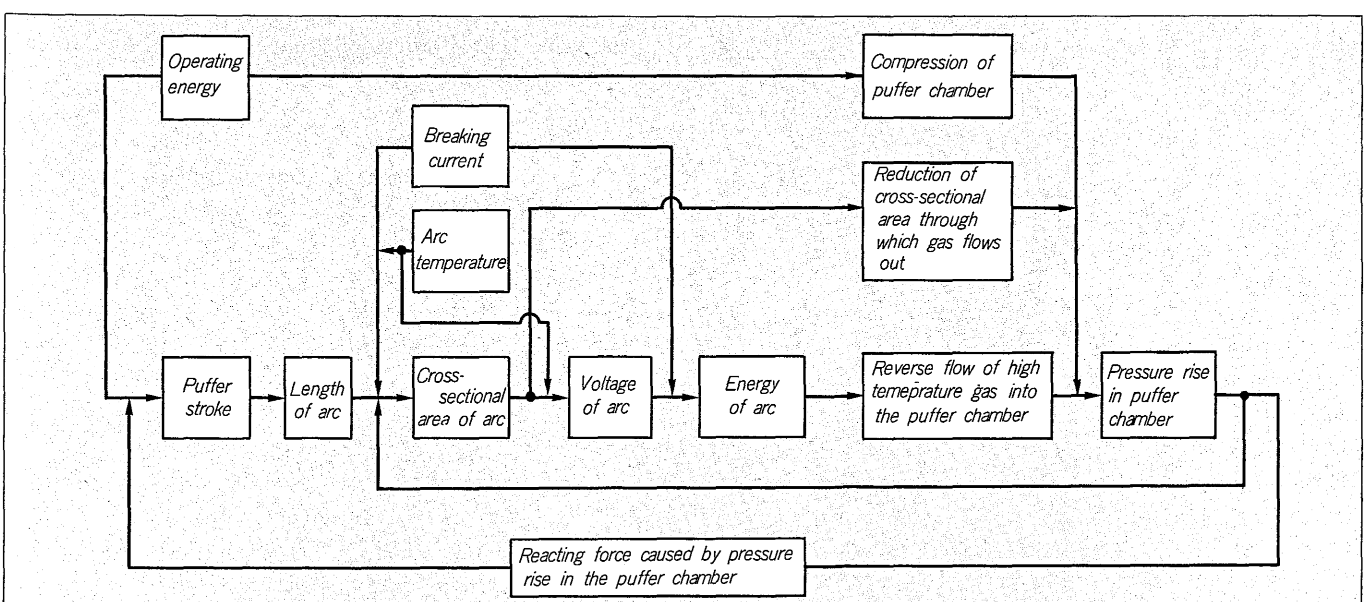
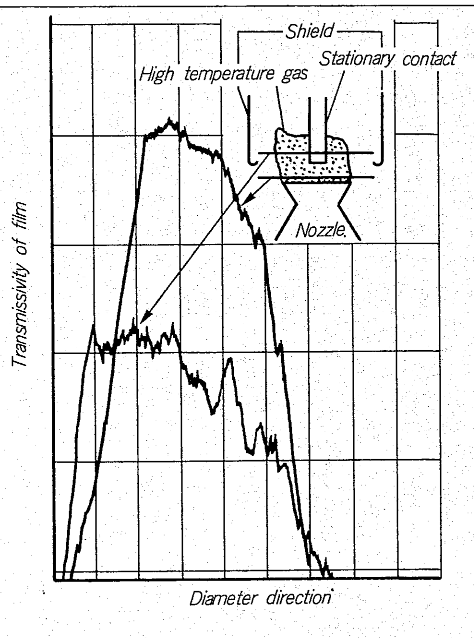


Fig. 3 Observation of down stream side of nozzle by the use of high speed camera

Momentary current: 56.6kA (Peak value of RMS value 40kA)
Filming velocity: 4000 frames per second
Exposure time: 4μs (per frame)

Fig. 4 Measurement of high temperature gas range by the use of a microphotometer



type circuit breaker, the behavior of high temperature gas in the down stream side of the nozzle caused at 40 kA interruption was observed by using a high speed camera. *Fig. 3* shows one shot.

Now, generally, when high temperature gas such as an arc is photographed, it is considered that higher the temperature may be, transmissivity of the film (positive film) increases. Thus, relative temperature distribution can be obtained by measuring transmissivity of film. Therefore, transmissivity of the film around current peak at which the high temperature gas range is widest (*Fig. 3*) was measured by using a microphotometer. *Fig. 4* shows the result.

In this figure, it is considered that high temperature gas exists in the portion where transmissivity is high. Therefore, it is considered that the distribution range at the down stream side of the nozzle does not differ from that at the nozzle outlet, and based on the fact that the transmissivity is greatly reduced at the down stream side of the nozzle, arc and gas temperatures are, in comparison with those at the nozzle outlet, considered to be considerably lowered in the down stream side of the nozzle. As described above, high temperature ags distribution range and tendency of temperature drop can be estimated by observing high temperature gas in the down stream side of the nozzle with a high speed camera.

Accordingly, shape of nozzle, shape of shield around the stationary electrode, etc. can be decided by directly observing the behavior of high temperature gas at the down stream side of the nozzle during high current breaking by using a high speed camera so that high temperature gas spread is minimized.

2.1.3 Examination of breaking performance in thermal reignition region

The current breaking characteristics for the severe duties of transient recovery voltage rising rate such as SLF and ITRV are phenomena in the vicinity of current zero (so called thermal reignition region), and with various arc models represented by such as Mayr's arc model, the current breaking characteristics have been analyzed.

Fuji Electric has used the thermal equation as an arc model. Based on the data such as arc voltage and current obtained by current breaking test and arc diameter and length obtained by optical observation, analyzations are made for these current breaking duties, and thus, the fundamental examinations are made to design efficient arc quenching chambers.

In this paper, as an example of analysis in the thermal reignition region which uses the thermal equation for the arc model, the ITRV breaking characteristics applied to those circuit breakers of 100 kV or higher ratings (established in the IEC standards during recent years) are indicated.

ITRV is a phenomenon similar to SLF which is caused by surge propagation at bus section of a substation. The peak value is only several kV, but time to peak is less than

Fig. 5 Calculation circuit

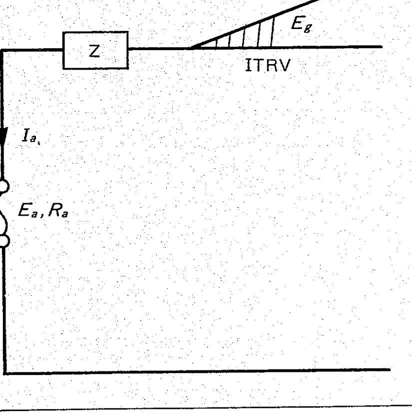


Fig. 6 Calculation waveform example

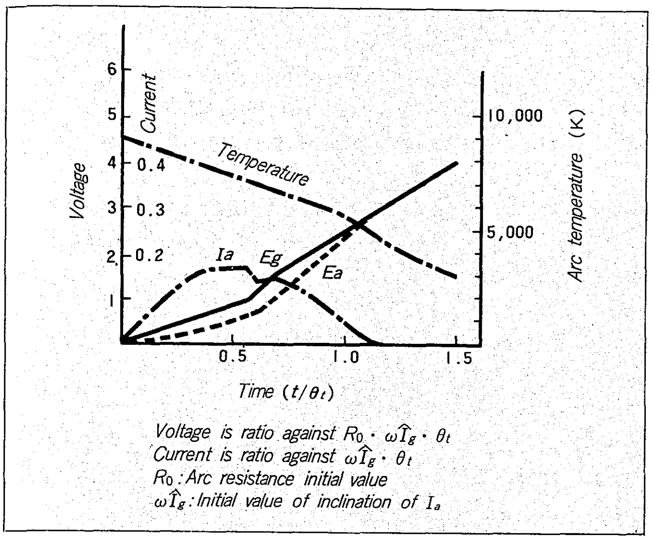


Table 1 Calculation results

Arc temperature (K)	SLF td = 0.5 μs		ITRV only	SLF td = 0 μs
	+ITRV	Without ITRV		
10,000	X	O	X	X
9,000	O	–	O	X
8,000	–	–	O	O

O: Succeeded in breaking
X: Failed in breaking (thermal reignition)

1 μs, and the rising rate reaches several kV/μs.

For a 90% SLF of 245 kV 40 kA, influences given to current breaking characteristics by existence or non-existence of ITRV were examined by using model circuits. *Fig. 5* shows the calculation circuit. The calculations were made as shown below.

$$Ea = Eg \cdot Ra/(Ra + Z) \quad \dots\dots (1)$$

$$Ea = Ea \cdot Ra \quad \dots\dots (2)$$

$$\frac{dS}{dt} = -\frac{S}{\theta t} + as \cdot \sigma(t) \cdot Ea^2(t) \quad \dots\dots (3)$$

where,

Eg : ITRV S : Heat flux potential
Z : Surge impedance θt: Arc time constant
Ia : Arc current as: Thermal duffusivity
Ra: Arc resistance σ : Electrical conductivity

Using the time constant for the case of 5 kg/cm² SF_6 gas pressure, initial arc temperature were 10,000K, 9000K and 8000K. *Table 1* shows the results, and *Fig. 6* shows the calculated waveform example.

According to the *Table 1*, under the condition of SLF td = 0 μs, current breaking barely succeeds at 8000K, and from this result, it can be understood that the condition is more severe than other conditions.

As this example indicates, the thermodynamic characteristics of arc can be related to the electric circuit to be interrupted by using the thermal equation.

2.2 Improvement of small current breaking performance

2.2.1 Small capacitive current breaking

Small capacitive current breaking such as in a charging current of unloaded power transmission line differs from a short-circuit high current breaking, where the breaking current is about 50A to 500A, and the current may be interrupted just after contacts seperation.

Accordingly, a high voltage is applied immediately after breaking current while distance across the contacts is still short. Therefore, if the insulation recovery is insufficient between the contacts, re-strike and reignition will occur.

For this reason, not only the electric field analysis at the closs and open position (which should be examined when designing a circuit breaker) but also electric field is repeatedly calculated at the individual position in the pole opening stroke, and thus, electrode and shield shapes and relative positions among these are decided.

Fig. 7 shows an electric field calculation example at a mid position in opening operation. *Fig. 8* shows voltage

Fig. 7 Electric field calculation example

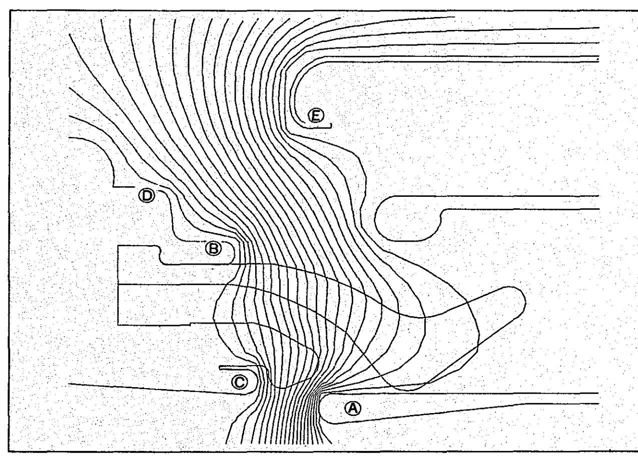
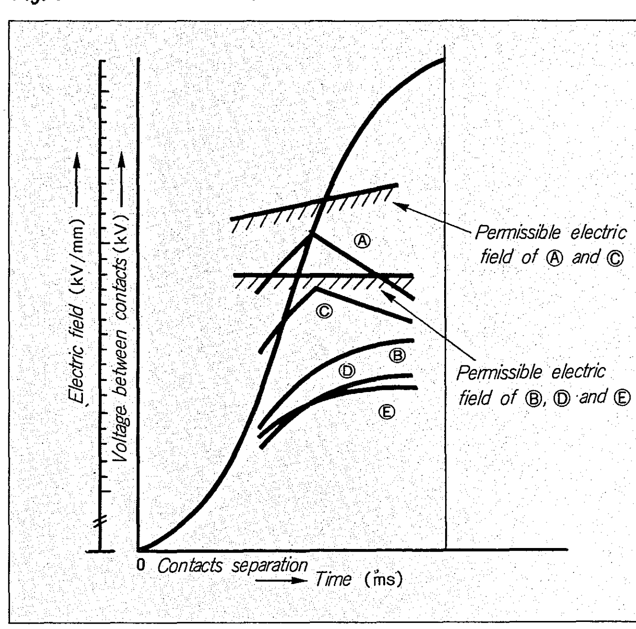


Fig. 8 Electric field analysis example



waveforms between contacts fot the case in which arc time in small capacitive current breaking is zero and electric field analysis example during the opening stroke obtained in correspondence with voltage waveforms between contacts. In this figure, the slash lines are permissible electric fields at the individual positions used as the design targets. For cases of (A) and (C), distribution of gas blow pressure is taken into consideration, and the test result is satisfactory.

Further, when proving a small capacitive current breaking performance, not only the charging current of unloaded power transmission line but also charging current of the cable, making/breaking of condenser bank current, and for the voltage, charging current breaking of the sound phase in case of a single line grounding are taken into considerations, insuring to provide a sufficient small capacitive current breaking performance.

2.2.2 Small inductive current breaking

The problems to be solved in breaking small inductive current arc to reduce the chopping current level as much as possible and to suppress over-voltage.

Generally, when arc quenching force is increased to enhance short-circuit breaking performance, chopping level at small current breaking increases, and this is not desirable from the points of view of over-voltage occurrence.

In a gas circuit breaker of new type, at the time of a short-circuit breaking, increase of blast pressure caused by the arc itself is used as indicated in 2.1 above, and pressure rise by a mechanical operating energy is minimized.

Fig. 9 Current chopping characteristics

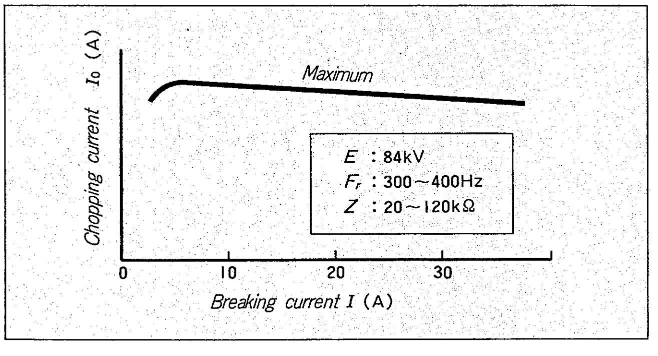
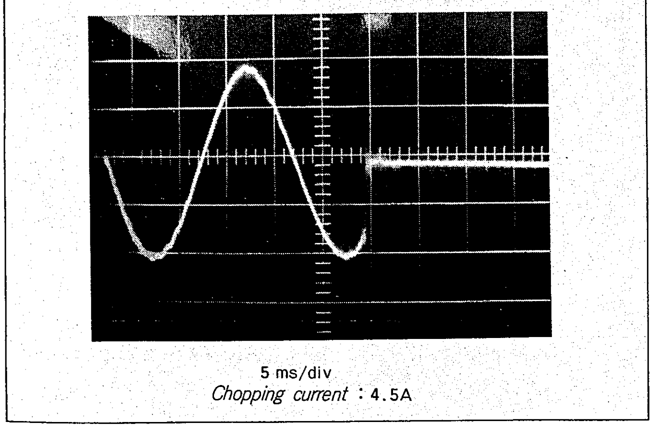


Fig. 10 Current waveform at chopping



According to JEC-181, breaking current at small inductive current breaking duty is 20A or less, and blast pressure is not increased by arc. Therefore, chopping current decreases, and generation of an over-voltage could be minimized. (Over-voltage is decided by the chopping current value and circuit configuration.)

Fig. 9 shows the current chopping characteristics of new gas circuit breaker and *Fig. 10* shows the chopping current waveform.

2.3 Technologies for three phase encapsulation of circuit breaker

The circuit breaker for a three phase encapsulated switchgear SDF have been developed and tested by using the established technologies for accomodating a triple pole circuit breaker in a common enclosure.

The major technical subjects involved in accomodating a triple pole circuit breaker in a common enclosure are:

(1) Influence given to the withstand voltage by the three phase arc energy injected into the same capsule.
(2) Countermeasure for electromagnetic force between the phases
(3) Performance proving method

First of all, to minimize the energy injected to the down stream side of the insulation nozzle, the nozzle was formed to a double flow nozzle, and further, to improve withstand voltage among the poles or against the capsule, optimization was made by checking blowoff of gas from the nozzle with a high speed camera.

Also, influence of sinuosity caused by arc electromagnetic force could be greatly reduced by increasing arc quenching force and by reducing contact stroke.

Further, as the dimensions were reduced, the electromagnetic force was examined, and the performance was checked to be sufficient.

In addition to the structural improvement of the arc quenching chamber, current breaking performance must be proved in response to the ratings of the circuit breaker.

Generally, the breaking conditions satisfied by a circuit breaker consists of (1) overall small current breaking, (2) terminal fault (BTF), (3) short-line fault (SLF), (4) out-of-phase switching, and (5) special current breakings under other special conditions. And, for 3-phase enclosure tank-type circuit breaker, (1) current breaking ability, (2) phase-to-phase withstand voltage and (3) phase-to earch withstand voltage must be proved under BTF condition under which the breaking current is maximum and applied voltage is high.

A new three-phase synthetic test method which satisfies these proving conditions economically and rationally was developed. *Fig. 11* shows the circuit.

The 1-st clearing pole breaking performance is demonstrated by applying Weil circuit V_1 (current injection method) to phase A. The second and third phases are broken for phase B and C. Immediatly after breaking phases B and C, current source voltage is used, and Skeats circuit V_2 (voltage injection method) is connected to phases B and

Table 2 Comparison of direct test with synthetic test

Item		Breaking current			Recovery voltage (E: Phase voltage)								
					Inter-pole			Against capsule			Inter-phase		
Phase name		A	B	C	A	B	C	A	B	C	A-B	B-C	C-A
Direct test	1st phase breaking	0	1	1	$1.5E$	0	0	$1.5E$	0	0	$1.5E$	0	$1.5E$
	2nd, 3rd phase breaking	0	0	0	$1.0E$	$1.0E$	$1.0E$	$1.0E$	$1.0E$	$1.0E$	$\sqrt{3}E$	$\sqrt{3}E$	$\sqrt{3}E$
Synthetic test	1st phase breaking	0	1	1	$1.5E$	0	0	$1.5E$	0	0	$1.5E$	0	$1.5E$
	2nd, 3rd phase breaking	0	0	0	$\sqrt{3}E$	$1.0E$	$1.0E$	$1.0E$	$1.0E$	$1.0E$	$\sqrt{3}E$	0	$\sqrt{3}E$

Fig. 11 New 3-phase synthetic test circuit

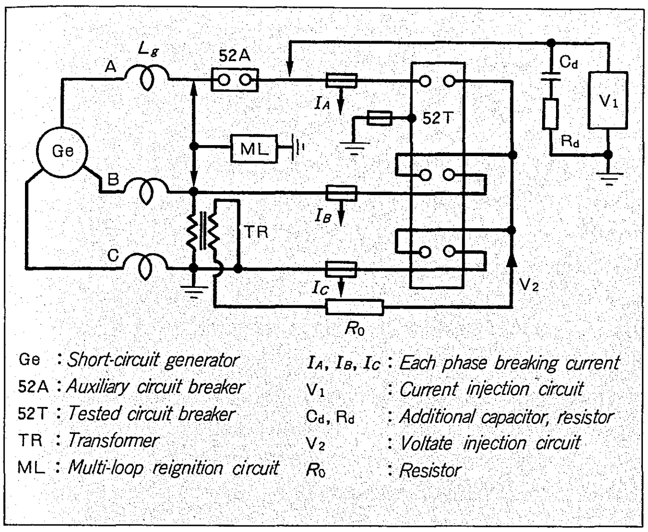
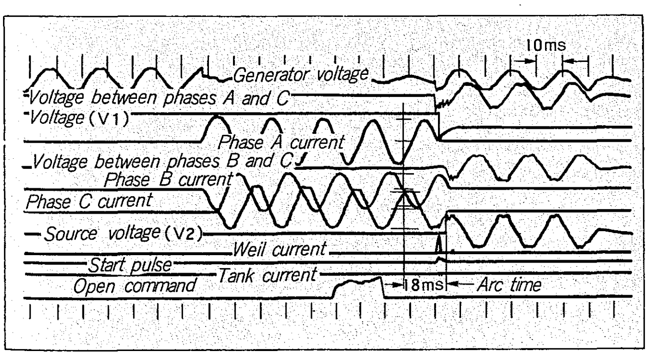


Fig. 12 Oscillogram for 3-phase synthetic test



C with the polarity reversed from V_1.

In this operation, V_1 is attenuated by Cd-Rd circuit attached to V_1 circuit before breaking B and C phase currents so that phase-to-phase voltage does not exceed $\sqrt{3}E$ (E: Phase voltage).

Table 2 compares voltage applied to the circuit breaker with the 3-phase direct test. From this table, it can be understood that this synthetic test is well matched with the direct test.

V_1 denotes voltage between contacts, V_1 and V_2 phase-to earch, $V_1 - V_2$ denotes phase-to-phase voltage, and phase A of the tested circuit breaker is inversely connected with phases B and C at the moving and stationary sides.

Each phase is provided with the multi-loop reignition circuit so that arc time can be decided freely.

For measurement of breaking current of phases A and B at a high electrical potential part, an optical fiber insulating method is used.

Fig. 12 is an example of test oscillogram for 3-phase enclosure tank-type GIS. With this method, performance of 72 to 204 kV rated voltage GIS was proved, and sufficient results could be obtained.

3 ISOLATOR AND EARTHING SWITCH

When developing the earthing switch and isolator for GIS, not only the already issued standards and customer's operating standards, but also the presently examined guide lines were referred to decide the subjective specifications of the development, first. Then, the construction, gas pressure, control conditions, etc. were optimized so that the specifications would be satisfied, and the performances were checked by type tests.

3.1 Required performance and specifications for current switching

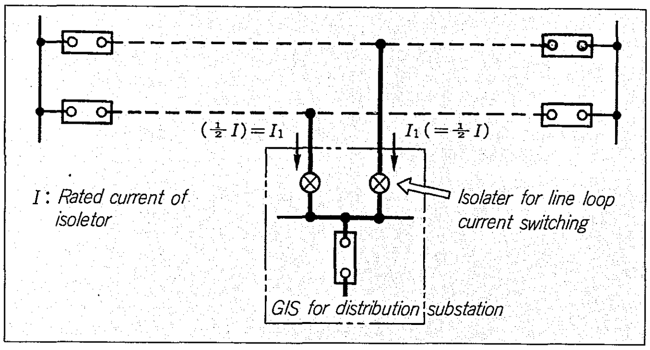
3.1.1 Isolator

When classified with the required switching ability, four types of switching can be listed as shown below.

(1) Closed loop current switching
(2) Small capacitive current switching
(3) Small inductive current switching
(4) Without switching ability

The closed loop current switching is further classified into line loop switching and parallel busbar loop switching. The line loop current switching is generally applied to isolators of GIS for distribution substation in a composition shown in *Fig. 13*, and the line loop switched at the time of transmission line switching is 50% of the rated current of the isolator. On the other hand, recovery voltage is approximated to be 0.4 Ω/km as it is 0.41 Ω/km with hard aluminum stranded wire A610 conductor or 0.39 Ω/km with heat resisting aluminum alloy stranded wire T1160 conductor, and thus, voltage drop (recovery voltage) with the rated current is calculated. For the subjective specifications of the development, it was established to be 5000V 800A by taking operating conditions of the power company into considerations. In this case, when the rated current is 800A,

Fig. 13 Line switching example of line loop current switching disconnector



it is equivalent to 15.6 km loop forming circuit length. As the line is consisted of distributed constant circuits, the rate of rise of recovery voltage (*rrrv*) which appears across poles of the isolator after breaking current can be calculated by formula (4).

$$rrrv = \sqrt{2}\omega \cdot I \cdot Z \times 10^{-9} (\text{kV}/\mu\text{s}) \quad \ldots\ldots\ldots\ldots (4)$$

Where, ω: Angular frequency ($2\pi f$)

Z : Surge impedance (Ω) (As a hint, 450 to 480 Ω for overhead wire or 30 Ω for cable)

I : Loop current (A)

For the parallel busbar loop current switching, an example of the composition is shown in *Fig. 14*. The most severe busbar switching condition is in the loop composition which causes the current to be the same as the rated current, and therefore, the switching current is required up to the rated current.

Recovery voltage V_R is generally expressed by formula (5).

$$V_R = k \cdot I \cdot l \times 10^{-3} (\text{V}) \quad \ldots\ldots\ldots\ldots (5)$$

Where, I : Loop current (A)

l : Length of circuit which forms the loop (m)

k : Constant decided by the material of busbar and composition (0.1 to 0.5 Ω/km)

For the recovery voltage, 300V (for 100m loop length suggested in "Standardization of gas insulated switchgears" by the Cooperative Electrical Research Committee in May, 1983) was employed. With the formula (5), loop length can be estimated to be 150 to 750 m when the rated current is 4000A. *rrrv* can be calculated by the formula (4) in the same manner as line loop switching, and Z would be 70 to 80 Ω in GIS.

As for small capacitive current switching, a large switching current is involved when the busbar is in a long layout and loaded electrostatic capacity is large. According to JES-196-1975 (Isolator), it is 1A when the rated voltage is less than 168 kV. However, the specifications were established to be 1A for 72/84 kV and 2A for 168 kV by taking the operating conditions into consideration. In this case, the loaded electrostatic capacity is equivalent to 66,000 pF.

Small inductive current switching is used when the isolator is installed in the primary side of a transformer.

According to the JEC-196-1975, the objective value of the switching current is 2A, or according to the suggestion by the Cooperative Electrical Research Committee, it is 3A. However, various operating conditions were taken into considerations, and it was established to be 5A.

3.1.2 Earthing switch

The primary purpose of an earthing switch is to ground the main circuit, and it requires a rated short-time withstand current ability. In some cases, as designated, the earthing switch is provided with a coupling current switching ability of a combined overhead cable, continuous current carrying capacity, fault current making capacity and capacity to discharge residual charge from a cable system.

The currents to be switched are inductive coupling current and capacitive coupling current. The inductive coupling current occurs on a system in which both terminals of the transmission line are grounded as shown in *Fig. 15*, due to an electromagnetic induction from the inducting circuit. The capacitive coupling current occurs on a system in which one end of the transmission line is grounded as shown in *Fig. 16*, due to an electrostatic induction from the inducting circuit.

Generally, in case of a switching for inductive coupling current, induced current I_2, induced voltage V_2 and rate of rise of recovery voltage *rrrv* are expressed as shown below:

$$I_2 = 0.1 I_1 (\text{A}) \quad \ldots\ldots\ldots\ldots (6)$$

$$V_2 = 0.06 I_1 \cdot l (\text{V}) \quad \ldots\ldots\ldots\ldots (7)$$

$$rrrv = \sqrt{2}\omega \cdot I_2 \cdot Z \times 10^{-9} (\text{kV}/\mu\text{s}) \quad \ldots\ldots\ldots\ldots (8)$$

Where, Z : Surge impedance of transmission line (450 to 480 Ω)

l : Length of transmission line (km)

Fig. 14 Example of busbar switching for large switching current

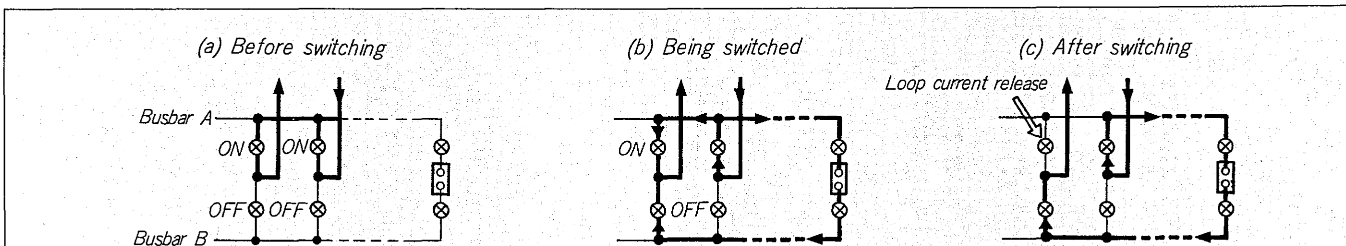


Fig. 15 Inductive coupling current

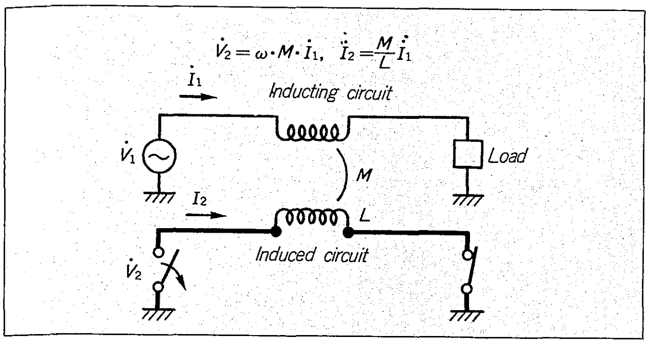
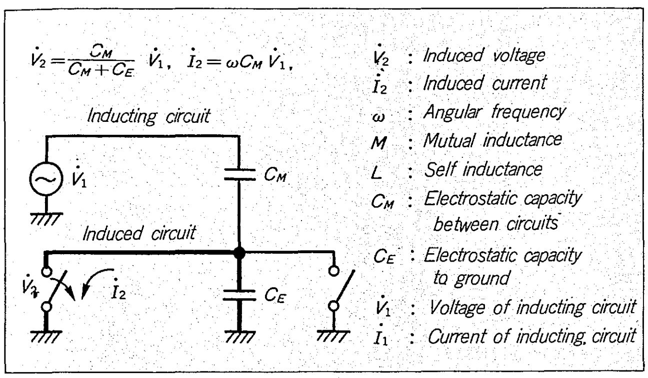


Fig. 16 Capacitive coupling current



I_1: Inducting current (A)

For the inductive coupling current switching specifications, the actual operating condition was taken into consideration, and the voltage and current were established respectively to be 1500V and 300A. In this case, when the inducting circuit current is 3000A, the length of transmission line is calculated to be 8.3 km by formula (7).

On the other hand, capacitive coupling voltage V_2 and capacitive coupling current I_2 can be indicated by the following formulas in the manner similar to the inductive coupling voltage and current.

$$V_2 = 0.1\ V_1 (\text{kV}) \quad \cdots\cdots (9)$$

$$I_2 = 0.06 \sim 0.1l (\text{A}) \quad \cdots\cdots (10)$$

Where, V_1 denotes a voltage to ground of the healthy phase.

For the capacitive coupling current switching specifications, the voltage and current were established to be 20 kV, 1A for the case where the rated voltage is 72/84 kV GIS. For tis decision, parallel wiring along a 275 kV line has been taken into consideration. In case of a parallel wiring along a 66 to 77 kV line, it may be considered to be maximum (84 kV/$\sqrt{3}$) x 0.1 = 4.8 kV. From formula (10), 1A current is equivalent to 10 to 17 km parallel line length. In case of a 168 kV line was taken into consideration, and the specifications were established to be 30 kV, 3A. In case of a parallel wiring along a 154 kV line, it may be considered to be maximum (168 kV/$\sqrt{3}$) x 0.1 = 10 kV. In this case, 3A current is equivalent to 30 to 50 km combined line length.

3.1.3 Guaranteed number of switching operations

Based on No. 4, Vol. 33 of the Electric Cooperative Study and [Standardization of Gas Insulated Switchgear] of the Electric Cooperative Study, the guaranteed number of switching operations was established as indicated below.

Closed loop current switching: 200 times.

Small capacitive current and small inductive current breaking: 2000 times.

Coupling current switching by earthing switch: 100 times.

In the above, contact erosion is largest at switching loop current and inductive coupling current.

Guaranteed number is judged by taking the following matters into considerations.

(1) No problem on the contact erosion until reaching the rated guaranteed number.
(2) No problem on the current carrying performance
(3) The rated insulation strength is still maintained after reaching the rated guaranteed number.

3.2 Arc-quenching method and breaking characteristics

For SF_6 gas insulated disconnectors, a free burning type and suction puffer type have been used practically. In order to further reduce GIS, the requirements of 3.1 above must be satisfied with a disconnector of smaller dimensions and operating energy. For this purpose, influence of sealed gas pressure, limit of the conventional method at the loop current zone, breaking characteristics with a new arc quenching method, etc. were examined.

3.2.1 Arc quenching method

Fig. 17 shows the construction and features of each method. The free burning type is a fundamental one used for a isolator and earthing switch, and does not use any particular arc quenching chamber. When opening speed of a motor-driven is expressed as one, some isolator feature a 20 times as great high opening speed realized by adding a spring. A high speed arcinghorn type is basically a kind of the free burning type. The difference is the further increased speed, and the arcinghorn portion is so designed that the contact is opened later at a high speed.

The suction puffer type is so designed that pressure of the puffer chamber reduces simultaneously with the opening operation, and the circumferential gas is sucked by the differential pressure. This gas flow cools and quenches the arc.

An arc chute type uses an arc chute plate with V-groove (magnetic body) which is so placed that it surrounds a half of arc. With this arc chute plate, arc is driven and expanded laterally, and cooled. Arc of loop current is extinguished within the chamber of this arc chute plate, preventing the arc outblowing into spaces between contacts and phases. This is one of the important points to reduce GIS.

3.2.2 Breaking characteristics

(1) Influence of gas pressure

The basic performances of a isolator are to break small capacitive current and small inductive current. Normally, the inter-pole recovery voltage of the former is higher and

Fig. 17 Construction and features of each arc quenching method of disconnecting switch

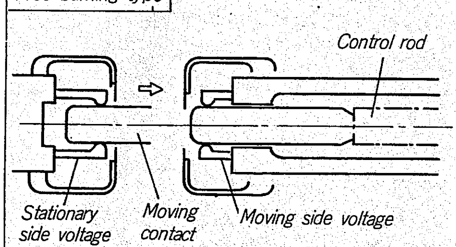
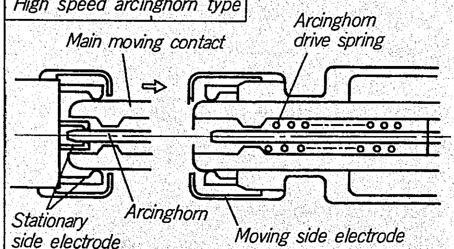
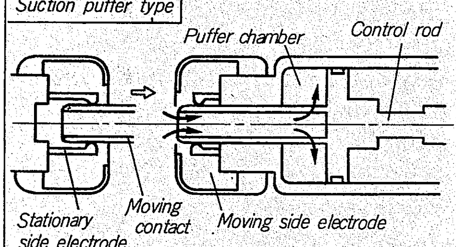
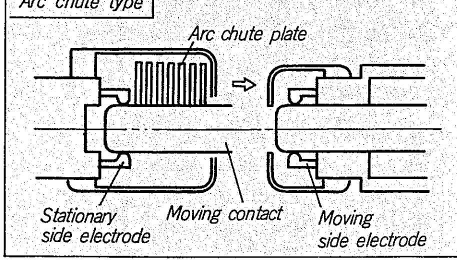
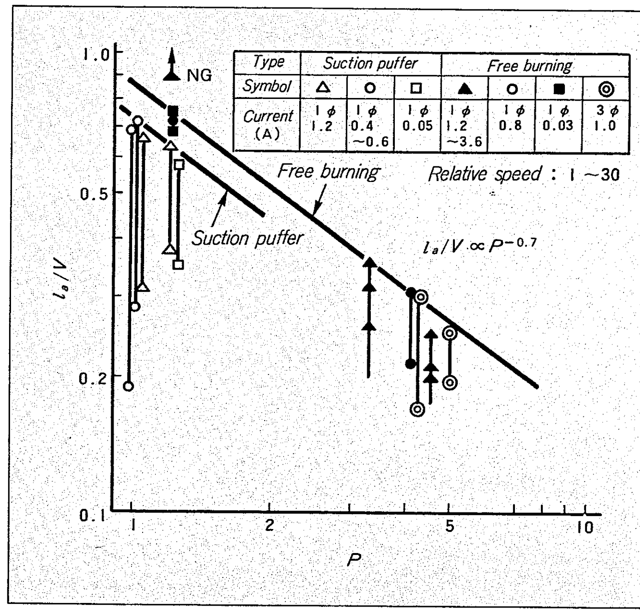
Construction of each type	Contact parting speed (ratio)	Operating energy (ratio)
Free burning type 	1 ~ 20	1 ~ 6
	(Feature) Simple construction	
High speed arcinghorn type 	1 (Moving contact) ~60 (Arcinghorn)	1
	(Feature) Complicated construction	
Suction puffer type 	10	6
	(Feature) Large control energy	
Arc chute type 	15	2
	(Feature) • Simple construction • Arc is not expanded into space between poles	

Fig. 18 Small capacitive current breaking characteristics



the arcing time tends to be longer. Therefore, the effect of gas pressure to the small capacitive current breaking was examined. The results are shown in *Fig. 18*. Arcing time *ta* greatly depends upon opening speed. Using inter-pole distance *la* which corresponds to the arcing time *ta*, the data within the range of 1 to about 30 relative speed can be normalized. The effect of gas pressure was tested in the range of 40 to 160 kV test voltage, and it can be normalized with *la*/*V*. As shown in the figure, as the absolute pressure *P* increases, *la* per unit voltage reduces and the upper limit curve is expressed by formula (11).

$$la/V \propto P^{-0.7} \quad \cdots\cdots (11)$$

where, *P* : Absolute pressure

When examined with the inverse numbers of formula (11), it is almost the same as the relationship between the dielectric strength and pressure. In other words, it means that the small capacitive current breaking performance is decided by the dielectric strength between contacts. From this result, it can be understood that *la* at gas pressure and test voltage should be obtained, and the design should be done so that the obtained *la* is less than 80% of the breaking distance ratio against distance between full open contacts. Further, in a zone where gas pressure is high, this curve can be established up to a comparatively high breaking current. Therefore, this theory can also be applied to an earthing switch for breaking capacitive coupling current.

(2) Examination on loop current breaking

To decide an arc quenching method suited for switching both busbar and line loop currents as described in 3.1 above, using the model isolator shown in *Fig. 17*, many number of tests were conducted. First of all, to examine the limit of the free burning type arc quenching method, including the high arcing horn type, influence of the opening speed *V* was examined. The results are shown in *Fig. 19*. As shown in the *Fig. 19*, as the opening speed *V* increases, arcing time *ta* reduces, while the corresponding *la* increases. When the switching life is taken into consideration, it is desirable that *ta* should be smaller. On the other hand, however, there is such a requirement as that *la* should be less than 80% breaking distance ratio, and with this curve, it can be understood that there is the optimum value for the opening speed *V* and that even if the opening speed *V* is increased, there is a limit for the free burning type.

Based on the above described *la*, the arc quenching type was compared with other types. The result is shown in *Fig. 20*. The free burning type is worst in the required closed loop current zone. The suction puffer type is best for line, however, for arc current over 2 kA, the suction is not sufficient and it is approximately same as the free burning type. Therefore, to obtain a sufficient perform-

Fig. 19 Opening speed — Arcing time curve

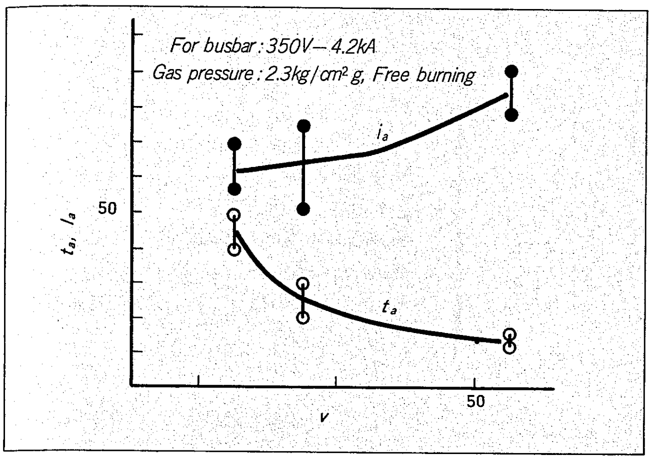


Fig. 20 Comparison of arc quenching method

Gas pressure: 3.8kg/cm² g

Type	For busbar 300V	For line 5000V	v (Ratio)	Result	
				For busbar	For line
Free burning	△	▲	15~25	×	×
Suction puffer	□	■	11	×	○
Arc chute	○	●	15	○	○

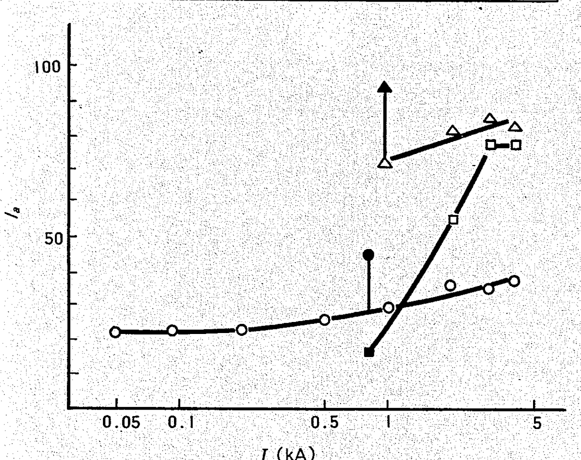
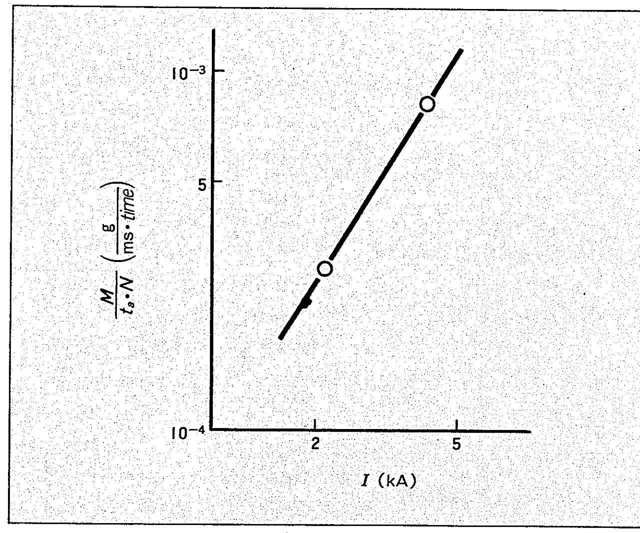


Fig. 21 Contact erosion rate curve



ance at this zone, a larger puffer chamber and operating energy are required. In comparison with the free burning and suction puffer types, in a large current zone, arc chute type's own effect of the electromagnetic force increases, suppressing the remarkable increase of *la*, and thus, the arc chute type indicates outstanding characteristics at the entire current zone.

For closed loop current and inductive coupling current, a switching life of 100 to 200 times is required. For this matter, influence of disolved gas, contact erosion, etc. were examined and it was confirmed that there was no problem. *Fig. 21* shows the result of the contact erosion test. Quantity of erosion M is generally indicated by the following formula.

$$M = k \cdot I^{a} \cdot ta \cdot N \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where,

M: Quantity of erosion (g) I: Breaking current (kAeff)
ta: Arcing time (ms) N: Number of breakings
k, a: Constants

From the *Fig. 21*, $a = 1.6$. k differs depending on the material of contact, but in case of refractory metal, it is less than 0.9×10^{-4} and erosion rate is very minor against the required specification.

As described above, the breaking performances of disconnector and earthing switch are affected by the arc quenching method, and therefore, the most rational arc quenching type and operating method (contact opening speed) must be selected.

4 POSTSCRIPT

For switching performances of Fuji Electric's circuit breakers, isolators and earthing switches, results of the performance given to each item in the standards or operating specifications were described.

When running a system actually, even those items which are not specified in the appropriate standards must be carefully examined and proper actions must be taken carefully. For these matters also, we are examining the data obtained through the Fuji Electric's past operating experiences, and by establishing a rational proving method, we are making perfection more perfect.

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(1) S. Sugiyama et al.: Electrical and thermal conductivities of SF_6 contaminated by copper vapor in arc-interruption processes. 1982 IEEE INTERNATIONAL CONFERENCE ON PLASMA SCIENCE, No. 4D5. May 17-19, 1982.

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