UDC 621.316.57.064:537.21

FUNDAMENTAL TECHNOLOGIES OF SF_6 GAS INSULATED SWITCHGEAR

Kiyokuni Nobuaki
Kiyoshi Matsuura
Fumio Natsume

1 FOREWORD

The insulation of a gas insulated switchgear consists of SF_6 gas having an extremely high dielectric strength and cast-resin insulators having excellent insulating performance, featuring its high reliability. Based on the actual operating performance and unflagging research and development toward many years, recently, it has been possible to compose insulations more compact.

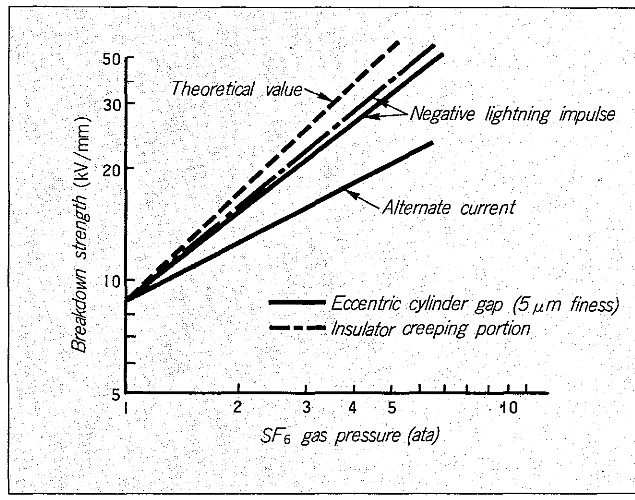
To realize more compact equipment with the reliability kept, a high insulation technology is required. Fuji Electric started the fundamental study for SF_6 gas insulations many years ago(1), and has enhanced the insulation technology. Including the description of the recent technological advancement, this paper introduces the insulation technologies of Fuji Electric's gas insulated switchgears.

2 SF_6 GAS INSULATION

2.1 SF_6 gas insulation technology

The reason why the dielectric strength of SF_6 gas is so high is because the electronegative intensity of fluorine (Electron attracting level) is much higher than air or other gas, allowing negative ion to be formed easily. As long as SF_6 gas density is kept constantly, dielectric strength is stable, and when electric field distribution is comparatively uniform, the breakdown is decided approximately by the maximum field strength which depends upon the gas pressue. *Fig. 1* shows breakdown strength of SF_6 gas. The dotted line indicates the breakdown strength decided by the breakdown theory of SF_6 gas. Actually, however, the breakdown level is lower than the theoretical value because of the field concentration caused by very fine projections on the electrode surface, and it differs depending on the fineness of the electrode surface and opposite electrode area. The full line indicates an example of the breakdown strength obtained for a gas space within an eccentric cylinder electrode. When designing a gas insulated switchgear, the surface fineness of the conductor must be managed, and permissible field must have been set by adding the size effect to it.

Fig. 1 Breakdown strength of SF_6 gas



In the *Fig. 1*, the dash-dot line indicates an example of breakdown strength of insulator creeping portion(2). In this case, the breakdown strength does not mean the breakdown strength arranged by the field along the insulator surface but with the maximum field in gas portion on the surface, and it does not differ too much from that in the case of a metal gap. For this reason, it may be said that the breakdown is decided approximately by the maximum field of the gas portion also for the creeping portion of the insulator.

Because insulation characteristics are affected by the maximum field as described above, when designing a gas insulated switchgear, field calculating technique is extremely important. Since the early stage, Fuji Electric has completed an electric field calculation program by means of a computer, and used for insulation design and research for machines and equipment. Each office is joined with the large capacity computer through the terminal equipment, and calculations can be made easily at daily design work. For this purpose, the programs have been made so that the input/output work can be simplified and calculation time can be minimized. Thus, the designers can obtain field values very easily.

Fig. 2 shows an example of field calculation result for

Fig. 2 Example of field analysis

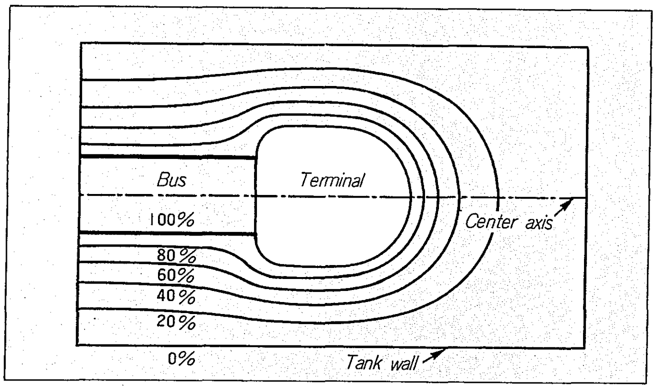


Fig. 3 *V-t* curves of SF_6 gas gap

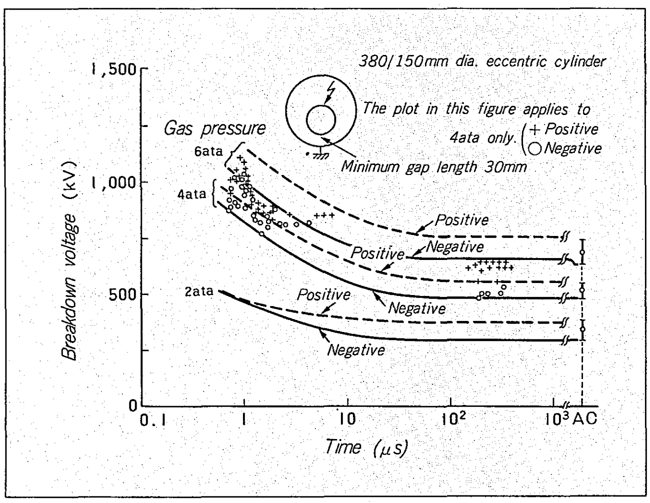
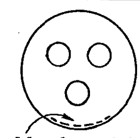
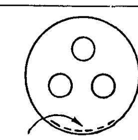


Table 1 Attitude of metal particles within 3-phase common housing

Experimental condition (Gas pressure 4.8 ata)	Bus arrangement (3-phase voltage applied)	With vertex faced downward		With vertex faced upward	
		 Metal particle		 Metal particle	
	Insulation coating on capsule interior	With	Without	With	Without
Results of experiment (phase voltage indication	Inception voltage of particle movement (kVeff)	50	20	160	80
	Breakdown voltage (kVeff)	160 <	160 <	160 <	160 <

Metal particle (0.2 mm dia. x 10 mm long, 20 pieces, straight and curled)

the terminal of a gas insulated switchgear bus. It is also possible to make calculation for other cases, for example, in case of a field with different dielectric constant such as a insulator. With the Fuji Electric's calculation programs, calculations can be made extremely easily. Therefore, at the stage of a machine development, examinations can be made for various shapes and the optimum insulation structure can be decided.

V-t curves of SF_6 gas insulation are important for the insulation coordination and for designing. In case of SF_6 gas, inclination of *V-t* curve is not as remarkable as that of other insulating materials such as oil-immersed insulation. *Fig. 3* shows in an example of *V-t* curves of an eccentric cylinder gap in SF_6 gas. At the side where time is shorter than the AC voltage, *V-t* curve rising tendency differs depending on various conditions such as gas pressure, gap length and polarity, while at the side where time is longer than the AC voltage, *V-t* curves are almost flat as well as in case of an air insulation.

2.2 Technologies to cope with metal particles

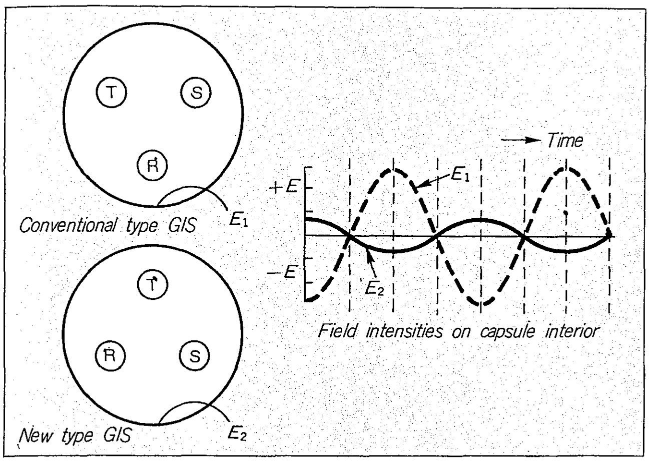
When manufacturing gas insulated switchgears, the work is proceeded so as not to allow metal particles entering the insulated units and the tank interior is cleaned thoroughly. Yet, the insulation construction and metal particle detecting method must be carefully examined so that flashover will not occur even if a metal particle enters. For this purpose, Fuji Electric has studied attitude of metal particles, developed several technologies to cope with metal particles, and reflected them on the actual machines and equipment. To be more specific, the following countermeasures are taken:

(1) Coating the tank interior wall with insulation
(2) Relieving electric field at the bottom of the tank interior as much as possible
(3) Providing the insulator with a rib
(4) Conditioning by applying voltage
(5) Detecting metal particles within the tank

Table 1 shows examples of examinations of metal particle resistance for (1) and (2) above. In a 3-phase common housing, 20 pieces of aluminum wires were placed willfully, and applying 3-phase voltage, attitude of metal particle was examined[5]. The inside of the housing was observed by means of a TV camera through the observation window attached on the housing. The voltage at which the particles begin to move is called "Inception voltage of particle movement". Effect of the insulation coated on the housing interior obviously indicates that the inception voltage of particle movement can be improved 2 to 2.5 times as high by the coating. The reason is because the metal particle is insulated from the electrode by the coating, causing the electrostatic force required in floating particles to be hardly to affect the particles.

In the same table, when attitude of particles with the vertex of triangle 3-phase bus faced downward in compared with that with the vertex of triangle 3-phase bus faced upward, the bus arrangement in which the vertex of triangle is faced upward causes the inception voltage of particle movement to increase 3 to 4 times as high. This occurs because the electric field in the lower portion of the hous-

Fig. 4 Field intensities on capsule interior



ing is greatly reduced by facing the vertex of triangle upward. *Fig. 4* shows examples of calculations of fields on the housing interior wall with 3-phase voltage applied. From this Figure, it can be understood that the electric field is greatly reduced at the bottom portion of the housing by facing the vertex of the triangle bus arrangement upward (indicated in the full line). Since metal particles are likely to be collected in the lower portion, it is more advantageous to relieve the electric field at the lower portion of the housing as much as possible. When designing bus arrangements for actual equipment, it is desirable to face vertexes of all the bus arrangements within a horizontal housing upward. Further, the electric field relieving effect can be increased at the lower portion by employing an isosceles triangle bus arrangement rather than equilateral triangle arrangement so that the 3-phase bus can be arrangement so that the 3-phase bus can be arranged in a higher position.

Table 2 shows examples of examinations on the effect of the rib provided on the insulator for countermeasure (3) above. In the examinations, metal particles were adhered on the insulator and voltage endurance was examined. When the insulator is not provided with a rib, creeping flashover occurs within a short period of time. This occurs because the discharge extended from the metal particles is blocked by the rib. Fuji Electric has provided insulators for gas insulated switchgears with ribs, and this has greatly contributed in securing reliability of insulations.

After taking the structural countermeasures as described above, the conditioning and particle detection are performed to eliminate metal particles as indicated in (4) and (5) at the time of equipment insulation test. The conditioning and particle detection are described in the following paragraph.

2.3 Insulation test technology

To prove the insulation quality, withstand voltage test of AC and impulse and partial discharge test are conducted on a completed gas insulated switchgear. In these tests, reliability can be further improved and internal fault can be detected more effectively by enhancing the test technology.

When applying AC voltage initially to the insulations at a factory test, voltage is applied gradually from as lower voltage as possible. This is called "Conditioning with voltage applied". If a high voltage is applied rapidly and a particle exists, it will be floated causing a flashover. Using a proper voltage applying method, the particle can be forced into a low electric field portion or recess so that the particle can no longer be floated.

As a method to detect metal particles from the outside of housing, the ultrasonic measurement is effective. To enhance measuring sensitivity, Fuji Electric has examined various sensors and amplifiers, and developed extremely high sensitivity measuring technologies. With the detector shown in the *Fig. 5*, metal particle was artificially caused to drop naturally from height *H*, and detecting sensitivity was examined by a sensor installed on the capsule exterior wall immediately below the particle. *Fig. 6* shows the

Table 2 Effects of ribs on supporting insulator

Test sample	Experimental condition	Rib	Life time
AC 200kV; Rib; Particle sticked position (In 3.3 ata SF_6 gas)	Clean	With	
		Without	
	With aluminum particles sticked	With	
		Without	
	With copper wire fixed (0.25mm dia. 10mm long)	With	
		Without	
	With copper wire fixed (0.25mm dia. 5mm long)	With	
		Without	

Time (h): 0, 5, 10

▬ Breakdown
▭→ No breakdown

Fig. 5 Metal particle detector

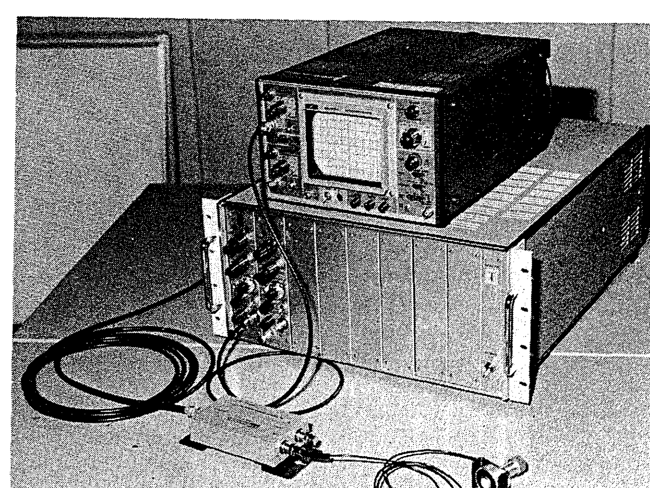


Fig. 6 Sensitivity of ultrasonic particle sensor

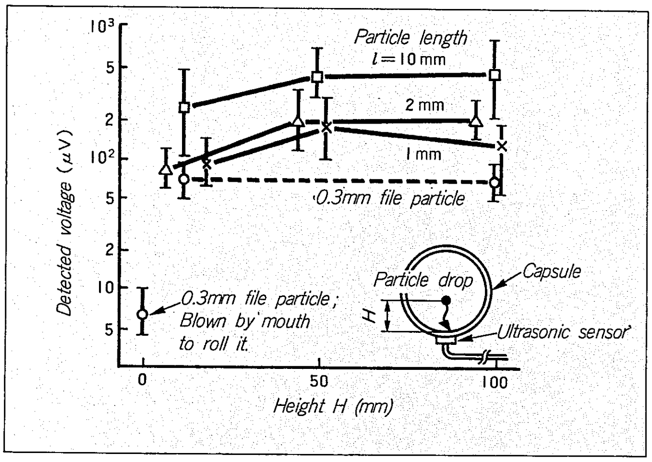
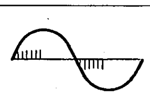
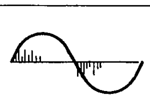
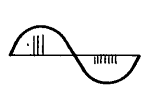
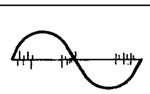
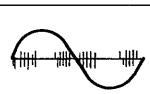


Table 3 Patterns of partial discharge

Particle discharge	Pattern	Features
Air bubble void discharge in resin mold		Pulses having same sizes Large voltage hysteresis
Void discharge during electrode peel off		Non-unified pulses Occurrence frequency is comparatively stable.
Sharp edge in SF_6 gas		Negative pulse occurs first. Positive pulse is large.
Free metal particles		Non-unified pulses Occurrence frequency is random.
Poor contact at conductive part		Polarity of pulse is not clear.

results. Even 0.3 mm aluminum file particles (0.1 mg) rolled by blowing air from the mouth could be detected.

The partial discharge test is one of the test items normally conducted to guarantee the quality. When an abnormal condition is recognized inside and the cause of fault can be estimated without disassembling the equipment, countermeasures can be established much faster and executed more securely. *Table 3* combines type of partial discharge and generation pattern through the experience. The data are not necessarily strict, however, useful to have hints. In the future, the patterns will be grasped further for various cases.

3 CAST-RESIN INSULATOR

3.1 Insulation technology of insulator

Epoxy cast resin is an electrically, mechanically and thermally excellent insulation material, and used in thousands of various machines and equipment. Fuji Electric has also used this material at a wide range of fields since this material first appeared. The dielectric strength of epoxy resin is about 100 kV/mm in lightning impulse voltage, which is far higher than that of SF_6 gas shown in the *Fig. 1*. When a voltage is applied to a insulator in SF_6 gas, the gas or creeping portion reaches the limit first. When designing the shape of a insulator, it is so designed that all the electrical, mechanical and thermal specifications are satisfied. As a point in the electrical design, however, first of all, it must be so designed that the electric field of the gas space is below the permissible level at the impulse and AC withstand voltage specifications, and the electric field inside the epoxy resin is below the value at which the insulator can thoroughly withstands against a long time operating stress. The reasons for the latter is because *V-t* curves of epoxy resin material itself is not as flat as in the case of a gas at the side where the time is longer. For this reason, it is important to grasp withstand voltage/life characteristics of epoxy resin. Fuji Electric has actively continued the fundamental study, grasped the regularity of the deterioration and life, and examined reliability evaluating methods.

When breakdown electric field of resin and life time are expressed respectively E and t, the following relationship can be established.

$$E = K \cdot t^{-\frac{1}{n}}$$

Where, K, and n are constants decided by the material. *Fig. 7* shows an example of *V-t* curve for epoxy resin having no void. When designing insulators, reduction of dielectric strength at the side where the time is longer is taken into consideration, and electric field within the resin is suppressed to the value at which breakdown does not occur even if operating voltage is applied toward many hours or less. The permissible electric field for epoxy cast resin is established by taking inclination of *V-t* curve, fluctuation of service life, etc. into considerations in addition to the past operating performance. Further, Fuji Electric uses the long duration test device shown in *Fig. 8* to apply high electric field to insulators for evaluating service life of an actual insulator. *Fig. 9* shows the results. Breakdown is not likely

Fig. 7 *V-t* curve of epoxy cast resin

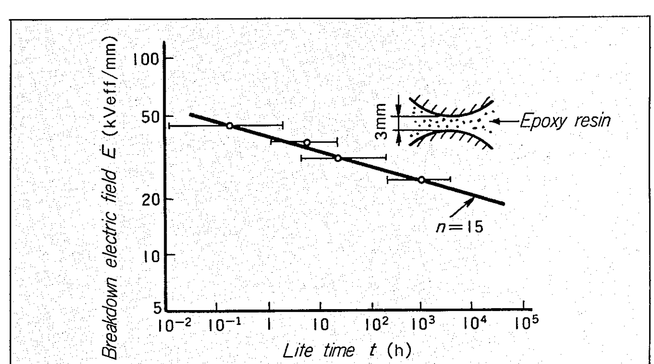


Fig. 8 Long duration test device for insulator

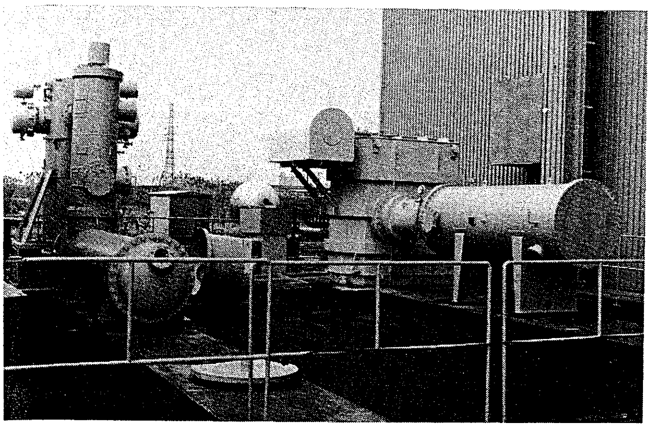
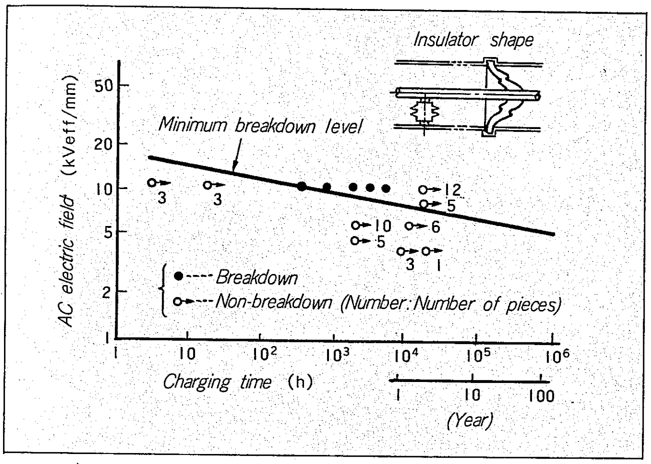


Fig. 9 Life test result for insulator



to occur because insulation thickness of the actual molded insulator is heavy and it is hard to obtain data for breakdown. However, it is estimated that the minimum breakdown level is, at present, on the full line. The electric field within resin of actual insulator is designed at several kV/mm or less in service, therefore, a considerably high safety factor is stil secured even after several tens of years. This life test will be continued in the future to obtain more data from actual products.

To respond the requirement of more compact gas insulated equipment, Fuji Electric has recently developed epoxy resin insulation the electric field and heat resisting performances of which are far higher than general purpose resin. *Fig. 10* shows the comparison of withstand voltage life curves. The life time was obtained by applying a constant electric field (several tens kVeff/mm) to the portion where the insulation thickness is 5 mm. System B and C indicate much longer life than system A (general purpose epoxy resin). These systems are suited to the gas insulated spacers which must be smaller in dimensions and satisfy heat-resisting specification.

As for mechanical design technologies of insulator, stress calculating programs have been developed by means of a computer, and utilized for the design. As well as the

Fig. 10 Characteristics of long life epoxy resin insulation

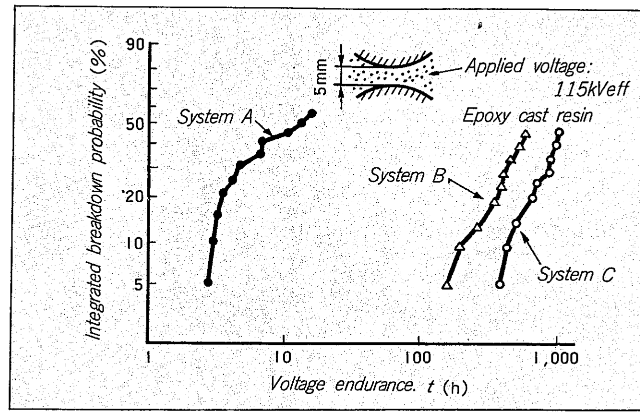
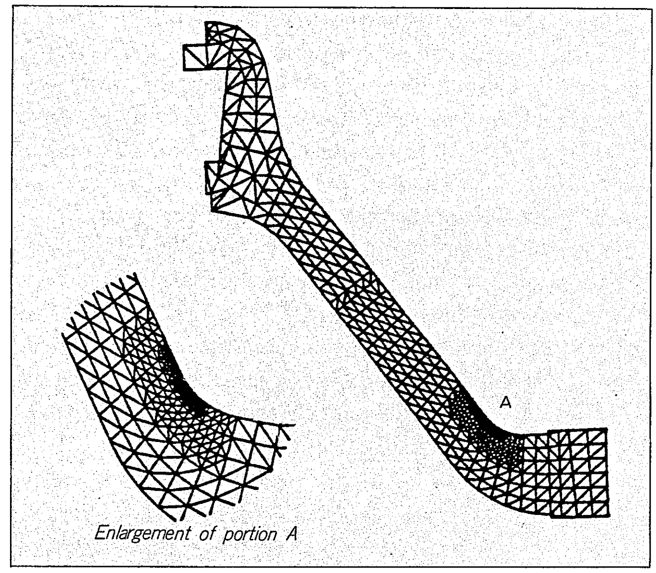


Fig. 11 Finite element split of cone shape insulator



electric field calculating program described in 2.1 above, the stress calculating program has also been devised so that input/output can be made easily, and this program is fully used at daily design work. *Fig. 11* shows an example of finite element split used for calculating stress distribution of corn shape insulators. To enhance the design accuracy, it is so arranged that the elements at the portion where stress is likely to be concentrated can be split finely and easily. To further enhance design accuracy, reduced size model method has also been developed. In this method, before making a metal mold in the actual size, a model in reduced size is made, and breakdown value with this model is grasped. *Fig. 12* shows a model in reduced size and actual spacer. With the reduction rate, breakdown strength can be estimated approximately.

3.2 Performance evaluation technology of cast resin insulators

Cast resin insulators are evaluated for the performance by applying electrical, mechanical and thermal stresses. These stresses do not necessarily act independently, and for this

Fig. 12 Model in reduced size and actual insulator

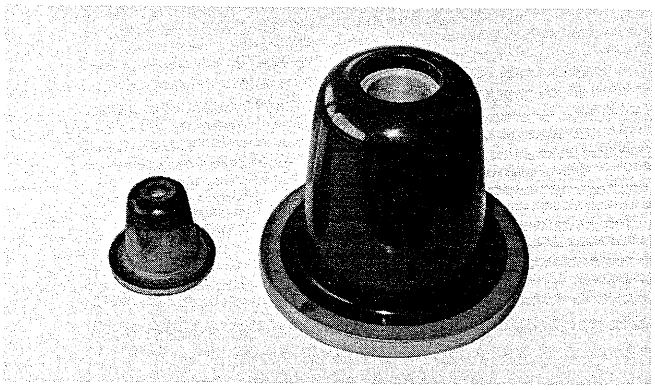


Fig. 13 Moisture absorbing rate of moisture absorbing agent and electrical values

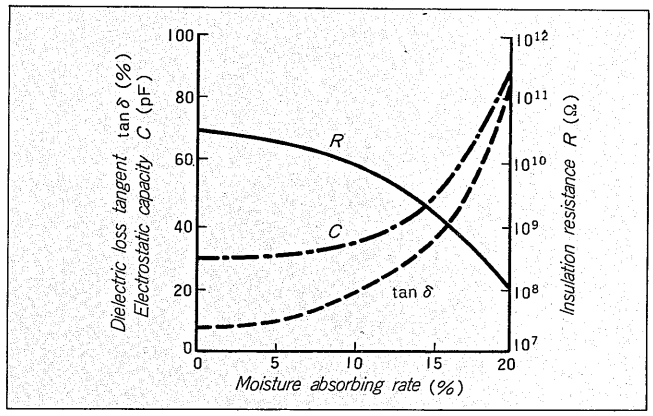
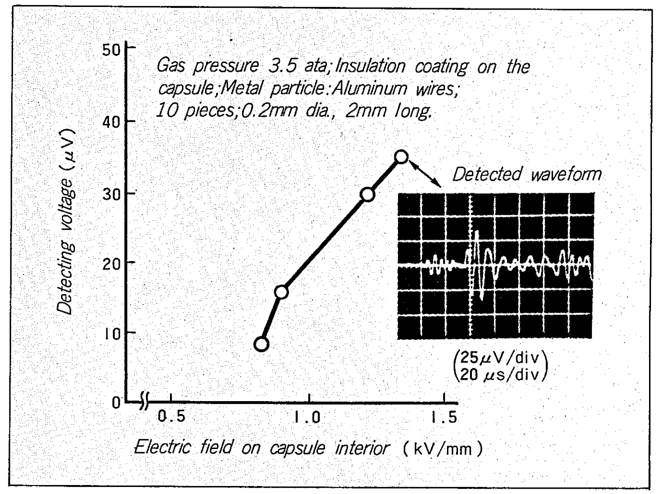


Fig. 14 Example of metal particle detection



reason, by the heat cycle test, partial discharge test, withstand voltage test, withstand load test, voltage endurance test, etc., stresses are applied to same test piece. Depending on a size of the stress applied to an actual product, heat cycle or voltage endurance test is conducted with a mechanical load applied to thr product is also conducted. Further, electrical and mechanical breakdown tests are also conducted, and fluctuation and safety factor are obtained.

At the product acceptance test, withstand load, partial discharge and withstand voltage tests are conducted on all products, ensuring to completely avoid faulty manufacturing. Further, breakdown test is conducted by means of a sampling, and with the broken pieces, fundamental characteristics of the material are checked. Thus, it is always supervised that the quality does not change.

4 PREVENTIVE MAINTENANCE TECHNOLOGY

The technology to diagnose gas insulated switchgears in service from outside, so called "preventive maintenance technology" is important, and Fuji Electric is concentrating efforts in developing this technology. The technologies related to the preventive maintenance are described below.

4.1 Electrical method

Occurrence of a fault such as poor contact of conductor and faulty insulation insulator causes partial discharge to occur, and to prevent it, it is effective to measure partial discharge[7]. Not only at the stage of factory test, but this measurement can be done on the equipment being charged at the site also, and as the matter of fact, measurements are being conducted practically.

By measuring electrical characteristics of moisture absorbing agent in a tank, the moisture absorbing rate can be found. A device in which moisture absorbing agent is held in between electrodes is set within a tank in advance, and through lead wires, insulation resistance, electrostatic capacity and dielectric loss tangent are measured from the outside. Then, condition of the built-in moisture absorbing agent and moisture abosrbing ability can be found without stopping the charging of the equipment because there are relationships between the above mentioned factors (insulation resistance, electrostatic capacity and dielectric loss tangent) and moisture absorbing agent as shown in *Fig. 13.*

4.2 Mechanical method

The metal particle detector using ultrasonic wave described in 2.3 above can also be applied to charged equipment, and the detector has been used practically. Particles were willfully sealed in a capsule, and metal particles moved by electric field were detected. *Fig. 14* shows an example of the detection.

4.3 Optical method

To detect discharge light generated when an abnormal condition occurs within a capsule, the highly developed recent optical technologies can be used. When detecting discharge of very minor light value such as partical discharge, light pulse received through a light receiving window can be detected by a photomultiplier. The photomultiplier counts light pulse within one gas section, and therfore, even if a shade of conductor or insulator exists, discharge light still can be detected as a reflected light.

4.4 Chemical method

When an abnormal condition occurs within a capsule and SF_6 decomposing gas is produced, it can be easily detected by a gas sensing tube. The operating principle is as such that when a small value of gas is taken out from a capsule and flowed into a sensing tube, the color reacting reagent sealed in the tube changes from yellow to pink if SF_6 decomposing gas is contained regardless of volume. Thickness of the decomposing gas can be found from level of this color change.

5 POSTSCRIPT

For the fundamental technologies of gas-insulated switchgears, Fuji Electric's insulation technologies were introduced. The gas-insulation designing, manufacturing, and quality guaranteeing technologies are consolidated and the comprehensive technologies have been applied to Fuji Electric's products. These fundamental technologies have greatly contributed in reducing dimensions of equipment. Fuji Electric will continuously concentrate the great efforts in studying the fundamental technologies.

References:

(1) K. Matsuura, T. Takano: Influence of conducting particles on flashover voltage over insulation surface of epoxy-resin insulation, International Meeting on GIS, Association des Ingenieurs Electricens, Liége (Belgium), Nov., 1979.

(2) F. Natsume, K. Matsuura, A. Kurahashi: Voltage endurance of epoxy mold insulation and evaluation of its life time, Fuji Electric Review, Vol. 23, No. 2, pp. 77-82 (1977).