Electrical Engineering in Japan, Vol. 174, No. 4, 2011
Translated from Denki Gakkai Ronbunshi, Vol. 128-B, No. 12, December 2008, pp. 1431–1438

Solid Insulated Switchgear and Investigation of its Mechanical and Electrical Reliability

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SUMMARY

SF_6 gas is widely employed in medium-voltage switchgear because of its high insulation reliability and down-sizing ability. However, SF_6 gas was placed on the list of greenhouse gases under the Kyoto Protocol in 1997. Since then, research on low-SF_6 or SF_6-free insulation has been carried out actively. Therefore, we focused on solid materials with higher dielectric strength than SF_6, and we have now developed solid insulated switchgear (SIS) that uses molding of all main circuits. A new epoxy casting material is used which contains a large amount of spherical silica and a small amount of rubber particles. This new material has high mechanical strength, high thermal resistance, high toughness, and also high dielectric strength because of direct molding of the vacuum bottle, as well as reduced size and high reliability. This paper describes the technology of the new epoxy casting material which makes possible SIS. In addition, mechanical and electrical reliability tests of SIS using a new epoxy resin were performed, and the effectiveness of the developed material and the mechanical and electrical reliability of the SIS were verified. © 2010 Wiley Periodicals, Inc. Electr Eng Jpn, 174(4): 28–36, 2011; Published online in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/eej.21057

Key words: switchgear; solid insulation; epoxy resin; SF_6-free; vacuum circuit breaker; vacuum disconnecting switch.

1. Introduction

Switchgear is an essential element of stable power supply underlying the social infrastructure. Since the advent of open-type switchgear in the 1890s, its history has lasted for more than 100 years. During this period, switchgear design has changed with the needs of the age from the open type to the housed type to the metal-enclosed type to the sealed type. The devices have become smaller in size and larger in capacity, more durable, more environment-friendly, more reliable, and less dependent on maintenance.

The evolution of switchgear design was strongly affected by progress in insulation techniques. The mainstream insulation techniques adopted in switchgear have changed from air insulation to air-based composite insulation (barrier insulation, cladding insulation) to SF_6 gas insulation. Insulation performance has improved and the devices have become more compact. At present, cubicle-type gas insulated switchgear (C-GIS) with low-pressure SF_6 gas sealed in a rectangular container are widely used in the medium-voltage range of 24 to 84 kV. SF_6 is a nontoxic, odorless, inert, nonflammable gas with excellent dielectric strength and arc extinguishing capacity, and thus it is widely used as an insulating and arc extinguishing medium in power switching equipment. SF_6 gas is a very stable compound with an atmospheric lifetime as long as 3200 years. Its global warming potential (GWP) is 23,900 times that of CO_2, and SF_6 was listed among the greenhouse gases by the 1997 Conference of the Parties on Climate Change (COP3) [1]. Since then, there has been extensive research on ways of replacing SF_6 gas, which has resulted in switchgear using high-pressure air and nitrogen [2–5]. In addition, solid insulation has been investigated for next-generation switches and transformers of the extra-high-voltage class [6].

The authors investigated solid insulators offering better insulation performance than low-pressure SF_6 gas, aiming at SF_6-free switchgear manufactured by molding the main circuits, including vacuum bottles, with epoxy resin. In 2002 and 2004 we developed 24/36-kV solid insulated switchgear (SIS) with considerably smaller and lighter design than conventional C-GIS [7, 8]. In this paper, we describe one of the underlying technologies of SIS, namely, epoxy resin technology. In order to verify the mechanical and electrical reliability of actual SIS using the newly developed epoxy resin, we carried out seismic resistance tests, crack resistance evaluation tests, and long-term (3.5-year) voltage tests. Here we report results on the effectiveness of the new material and the reliability of SIS.

2. Technical Problems of Solid Insulated Switchgear

Due to its outstanding electrical, mechanical, and thermal properties, epoxy resin has long been used for high-voltage devices. However, in SIS with molded main circuits, the requirements imposed on the electrical, mechanical, and thermal properties of epoxy resin are even more stringent, as explained below.

(1) Ceramic vessels with different thermal expansion coefficients must be molded, and cracks and other defects are not allowed.

(2) Since epoxy resin is a structural component of the switchgear, high mechanical reliability is required.

(3) Since epoxy resin is the main insulation medium, high insulation reliability is required.

(4) Since the main circuit is completely covered with epoxy resin, high thermal resistance is required.

Below we explain the methods of solving these technical problems.

3. Mechanical and Electrical Properties of Epoxy Resin

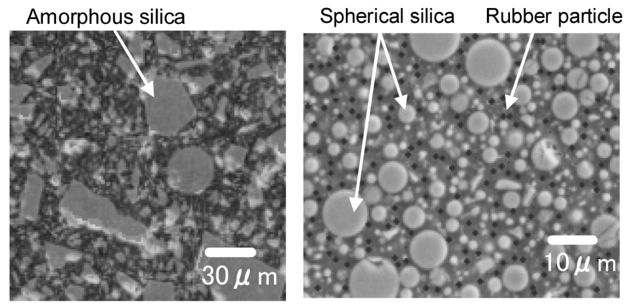
3.1 Outline of epoxy resin

The compositions of the conventional and the newly developed epoxy resins are given in Table 1, microscopic models are shown in Fig. 1, and their material properties are compared in Table 2. The conventional material is a blend of bisphenol-based epoxy resin with an anhydride hardener, filled with crushed silica. The newly developed material uses a different bisphenol and a different anhydride hardener with better resistance. In addition, spherical silica and rubber particles are used as the filler. The effects of the filler and material properties are discussed below.

Table 1. Composition of epoxy resin

Material	Conventional material	Developed material
Epoxy resin	Bisphenol I (100)	Bisphenol II (100)
Hardener	Acid anhydride I (80)	Acid anhydride II (85)
Silica filler	Amorphous (390)	Spherical (530)
Elastomer	-	Rubber particle

():per hundred of resin by weight



(a) Conventional material (b) Developed material

Fig. 1. Microscopic models of epoxy resin.

3.2 Mechanical properties

When used in SIS, epoxy resin is not only the main insulation medium, but also a structural element, and thus it must support itself and also resist mechanical shocks during operation. Therefore, excellent mechanical strength is needed as well as dielectric strength. We compared the conventional and newly developed material in terms of tensile strength, which is an index of mechanical strength.

A cross section of the sample used for tensile strength tests is shown in Fig. 2. The 150-mm-long sample was dumbbell-shaped, with a diameter of 30 mm on the ends, and of 14 mm in the middle portion where rupture occurs. Metal fixtures embedded on both ends were clamped, and tension was applied at a head speed of 5 mm/min at constant

Table 2. Material properties

Property	Conventional	Developed
Tensile strength(MPa)	79	102
Tensile modulus(GPa)	12.5	14.7
Flexural strength(MPa)	118	151
Flexural modulus(GPa)	12.1	12.2
Fracture toughness K_{IC} (MPa-m$^{0.5}$)	2.5	2.5
Thermal expansion Coefficient (10^{-5} K)	2.1	1.8
Glass transition temperature (℃)	108	136
Volume resistivity(Ω·cm)	8.2×10^{16}	8.5×10^{15}
Dielectric constant	3.5	3.4
Dielectric loss (%)	0.30	0.13
Specific gravity	1.77	1.80

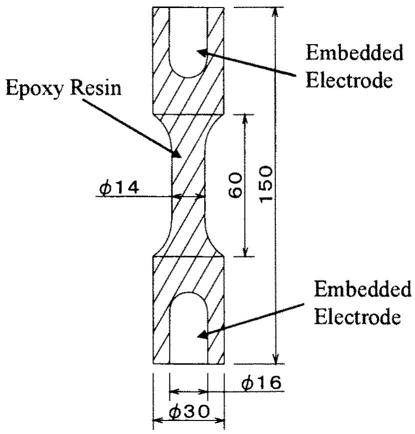


Fig. 2. Cross section of tensile strength test sample.

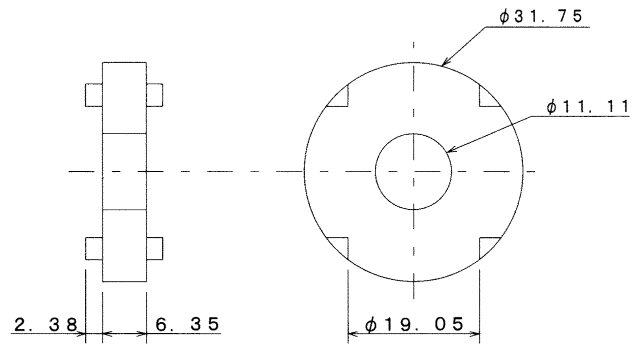


Fig. 4. Shape of Olyphant washer.

ambient temperature. The measured temperature dependence of the tensile strength is shown in Fig. 3. In the diagram, black and white dots represent the newly developed and conventional materials, respectively. The plots are based on average values for five samples. As is evident from the diagram, the newly developed material has a tensile strength about 1.3 times that of the conventional material at room temperature, increasing to about 2 times at higher temperatures. This can be explained by the fact that the filler contains very small silica particles measuring several micrometers in addition to larger particles measuring several tens of micrometers, thus providing a larger adhesion area between the resin and filler.

3.3 Crack resistance

Crack resistance is an important material property required for the implementation of SIS. In order to mold vacuum bottles containing ceramics with much different thermal expansion coefficients, the crack resistance of materials must be improved. Thus, we evaluated crack resistance by means of Olyphant washer tests.

Specifically, the steel pieces shown in Fig. 4 were molded in test samples with a diameter of 55 mm and a thickness of 14.1 mm. These samples were exposed to heat cycles as shown in Table 3. A crack index was used for evaluation. For example, the index was 0 if cracks occurred before the test, and 16 if no cracks occurred after all heat cycles.

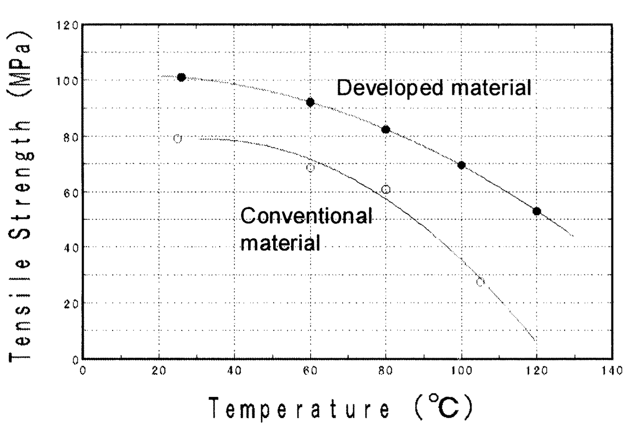


Fig. 3. Temperature dependence of tensile strength.

Table 3. Crack index by Olyphant washer method

Cycle No.	Temperature condition(℃)	Holding time(min)	Crack Index
1	Initial	–	0
2	25 → 5	10	1
3	5 → 25	30	2
4	25 → −15	10	3
5	−15 → 25	30	4
6	25 → −35	10	5
7	−35 → 25	30	6
8	25 → −55	10	7
9	−55 → 25	30	8
10	25 → 130	30	9
11	130 → −55	10	10
12	−55 → 150	30	11
13	150 → −75	10	12
14	−75 → 170	30	13
15	170 → −75	10	14
16	−75 → 25	30	15
17	All cycles passed	–	16

Table 4. Crack resistance of materials

Material	Conventional material	Developed material	Reference material
Thermal expansion coefficient (10^{-5}/K)	2.1	1.8	1.8
Tg (℃)	108	136	136
Fracture toughness K_{IC} (MPa-m$^{0.5}$)	2.5	2.5	1.8
Crack index	11.0	16.0	10.0

The results for the conventional and newly developed materials are compared in Table 4. In addition, material with the same composition as the proposed material, except for the rubber particles, was also tested as a reference material. The crack resistance is determined by the thermal expansion coefficient, the glass transition temperature (Tg), and the mechanical strength. Usually, materials with a higher Tg are more brittle [9]. However, the newly developed material proved much more crack resistant than the conventional material. Comparing materials with the same thermal expansion coefficient and Tg, higher crack resistance can be explained by better toughness due to the rubber filler [9].

3.4 Dielectric breakdown characteristics

SIS employs epoxy resin as the main insulating medium. Therefore, the insulation performance of epoxy resin must be further improved to assure insulation reliability of the switchgear. Thus, we compared the dielectric breakdown characteristics of the proposed and conventional materials.

A cross section of the samples used in the tests is shown in Fig. 5. The sample is an epoxy resin mold with a diameter of 80 mm and a height of 100 mm. Electrodes with a diameter of 40 mm were embedded in the gap of 3 mm. In the tests, the voltage was increased in steps of 10 kV_{rms} every minute from 50 kV_{rms} to breakdown. The tests were performed in an atmosphere of SF_6 at a high pressure of 0.4 MPa, thus preventing outside flashover.

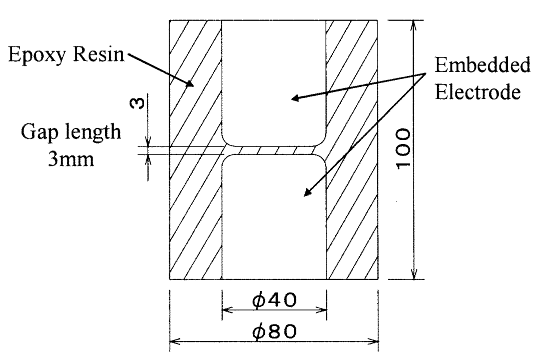


Fig. 5. Cross section of breakdown test sample.

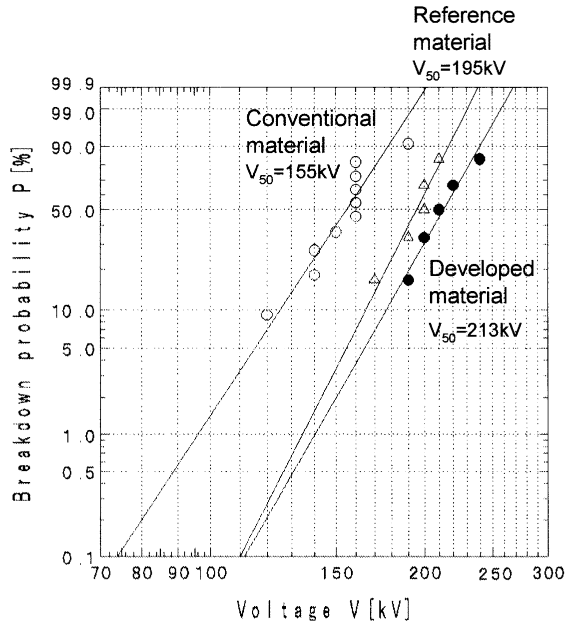


Fig. 6. Dielectric characteristics of epoxy resin.

Figure 6 illustrates the Weibull distribution of the breakdown voltage. In the diagram, the marks ○, ●, and △ represent respectively the conventional material, the newly developed material, and the reference material (with the same composition as the proposed material but without rubber particles). The 50% breakdown voltage V_{50} was 155, 195, and 213 kV, respectively, for the conventional material, reference material, and newly developed material. Thus, the reference material performed about 1.3 times better than the conventional material, and the newly developed material performed about 1.1 times better than the reference material. Electric trees collide with the filler inside the epoxy resin, and develop along the interface between the filler and resin, which constitutes a relatively weak path [10, 11]. The reference material with spherical silica is less vulnerable to micro defects at the filler/resin interface than the conventional material with crushed silica. As a result, tree development is reduced [10], and the trees branch because of the small silica particles, so that the electric field at the tree tip is apparently relaxed, which may explain the improvement of the breakdown voltage [12]. One can also assume that addition of the small rubber particles enhances the beneficial effect of the silica filler.

4. Specifications of SIS and Reliability Verification

4.1 Specifications of SIS

An example of the configuration of SIS is shown in Fig. 7. Here an SF_6-free device is implemented using a vacuum circuit breaker (VCB) and a vacuum disconnecting switch (VDS). The whole circuit including the VCB and VDS is molded in the newly developed epoxy resin. In addition, the conductors in the main circuit are simplified, and the conducting layers of every phase are provided with separate outer shields, in order to achieve a more compact design as well as to reduce phase-to-phase short faults and to improve safety. In addition, a simple balanced electromagnetic actuator (BMA) with permanent magnet hold is employed, which results in fewer structural components, thus improving reliability and decreasing maintenance effort. The conventional approach to SIS assumed a totally fixed circuit. This design offers considerable freedom of circuit configuration because the component devices are implemented as separate molds, and an interface insulation technology has been developed to connect the mold blocks [7].

The SIS specifications are listed in Table 5. Presently, two models have been designed and manufactured, with rated voltages of 24 and 36 kV, a rated current of 2000 A or less, and a rated breaking current of 25 kA.

Below we describe the verification of the mechanical and electrical reliability of the SIS devices using the newly developed epoxy resin.

4.2 Seismic tests

The seismic test setup is shown in Fig. 8. In these tests, the incoming panel and feeder panel were arranged in a row on a shake table. In order to observe vibrations in different parts of the SIS, acceleration sensors were installed at 12 points on the mold blocks and panel surface. As shown in Table 6, the seismic tests were carried out in the order of sweep test, actual seismic test, resonant three-cycle sine wave test, 30-cycle sine wave test, and withstand acceleration test. The input acceleration and oscillation frequency in each test were set as in Table 6, and the table was shaken along two horizontal axes, right/left and forward/backward. In the actual seismic test and withstand acceleration test, opening/closing operations of the VCB were performed to verify appropriate functioning. The tests were performed in the presence of a resonant three-cycle sine wave with a horizontal acceleration of 0.3 G according to the *Guide to Seismic Countermeasures for Substations and Other Facilities* (JEAG 5003-1998); in addition, an actual seismic test, a 30-cycle sine wave test, and a withstand acceleration test were performed at accelerations up

Table 5. Specifications of solid insulated switchgear

Rated voltage		24kV	36kV
Rated power-frequency withstand voltage	Phase-to-earth, Between phases	50kV	70kV
	Across the isolating distance	60kV	80kV
Rated lightning impulse withstand voltage	Phase-to-earth Between phases	125kV	170kV
	Across the isolating distance	145kV	195kV
Rated frequency		50/60Hz	
Rated current		630/1250/2000A	
Rated current for busbars		630/1250/2000A	
Rated short-time withstand current		25kA	
Standard		JIS,JEC,JEM,IEC	

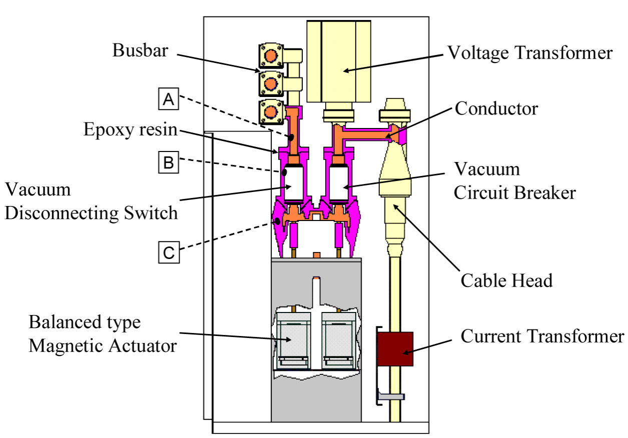


Fig. 7. Configuration of solid insulated switchgear.

Fig. 8. Seismic test setup.

Table 6. Seismic test sequence

No.	Item	Input acceleration	Waveform	Frequency	Shaking time	Others
1	Sweep test	0.05G	Sine wave	1-30Hz	-	
2	Actual seismic test	0.3G,0.5G,1.0G	ElCentro earthquake	-	40sec	Opening and closing operation test
3	Resonant three cycles sine wave test	0.3G,0.5G,1.0G	Sine wave	Resonance frequency	3 cycles	
4	Sine wave test during 30 cycles	0.5G,0.8G	Sine wave	5Hz,10Hz	30 cycles	
5	Withstand acceleration test	0.5G,0.8G	Sine wave	3Hz,5Hz,9Hz	20sec	Opening and closing operation test

to 1.0 G. The *Guide* deals with equipment rated for 170 kV and higher, but we applied it to the developed switchgear. The actual seismic test used the El Centro waveform, the world's first recorded seismic wave exceeding 0.3 G, which is still the most popular in seismic tests.

Typical waveforms of the acceleration sensors attached to the mold blocks are shown in Fig. 9. The greatest acceleration, about 98 m/s^2, was registered at the resonant frequency. The switching operations during the tests were performed appropriately, and no unwanted operation was observed during acceleration. When the series of seismic tests had been completed, partial discharge tests and power frequency withstand voltage tests were performed; no changes caused by the seismic tests were observed.

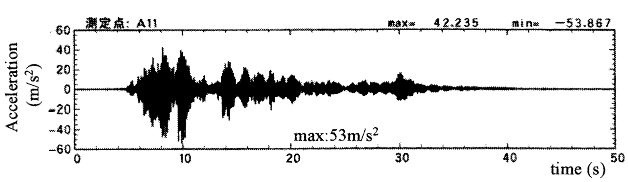
4.3 Crack resistance evaluation tests

The evaluation of crack resistance was based on the standard IEC 60068-2-14 (1984) [14]. Specifically, heat shock tests at 100 °C ↔ 0 °C (in water) and heat cycle tests at –40 °C ↔ 100 °C (in air) were performed. The heat shock tests were performed on all individual mold components of the SIS and their assembly; in the latter case, components A (busbar bushing mold), B (vacuum bottle mold), and C (moving portion mold) shown in Fig. 7 were connected in the same way as in the actual SIS. The sequence of the heat shock tests is illustrated in Fig. 10; ten cycles of 100 °C (1 H) → 0 °C (1 H) were repeated. In both the individual components and the assembly, the molds were inspected visually after the test to check for cracks or other defects. In addition, partial discharge tests and power frequency withstand voltage tests were carried out, and no changes caused by the heat shock tests were observed.

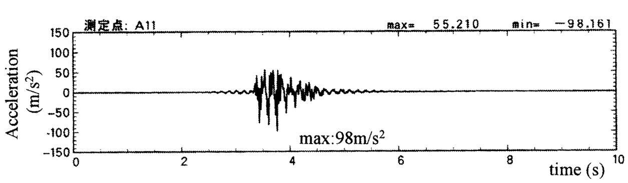
The sequence of the heat cycle testing is shown in Fig. 11. The tests performed on component B (Fig. 7) included 14 cycles of –40 °C (3 H) → 100 °C (3 H). The temperature was raised and lowered at a rate of 1 deg/min. After the test, the molds were inspected visually to check for cracks or other defects. In addition, partial discharge tests and power frequency withstand voltage tests were carried out, and no changes caused by the heat cycle tests were observed.

4.4 Long-term withstand voltage tests

The outdoor setup for long-term voltage tests of the SIS (24 kV, 1,250 A) is shown in Fig. 12. Three types of



(a) Actual seismic test (Input acceleration: 1 G)



(b) Resonant three cycles sine wave test (Input acceleration: 1 G)

Fig. 9. Typical waveforms of seismic tests.

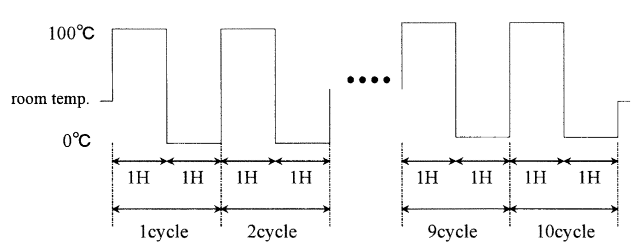


Fig. 10. Heat shock test sequence.

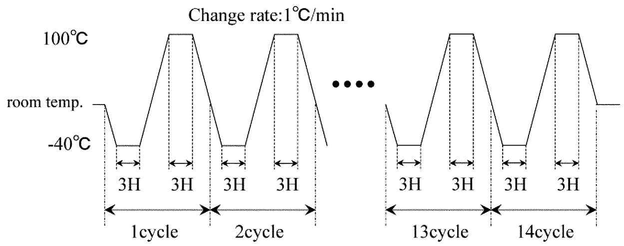


Fig. 11. Heat cycle test sequence.

SIS were used in the tests. The respective test conditions are given below.

(1) Test device 1: Partial discharge test with an SIS that had passed factory acceptance testing

Long-term test with applied voltage of 23 kV (1.8 E)

(2) Test device 2: Partial discharge test with an SIS that had passed factory acceptance testing

8-hour test with applied voltage of 50 kV (3.9 E)

(3) Test device 3: Partial discharge test with an SIS that had failed factory acceptance testing

Long-term test with applied voltage of 38 kV (3.0 E)

*Here 1.0 E is the working voltage ($22/\sqrt{3}$ kV).

For every test device, the initial characteristics were measured before the withstand voltage test. In addition, power frequency withstand voltage tests (50 kV, 1 min) and partial discharge tests were carried out. The results of the long-term withstand voltage tests are presented in Fig. 13.

In Fig. 13, the symbols ○, △, and ■ respectively represent test devices 1, 2, and 3. The arrows indicate that dielectric breakdown did not occur. Device 1 was tested at 23 kV for about 3.5 years, device 2 was tested at 40 kV for 8 hours, and device 3 was tested at 30 kV for about 3.5 years (accelerated deterioration); no problems were observed in any test. For device 1, the partial discharge tests and power frequency withstand voltage tests were performed for a half-year but no changes of characteristics from the initial values were registered.

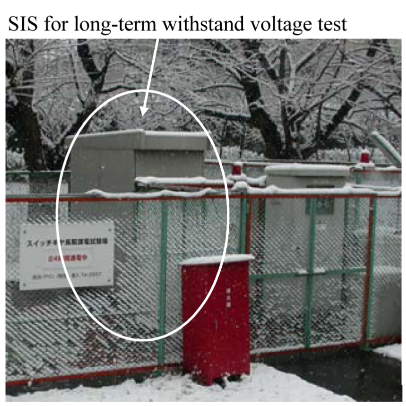


Fig. 12. Long-term withstand voltage test.

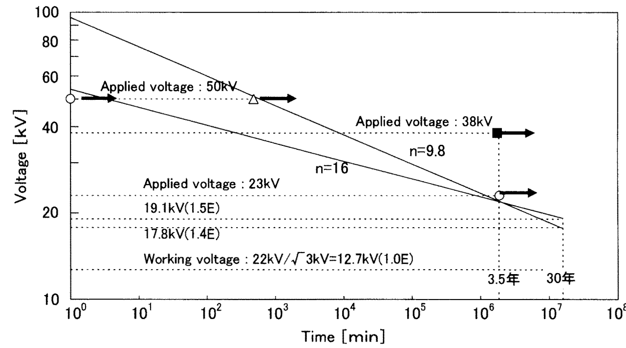


Fig. 13. Long-term withstand voltage test results.

Generally, the relationship between the applied voltage and breakdown time is known to follow an inverse power law as in Eq. (1) [15]. There are reports of the gradient n of the V–t characteristic of epoxy resins with organic fillers; in particular, the value is n = 9.8 to 16 for void-free molds [16, 17]:

$$V = A \cdot t^{-1/n} \tag{1}$$

Here V is the breakdown voltage, t is the time to breakdown, A is the constant, and n is the gradient of the V–t characteristic.

As shown in Fig. 13, the regression lines using these values of n suggest that even at n = 9.8, a voltage of 1.4 E or higher corresponds to 30-year accelerated deterioration, which confirms sufficient long-term insulation performance.

We also applied long-term voltage tests to test device 3 with voids in the molded portions. This device was rejected in acceptance testing because the partial discharge inception voltage was 3 kV. The device was subjected to accelerated deterioration at a voltage of 38 kV for about 3.5 years, but dielectric breakdown did not occur. We also examined the variation of partial discharge; the relationship between this variation and discharge degradation of the epoxy resin requires further exploration.

5. Conclusions

We have demonstrated that epoxy resin filled with small spherical silica and rubber particles offers better mechanical strength, crack resistance, and dielectric strength than conventional material. In addition, we performed evaluation tests (seismic tests, crack resistance tests, long-term withstand voltage tests) of the mechanical and electrical reliability of solid insulated switchgear using the newly developed resin, and confirmed the effectiveness of the newly developed epoxy resin as well as the sufficient reliability of the solid insulated switchgear.

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