UDC 621. 315. 613: 621. 313. 048. 1

F-RESIN INSULATION (NEW INSULATION SYSTEM FOR STATOR COILS OF LARGE ALTERNATOR)

Kanji Tsukamoto
Kawasaki Factory
Hiroyuki Yamaguchi
Hirotoshi Sasaki
Tomio Shimada
Central Research Laboratory

I. FOREWORD

The output and the voltage of turbine generators have increased rapidly in recent years, and generator coil insulation having better insulating characteristics and more stable quality than conventional insulations is demanded.

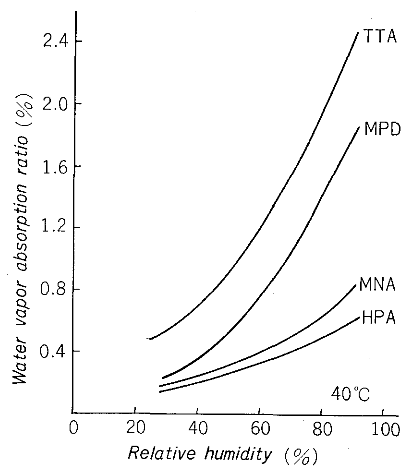
In 1958 we led the industry in stator coils for large generators with the development of a high performance insulation system (F-resin insulation) by vacuum impregnation of epoxy resin in mica tape insulating layers. Since then, we have continued research on larger coils and higher voltages and have made many improvements in insulation techniques. We have now improved coil production methods, insulating materials, and construction, and have developed highly reliable insulation suitable for high voltage, large machines to stabilize product quality. Functional tests on actual models have confirmed that this new insulation system satisfies characteristics for large generators insulation.

The features and characreristics of the new F-resin insulation are introduced here.

II. F-RESIN INSULATION

1. F-Resin (Epoxy Resin for Coil Impregnation)

At the present time, epoxy resin is considered to have a number of superb properties as coil impregnating resins. We have employed epoxy resins for many years and have improved the impregnating and various other properties. There are a number of epoxy resins having different chemical construction, but bisphenol A type epoxy resins obtained from bisphenol A and epichlorohydrin currently have the best balance of properties. There are also a large number of curing agents such as amines, acid anhydride, etc., and the properties of the resin differ considerably with the curing agent. Consequently, detailed studies must be conducted on the viscosity, pot life, and various other properties of the resin used in coil impregnation. Generally acid anhydride cured epoxy resins exhibits excellent workability in impregnation, thermal stability and moisture resistance. The differences in water vapor absorption coefficient of various curing agents is shown in *Fig. 1* as one example of moisture resistance characteristics. This figure shows the water vapor absorption for bisphenol A type epoxy resin cured with aliphatic amine (triethylene tetramine), aromatic amine (metaphenylene diamine), or acid anhydride (hexahydro phthalic anhydride, methylendmethylene tetrahydrophthalic anhydride).



Epoxy resin: Bisphenol A type
Hardener: TTA (triethylene tetramin)
MPD (m-phenylene diamine)
MNA (methylendmethylene tetrahydrophthalic anhydride)
HPA (hexa hydro phthalic anhydride)

Fig. 1 Water vapor absorption isotherms of expoxy resins

Moreover, difference in properties are also produced by the composition ratio and type and amount of accelerator even when the same curing agent is used. These differences for bisphenol A type resin and acid anhydride are shown in *Fig. 2*. *Fig. 2 (A)* shows the relationship between the composition ratio and volume resistivity when the amount of accelerator (amine) was varied.

Fig. 2 (B) shows the case when the type of accelerator was varied. The fact that the characteristics of cured epoxy resins can be varied by the type and

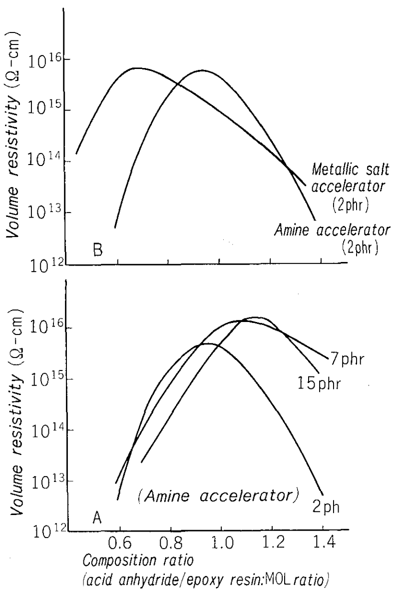


Fig. 2 **Effect of acid anhydride content on volume resistivity**

Table 1 **Various properties of impreganating resins**

Item		F-Resin	Polyester
Specific weight	(25°C)	1.2	1.0∼1.2
Viscosity*1	(Poise)	0.4	0.1∼2
Shrinkage*2	(%)	3	6∼9
tanδ (100°C, 50 Hz)	(%)	1.1	1∼3
Volume resistivity (100°C)	(Ω-cm)	5×10^{15}	$10^{10\sim14}$
Flexural strength (100°C)	(kg/mm^2)	6.5	(1.5∼4.5)*3
Tensile strength (100°C)	(kg/mm^2)	5.5	0.5∼3.0

*1 Viscosity at impregnating temp.
*2 Volume shrinkage
*3 Value at 50°C

amount of accelerator as well as contents of acid anhydride can be clearly understood.

The selection of F-resin is the result of detailed studies of these various items F-resin insulation primarily consists of a low viscosity bisphenol A type epoxy resin and acid anhydride curing agent. The various characteristics of F-resin are given in *Table 1.* The characteristics of the unsaturated polyester resins generally used for coil impregnation are also given in the same table. The main features of F-resin are good impregnability, little shrinkage, and various valuable characteristic which are maintained even at high temperatures.

2. Insulation Composition and Production Methods

The main materials used in the production of the new F-resin insulation are mica tape and epoxy resin. This basic composition is the same as the older F-resin insulation which has a good operating record over a long period of time. However, as the result of some improvements of material and resins, the insulation has higher thermal stability, and reliability has been improved with respect to the heat cycle applied when the load changes. For a large coil to withstand the heat cycle and maintain its insulating chcracteristics during the operating period of the machine, the main insulation and must have good adhesion and setting properties. Therefore, in the new F-resin insulation system, an intermediate layer of special mica tapes is placed between the main insulation and to improved the characteristics. This intermediate layer absorbs thermal stress between main insulation and strand insulation. This has been confirmed by various functional tests. The basic production method of F-resin insulation is continuous taping of mica tapes through the slot and coil end part and vacuum impregnation of low viscosity epoxy resin, so there are no voids in the insulation layer.

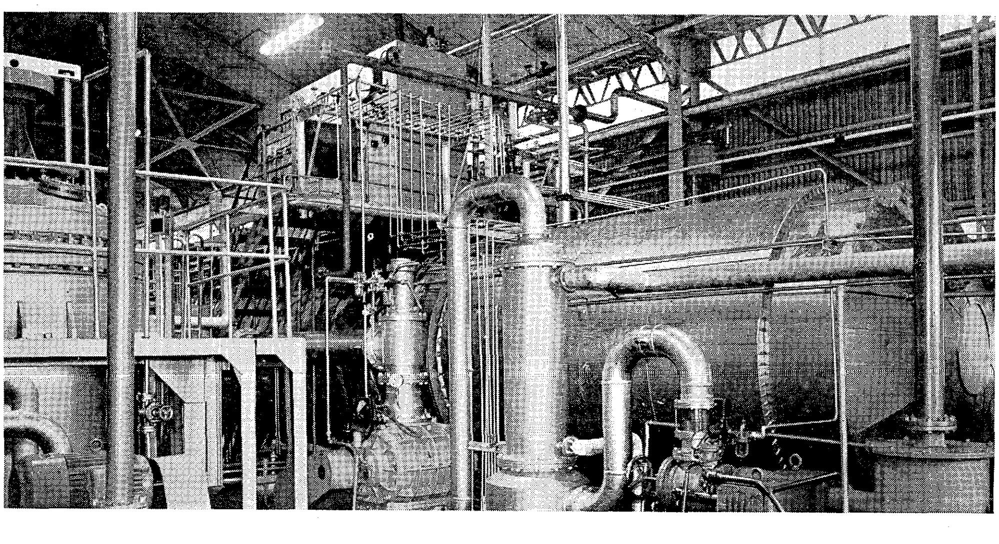


Fig. 3 **Manufacture of F-resin insulation (Autoclave with pumping set)**

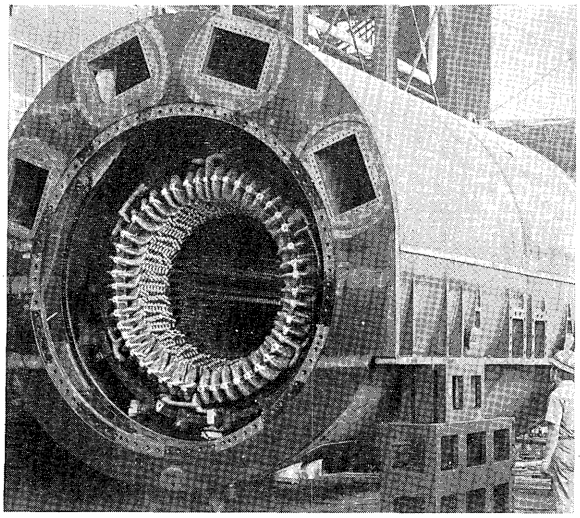


Fig. 4 Stator winding of F-Resin insulation (250 MVA turbine generator)

Considerable factors which have a large effect on coil quality are pre-drying temperature and time, viscosity of the impregnating resin, vacuum of the impregnation tank, resin curing temperature and pressure during curing. The production method for F-resin insulation was decided by considering these factors. The vacuum of the tank during impregnation has an especially large effect on quality and a suitable vacuum has been confirmed by test results related to degree of vacuum and coil characteristics.

An external view of the impregnation equipment for large coils applicable for 600 MW class generator coils is shown in *Fig. 3*. This equipment can raise the vaccum inside of the impregnation tank to 10^{-2} mmHg in a short time considering the importance of the degree of vacuum during impregnation. Moreover, in order to prevent deterioration of the resin by the water moisture in air and the entry of dust, epoxy resin is perfectly sealed from the outside air. In order to increase the impregnability of the resin into the insulation layer, a pressure of several atmospheres can be applied to the impregnation tank and various controls are taken to maintain product stability.

Another important factor from the standpoint of coil stability, in addition to these impregnation operation, is low and stable F-resin viscosity. Various characteristics tests and dielectric with stand tests are performed on the completed coils. Then, the coils are sent to the next process based on a strict quality control system. A high capacity turbine generator stator coil manufactured with F-resin insulation is shown in *Fig. 4*.

III. CHARACTERISTICS OF F-RESIN INSULATION COIL

1. General Properties of Coils

The insulation layer of the F-resin insulation coil is tough and has good electrical, mechanical, thermal and chemical characteristics. The characteristics of the insulation layer are shown in *Table 2*. The system in which asphalt compound is impregnated in mica tape and the system in which mica sheet is baked with shellac have a long record of achievements and their characteristics are still praised. But F-resin insulation has better characteristics than either of these systems.

Table 2 Various properties of coil insulating layers

Item	F-Resin • mica	Asphalt • mica	Shellac • mica
Flexural strength (25°C) (kg/mm²)	25	10~14	15~18
Modulus of elasticity (25°C) (kg/mm²)	2.5×10^3	3.0×10^3	3.5×10^3
Volume resistivity (25°C) (Ω-cm)	6×10^{15}	$5\sim10\times10^{14}$	$5\sim10\times10^{13}$
Dielectric strength (25°C) (relative value)*1	100	70~75	80~85
Thermal expansion coefficient (1/°C)	12×16^{-6}	10×10^{-6}	9×10^{-6}
Thermal conductivity (W/m • °C)	0.35~0.4	0.2~0.25	0.24

*1 Valued 100 for F-Resin • mica

The temperature characteristic of tanδ of the F-resin insulation coil is shown in *Fig. 5*. Temperature charcteristics of the dielectric strength and flexural strength of the insulation layer are shown in *Fig. 6*. In *Fig. 6*, the value at 25°C is made 100%, and

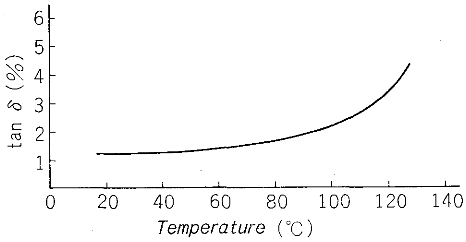


Fig. 5 tanδ vs. temperature characteristics of F-Resin coil

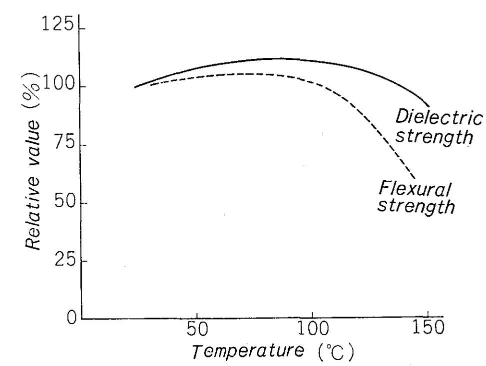


Fig. 6 Flexural strength and dielectric strength vs. temperature characteristics of coil insulating layers

also has a good characteristics. at high temperature The thermal expansion approaches that of copper and heat transmission coefficient is high.

An example of the tanδ-voltage characteristic of a typical F-resin insulation coil is shown in *Fig. 7*. From this characteristic it can be seen that tanδ doesn't increase up to the rated voltage and that there are almost no voids in the insulation layer.

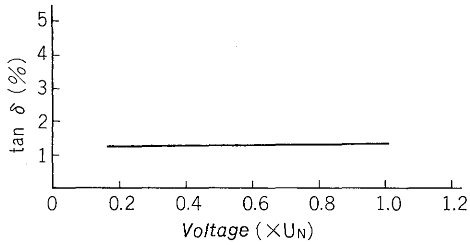


Fig. 7 tanδ vs. voltage characteristics of F-Resin coil

The maximum partial discharge at the normal voltage is under 10^{-9} Coulomb and partial discharge which has an adverse effect on the life of the coil is not produced. It is necessary to control these characteristics to within a small range between all the coils. The frequency percent of Δtanδ (difference between tanδ_0 and tanδ at the rated voltage) is shown in *Fig. 8*.

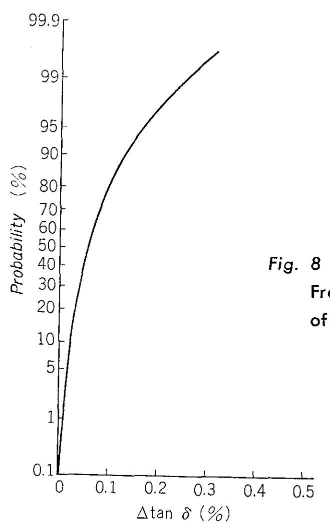


Fig. 8 Frequency percent of Δ tan δ

2. Voltage Endurance Characteristics

The coil insulation is gradually deteriorated by the continuous operation of the generator over a long period of time. This is considered to be caused by the mechanical stress due to heat or heat cycle, impressed voltage, partial discharge, and electromagnetic force. Usually these factors effect on insulation not seperately but together and their combined effects accelerate deterioration. It is impossible to perform a test which actually reproduces an actual state containing all these factors. The various insulation organizations can be compared and practical characteristics can be presumed by performing tests which approach actual use and severe tests by combining several important factors. We have performed generator coil deterioration tests, for example, voltage endurance test, thermal stability test, heat cycle test, mechanical strength test, and fatigue test, for many years and have improved reliability.

The voltage endurance curve (V–t curve) of F-resin insulation is shown in *Fig. 9*. The test coil is

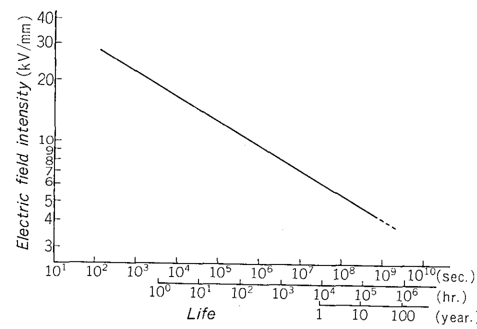


Fig. 9 Voltage endurance curve of F-Resin coils

first heat treated corresponding to 10～20 years of actual machine operation and the frequency of the impressed voltage in an electric field over 7 kV/mm is made 50 Hz and 500 Hz in a field under 7 kV/mm. Life (t) and electric field intensity (V) are indicated logarithmetically and good linearity ($t=kV^{-n}$: k, n are constants) is obtained. From the results it is assumed that voltage endurance of F-resin is extremely long and that insulation deterioration by dielectric stress is neglegible.

3. Thermal Stability

The thermal deterioration characteristics of insulation is one of the vital properties affecting coil life. Both shape stability at high temperature and the thermal deterioration characteristics when heated for a long time at a comparatively high temperature must be considered in evaluating thermal resistance properties. Since the active energy of the thermal deterioration reaction varies above a certain temperature, careful attention is required and comparison of the heat resistance properties of material is generally performed at a comparatively high temperature. However, finally a long term test at a nearly actual usage temperature must be performed in coil shape. *Fig. 10* show the change of dielectric strength by thermal aging of F-resin insulation at a temperature of 160°C and 190°C. Moreover, the Δtanδ of an actual coil after aging for 1,000 hours at the specified temperature is shown in *Fig. 11*.

This type of F-resin insulation has very small property changes even at fairly high temperatures. But

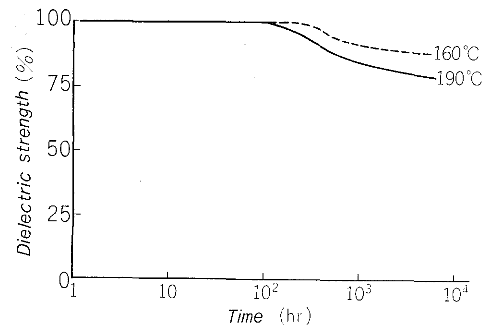


Fig. 10 **Change of dielectric strength of F-Resin insulating layers by thermal aging**

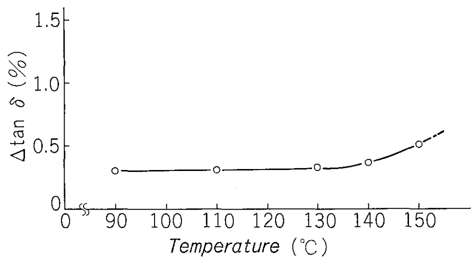


Fig. 11 **Δtanδ vs. aging temperature characteristics of F-Resin insulating coil**

in large coils, it is necessary to have resistance to not only heat or dielectric stress but also thermal or mechanical stresses and electromagnetic forces. Electromagnetic forces are usually considered in case of short circuit accidents which causes great mechanical stresses on the coil end and the electromagnetic vibration during operation. In oder to examine coil insulation stability with respect to these forces, various test must be performed. Therefore, the stability of the F-resin insulation is confirmed by performing such tests as mechanical stress tests or repeated fatigue tests.

4. Evaluation by Functional Test

When the stator coil of a generator becomes large, the stress applied to the insulation layers increases accompanying variations in the load. For this reason, the coil must have highly reliable heat cycle resistance characteristics. In other words, the conductor is repeatedly expanded and contracted by the heat cycle accompanying changes in the load, and stress is applied to the insulation layer because of the difference in the thermal expansion coefficient and the difference in the temperature of the insulation layers at this time and the insulation layers may be exfoliated cracked by some insulation system. In large turbine generators employing the previously mentioned asphalt system or shellac system, separation, cracking, etc. called girth crack or tape migration is produced in the insulation layer near the slot outlet. However, this danger has been almost eliminated with synthetic resin impregnated coils with technical advances in manufacture. However, when a severe heat cycle is repeated, small cracks are produced inside the insulation layers or small separation are produced between the base materials, deterioration in mechanical strength occur and due to partial discharge at that point, also a drop in the dielectric strength must be considered. An example of a functional evaluation test centered around the heat cycle and with various other important factors added is described here.

1) Model slot and test coil

The model slot of functional test described here uses a laminated iron core patterned after the actual turbine generator. Slot length is 4 m and the number of slots is 2. The coil has a rated voltage of 15.4 kV, the straight part is approximately 4.4 m and the overall length is approximately 6.4 m, including the coil end. The conductors are transposed and are hollow conductors to pass cooling water. The state with the coil housed in the model slot is shown in *Fig. 12*, and a coil cross sectional view is shown in *Fig. 13*.

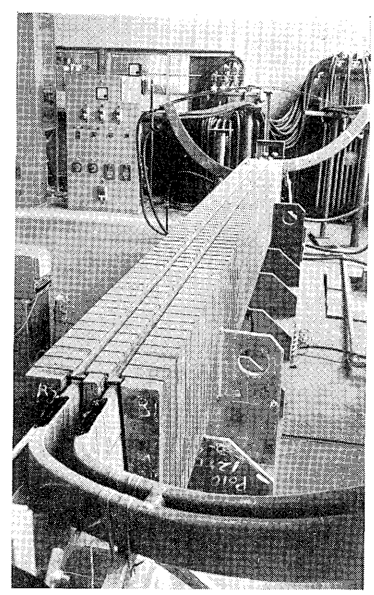


Fig. 12 **Model slot for functional evaluation test**

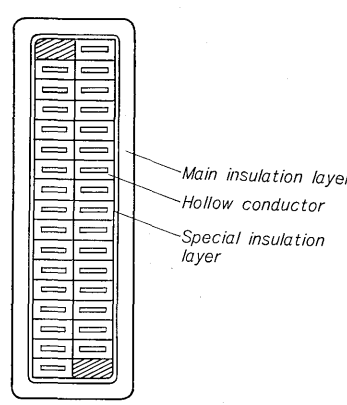


Fig. 13 **Section of coil**

2) The conditions of a functional evaluation test

The test condition are made more severe than actual conditions. However, since correspondence with the usage state will be lost if the conditions are too severe, they must be decided prudently. Various studies are performed on these factors and several heat cycle conditions are selected. An example is given in *Fig. 14.* That is, 1 cycle is made 70 minutes and the rated voltage is applied to the coil. Moreover coil is heated by passing current and suddenly cooled by passing normal temperature water through the conductor. All of these heat cycles are automatically performed and the temperature of each part of the coil, elongation and contraction of the coil, permanent displacement of the insulation layers are continuously recorded automatically.

Moreover, operation is halted periodically, a withstand voltage test (2 × rated voltage + 3 kV) and non-destructive insulation characteristic test are performed, and at the same time, the coil is visually inspected for mechanical damage of the insulation layers.

3) Test results

The conductor temperature change in heat cycle is shown in *Fig. 14.* The insulation layer temperature change accompanies this change, but since the cooling medium is normal temrerature water, the insulation layer temperature doesn't drop suddenly even through the conductor is cooled approximately 100°C within several minutes. For this reason, since

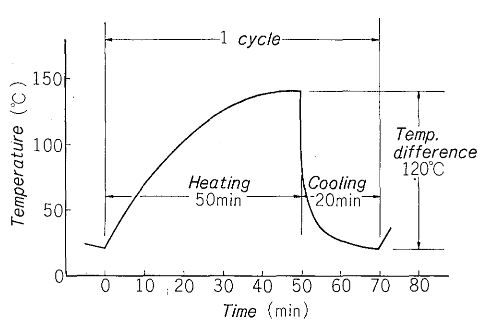


Fig. 14 **Diagram of heat cycle**

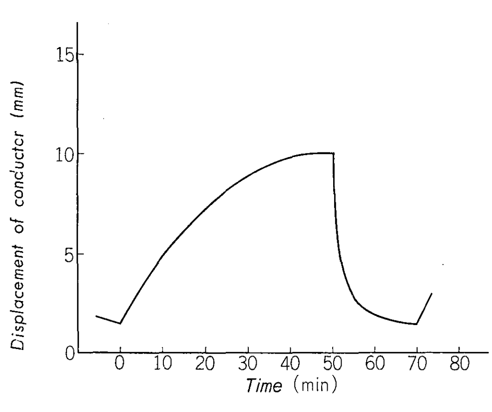


Fig. 15 **Displacement of conductor in a heat cycle**

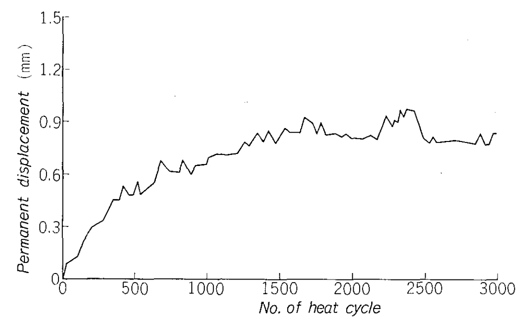


Fig. 16 **Permanent displacement of coil surface by heat cycle**

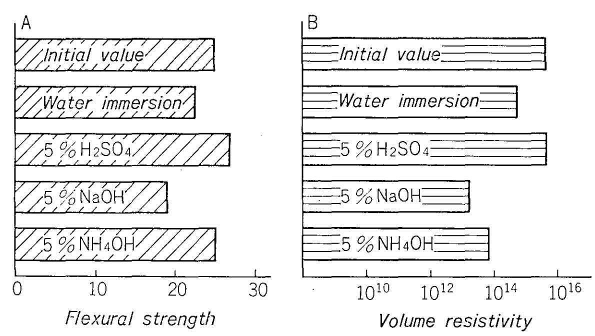


Fig. 17 **Chemical resistivities of F-Resin insulating layers**

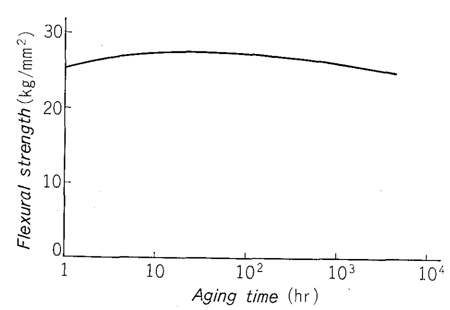


Fig. 18 **Effect of aging in turbine oil on the flexural strength of F-Resin insulating layers**

a temperature difference of several tens of degrees is produced during this period, the test conditions are more severe than practical conditions. The displacement of the conductor due to conductor temperature change is shown in *Fig. 15.*

The permanent displacement of the coil surface with heat cycles is shown in *Fig. 16*, but its value is extremely small and no abnormalities were found at the coil or slot outlet by visual inspection. Approximately 4,000 heat cycles were performed and the increase of $\tan\delta$ by the normal operating voltage in the $\tan\delta$-voltage characteristic was very small. Moreover, the increase of $\tan\delta$ at approximately 1,000 cycles almost reached the saturation state and over this, the deterioration of the insulation layer due to heat cycle was very small. Moreover, a withstand voltage test (2 E + 3 kV) was periodically performed up to 4,000 cycles. After 4,000 cycles, the withstand voltage test was performed at a voltage double this testing voltage and this voltage was withstood without any problems.

The F-resin insulation maintained good insutation performance after more than 4,000 heat cycles even under severe conditions which would never be considered in actual use.

5. Resistance Against Chemicals and Oil

The flexural strength and volume resistivity of an F-resin insulation layer after immersion in 20°C water, acid (sulfuric acid: H_2SO_4), alkali (sodium hydroxide: $NaOH$), and ammonia water (NH_4OH) for 30 days are shown in *Fig. 17*. The F-resin insulation exhibits good water and chemical resistance. There are cases when a small amount of lubricating oil is applied to the coil from the lubricating system when a turbine generator, is initially operated or when it is disassembled for inspection. We perform a wide range of tests on the ability of insulation material to withstand lubricating oil, insulating oil, or nonflammable oil and have confirmed that there are absolutely no problems concerning the ability of the insulation to withstand oil. Flexural strength change when the F-resin insulation layer has been immersed in turbine oil (120°C) is shown in *Fig. 18* as an example.

IV. CONCLUSION

The materials working methods, and performances of the new F-resin insulation related to large alternator stator coil insulation have been introduced. F-resin insulation coils are manufactured by vacuum impregnation of an epoxy resin having good impreg nation properties and other various characteristics and it's main features are:

(1) superb $\tan\delta$-voltage characteristic, partial discharge characteristics,
(2) stable quality at manufacture and little deviation,
(3) tough insulation layer and superb heat cycle withstand characteristics,
(4) superb thermal stability, dielectric strength, and moisture resistance.