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F-RESIN/G INSULATION SYSTEM FOR HIGH-VOLTAGE SMALL AND MEDIUM MOTORS

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I. INTRODUCTION

Fuji Electric has developed a new F-resin/G insulation system for high-voltage small and medium motors which greatly improves the insulation reliability by adopting the continuous mica taping on an entire stator coil and vacuum pressure epoxy resin impregnation of an entire stator. The insulation reliability improvement contributes to maintenance cost reduction and facilitates using the motor in humid or dusty environment with frequent start-stop operation. The system shows excellent environment resistivity and guarantees the F-class thermal endurance.

This article describes the manufacturing process, quality control and insulation properties of F-resin/G insulation system.

II. INSULATION SYSTEM DESIGN, MANUFACTURING PROCESS, AND QUALITY CONTROL

1. Insulation System Design

In developing the present insulation system, we focused our effort on improving insulation around a stator coil end, because insulation breakdown occurs more frequently around a stator coil end than in any other part of a motor, especially when it is used in hazardous environments. If we adopt different insulation for a slot and a slot end only for improving slot end insulation, insulation inhomogeneity at the slot-slot-end boundary will deteriorate whole insulation system; in any occasion, insulation uniformity of the whole insulation system should be retained. Therefore, we examined a manufacturing process which impregnates the stator coil and core slot simultaneously with resin. The process consists of continuous mica taping and vacuum pressure impregnation of the stator core and coils. More in detail, unimpregnated mica tapes are wound around the coils. The coils are then inserted into core slots to build a stator winding and the stator winding is vacuum pressure impregnated with epoxy resin. If we carefully prevent incomplete resin impregnation and resin flowout, this new insulatinon method improves environment resistivity of an insulation system of a high-voltage motor because whole stator windings, including slot part of stator coils, jumper wires and joints, are simultaneously impregnated.

2. Manufacturing Process and Quality Control

Fig. 1 shows the entire manufacturing process and quality control items of the F-resin/G insulation system. For the coil conductor, the heatresistant film taping wire or mica tape insulating wire is used corresponding to the thermal endurance class and voltage class. Main and end insulation work starts with wrapping a slot and a slot end of the stator coil with glass backed mica tape which shows excellent thermal endurance and resin impregnability. A well tuned automatic taping machine facilitates obtaining continuous, uniform and tight insulation layer from the slot end to the slot of the stator coil. *Fig. 2* shows taping work by an automatic taping machine. For the motors, of which rated voltage exceeds 6 kV, a semi-conductive shielding tape is also used to prevent partial discharge in the slot end.

After all the tapings are performed, the diamond shaped coils are inserted into the core slots. In this process, care should be taken so as not to damage the insulation layer by mechanical stress or a slot edge.

Connection parts of the coils, jumper wires and line cable are first wound with the same tape that is used for main insulation and wrapped again with the resin flow-out preventing tape.

After the finishing work around the coil end is over, the layer test of the conductors and the DC high voltage test are conducted on the stator coil to inspect mechanically induced faults.

Next, vacuum pressure impregnation with resin is conducted on the stator winding. We carefully control the impregnation resin and impregnation conditions so as not to induce unwanted faults. We use an impregnation tank, as shown in *Fig. 3*, for the vacuum pressure impregnation. After placing the stator winding in the tank, the tank is evacuated to remove air, moisture and volatile materials like residual solvent. After pumping out the residual gases, impregnation resin is poured to the level enough to cover the entire stator winding. The evacuation continues not only during the resin pouring but also after the resin pouring so that the resin is completely degassed. After the degassing the impregnation resin, dry gas is fed into the tank and the tank is pressurized quickly. The tank contents are then

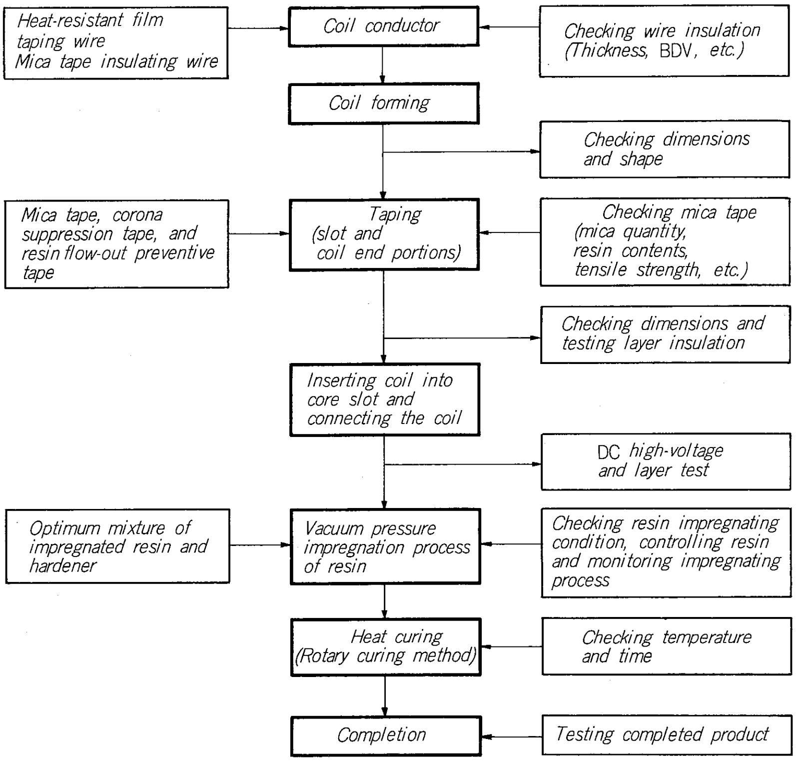


Fig. 1 Manufacturing process and quality control of F-resin/G insulation system

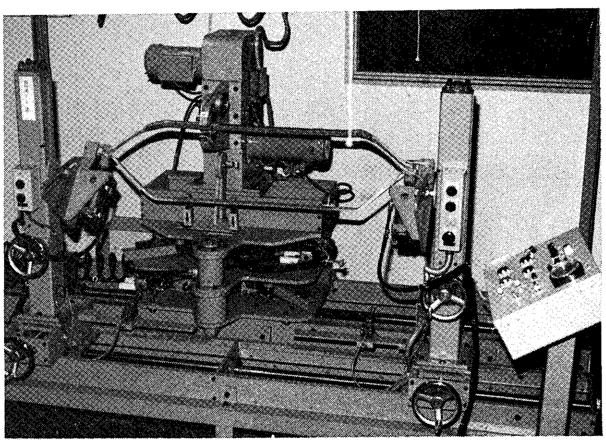
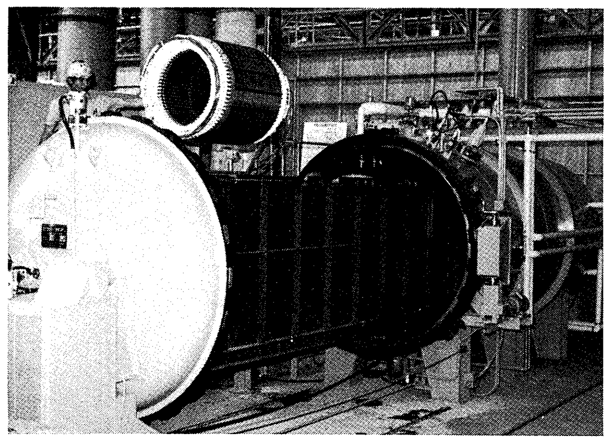
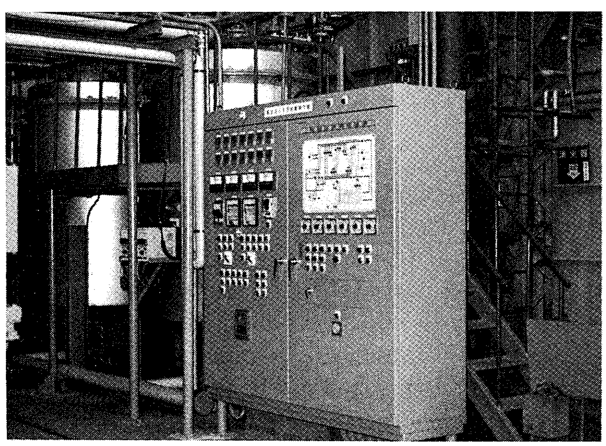


Fig. 2 Taping works by automatic taping machine



(a) Impregnation tank (2000mm dia. x 4300mm, 16 m^3)



(b) Control board

Fig. 3 Vaccum pressure impregnation tank and control board

maintained under a constant pressure for predetermined period.

The optimum impregnation conditions for the F-resin/G insulation system were established in this work by analysing impregnation mechanism theoretically and experimentally. By the analysis we found also that capacitance measurement of a stator winding during impregnation provides us with a very useful measure for monitoring resin impregnation into insulation layers and impregnation saturation. Since the dielectric constant of the liquid impregnation resin is very high, the capacitance of the stator winding changes clearly as shown in *Fig. 4* as impregnation proceeds. The capacitance change monitoring also provides us with very useful information for quality control and rationalization of the

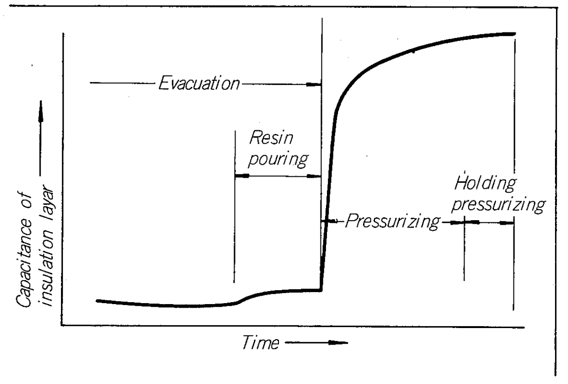


Fig. 4 Change in capacitance of stator windings during impregnation process

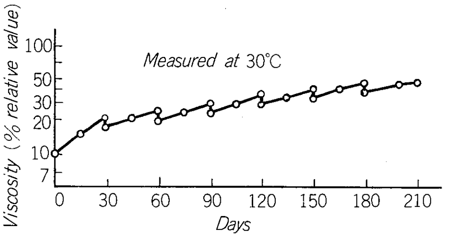


Fig. 5 Viscosity change of impregnation resin

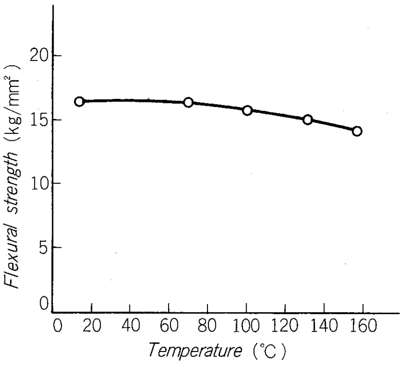


Fig. 6 Flexural strength vs. temperature of insulating layers

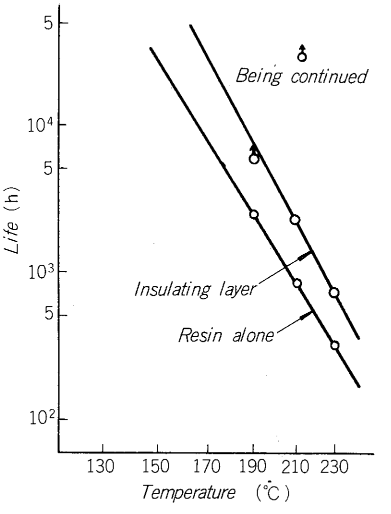


Fig. 7 Thermal endurance curves of insulating layers

impregnation.

We adopted the F-resin® as the impregnation resin for the present insulation system. Though the F-resin® has already been successfully used in the other insulation systems (F-resin/F-insulation and F-resin/S-insulation systems of our company), we carefully control the F-resin® for the present insulation system so that many excellent cycles of impregnation works can be performed with it.

After the impregnation work finishes, the stator is immediately cured in a pre-heated curing oven. We have succeeded in uniformly curing the resin by adopting the rotating curing technique which originated in Fuji Electric.

The stator thus finished is subjected to the conventional insulation tests to guarantee its quality. It is also subjected to the insulation resistance and dielectric strength tests under water or in humid condition, if necessary.

III. INSULATION CHARACTERISTICS

1. Impregnating Resin and Mica Tape

The most important materials in F-resin/G insulation system include impregnating resin and mica tape.

The main compornents of this resin are bisphenol epoxy resin and acid anhydride hardner.

We selected the F-resin® because it showed desirable characteristics in viscosity, storage stability, gelling time, post-curing electrical properties and post-curing mechanical properties.

Fig. 5 shows the storage stability of the F-resin®. The storage stability was examined at 30°C assuming that one impregnation work cycle consists of 8 hours of working followed by 16 hours of storage and 10 weight percent of the resin is replaced with fresh one after 30 impregnation cycles are performed. We know from *Fig. 5* that the viscosity increases at tolerable rate during impregnation work and the resin remains stable for long storage period. We selected a glass cloth backed mica tape treated with an optimum volume of accelerator considering the following items.

1) Tensile strength appropriate for automatic machine taping.
2) Working easiness and efficiency.
3) Wear resistance (no peel off or drop off of mica layer).
4) Impregnability and wettability with the resin.
5) Thermal endurance.
6) Electrical properties.
7) Compatibility and reactivity with the impregnating resin.

Fig. 6 shows the temperature variation of the flexural strength of the insulation layer formed with the resin and mica tape. *Fig. 7* shows the thermal endurance of the insulation layer, where the life is defined as a heating period required to reduce the bending strength to half the initial value. We know from these figures that the insulation layer shows an outstanding thermal endurance.

2. Coil Insulating Layer

We evaluated the coil insulating layer in electrical properties, thermal properties and environment resistivity.

1) Electrical properties

Fig. 8 shows the Weibull's plot of the breakdown voltages (BVD) measured on a 6 kV class model coils with imitation slots and stator coils installed in an actual motor. The breakdown voltages of the model coil and the stator coil well coincide with each other and distribute in a narrow range. The BVDs exceed five times the rated voltage. This indicates that the coil insulation layer possesses stable properties and sufficient initial strength.

Fig. 9 shows the voltage endurance (V-t characteristic) of coil insulating layer at room temperature and 155°C. The voltage endurance at 155°C does not deviate from the values at room temperature. We know from *Fig. 9* that the life of the coil insulation layer under the normal earth voltage is long enough for practical use. *Fig. 10* shows the applied voltage variation of dielectric loss tangent (tan δ) of the model coil and stator installed in an actual motor. The dielectric loss tangent of the insulation layer remains constant even when the applied voltage exceeds 6 kV, as tan δ of the model coil with a guard electrode remains constant. The dielectric loss tangent of the stator increased at high applied voltage simply because the corona shielding tape was applied around the slot end. The maximum partial discharge at the normal earth voltage did not exceeds 200pC.

2) Thermal endurance

We evaluated insulation clraracteristics change and BVD by heating the coils at high temperature for a long period. *Fig. 11* shows the BVD change caused by thermal aging at 170°C. Even after heating for 3000 hours, the BDV changed only by 6%. We know from this that the coil insulation shows an excellent thermal stability.

Fig. 12 shows the thermal endurance of F-resin/G insulation system tested with motorett coils by the conventional thermal life test specified by the IEEE Standard 275. We know from *Fig. 12* that the F-resin/G insulation system guarantees the F-class thermal endurance.

We also evaluated the water proof ability by the water-immersion insulation resistance test. The test was conducted at the end of each moisture absorbed high-voltage test cycle by immersing the motorette coils, heated at 210°C, in water down to the line cable end. *Fig. 13* shows the test result. The insulation resistance of coils is stable even after 16 cycles of such an extremely severe test. This result shows that the whole winding of this insulation system shows an excellent moisture and water proof ability.

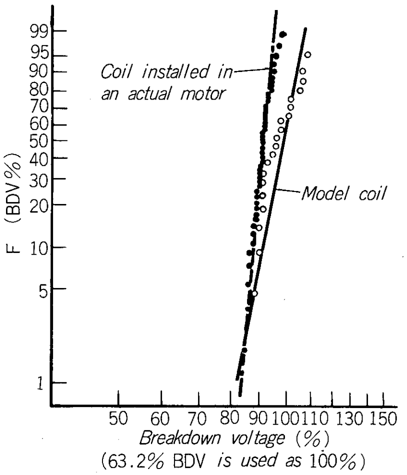


Fig. 8 **Weibull's distribution of breakdown voltage**

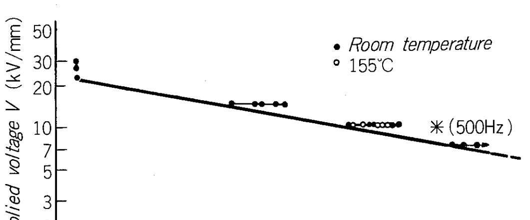


Fig. 9 **Voltage endurance characteristics**

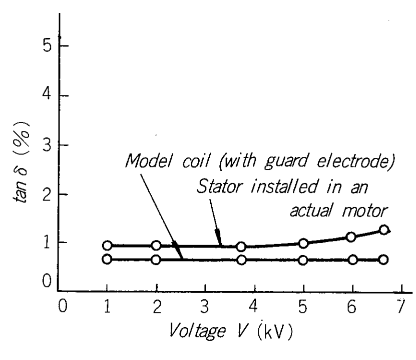


Fig. 10 **Tan δ vs. voltage characteristics**

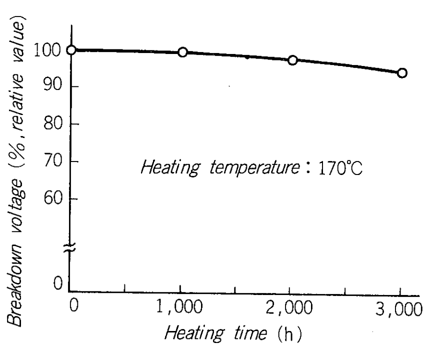


Fig. 11 **Change in breakdown voltage during thermal aging at 170°C**

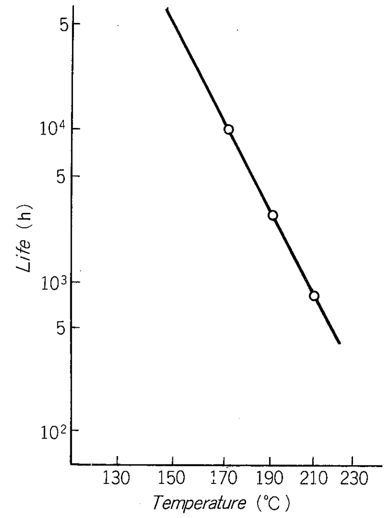


Fig. 12 Thermal endurance curve of F-resin/G insulation system

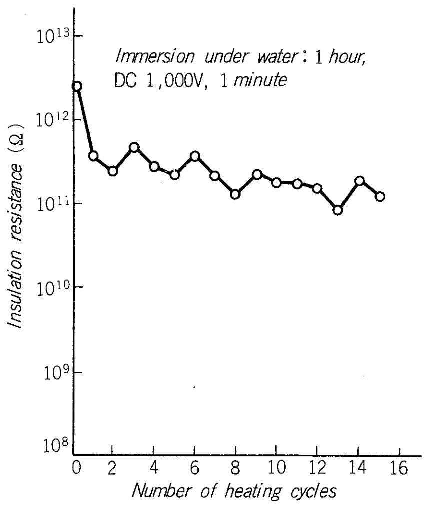


Fig. 13 Change in insulation resistance by water-immersion test with 210°C aging motorett

3) Heat cycle character

We conducted a heat cycle test on an actual stator under the test conditions shown in *Fig. 14* (a). We also monitored insulation properties and executed periodic high-voltage test. Typical insulation characteristics up to 500 heat cycles is shown in *Fig. 14* (b). The tan δ of the windings did not deviate from the initial value. Neither peel off nor crack were visually obserbed in the insulation layer of the stator coil end. The stator windings also withstand against the high-voltage test (2E+1 kV, 1 minute). Thus the F-resin/G insulation system shows an excellent immunity to the thermal stress cycle.

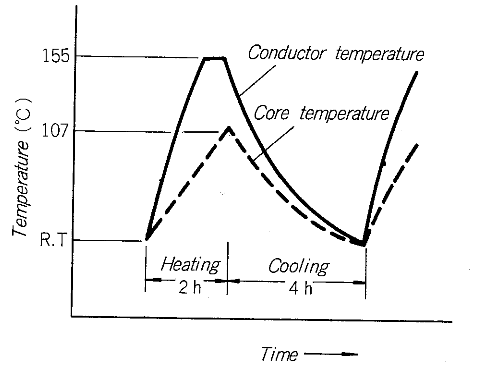
Fig. 15 shows the heat cycle test equipment.

4) Environment resistivity

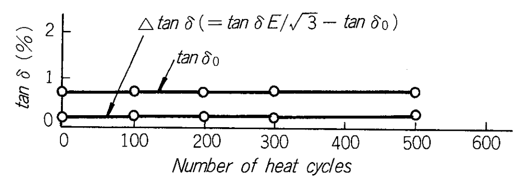
Recently, high-voltage motors are often used in very dusty or humid environment.

Fig. 16 shows a coil end covered by thick cement dust deposit. When the motors are operated in the hazardous environment, the contaminants grow weak-points in the insulation, and the weak-points cause an accident.

For evaluating the reliability of the insulation used in hazardous environments, the test specified by IEEE Standard 275 is not suitable, because it does not consider contamination. Therefore, we developed a new evaluation test method, which considers contamination, humidity and electrical charging, for evaluating environment resistivity of insulation systems.



(a) Conditions of heat cycle test



(b) Change of tan δ characteristics by heat cycle

Fig. 14 Heat cycle test conditions and change of tan δ characteristics

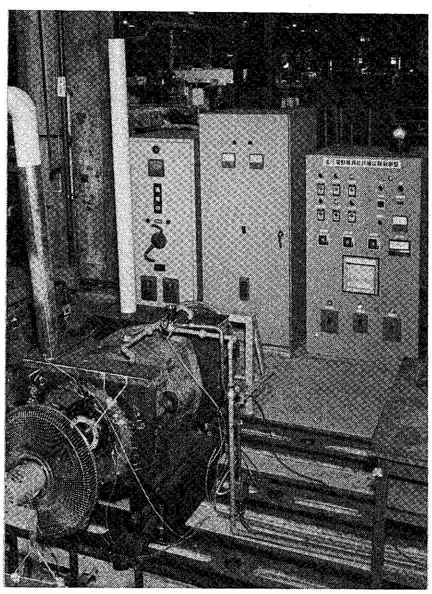


Fig. 15 Heat cycle test equipment

Fig. 16 View of cement-dust on the coil end

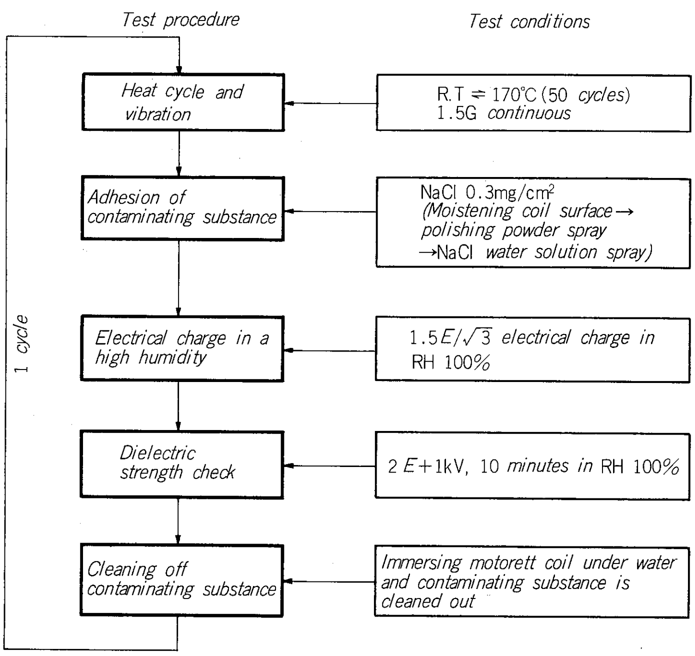


Fig. 17 Environmental evalution test conditions

Our evaluation test uses a motorett coil specified by IEEE Standard 275, and evaluates it by the procedure shown in *Fig. 17. Fig. 17* also shows the test conditions. This evaluation test assumes that insulation breakdown caused by contamination occurs at the coil end portion through the following processes;

(1) Local heating, heat cycle and mechanical vibration produce weak-points in an insulation layer of the coil end.
(2) Deposited contaminants and moisture deteriorate insulation resistance at the weak-points.
(3) When the operation continues, leakage current increases at the weak-points and the tracking starts.
(4) The tracking gradually grows to a total line breakdown.

Our evaluation test method facilitates improving insulation systems because the method offers a powerful measure to discover actual and potential weak-points in insulation systems. Excellent environment resistivity of the F-resin/G insulation system was verified by the evaluation test method.

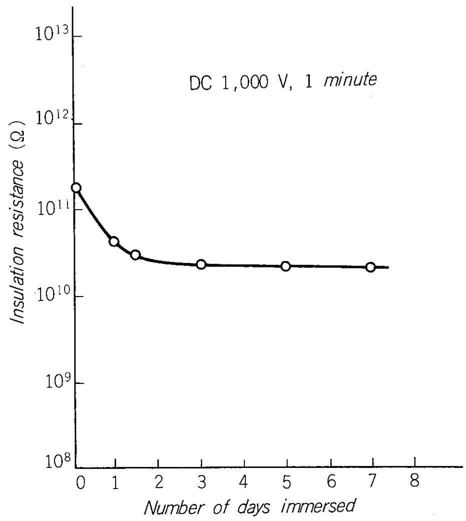


Fig. 18 Change in insulation resistance of stator windings under water-immersion

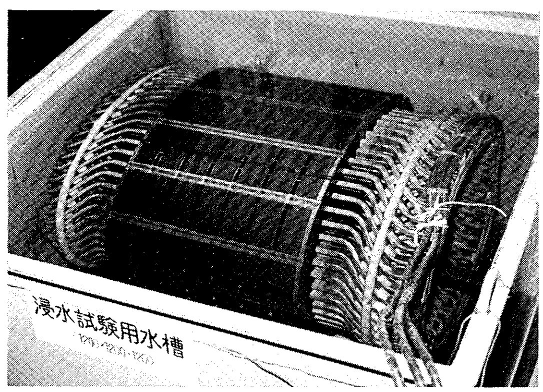


Fig. 19 Water-immersion test of stator windings

F-resin/G insulation system passed also in NEMA testing. As shown in *Fig. 18*, even when an actual stator winding made from the F-resin/G insulation system was immersed in water for a long period, the insulation retained high resistance. *Fig. 19* shows an actual stator winding immersed in water for testing.

IV. SUMMARY

The F-resin/G insulation system for high voltage small and medium motors offers a highly reliable insulation system by adopting contionus mica taping and vacuum pressure epoxy resin impregnation for a core and coils. In addition to its excellent electrical performance, the system also shows outstanding heat cycle resistance and guarantees F-class thermal endurance. The outstanding moisture resistance and environment resistivity of the insulation system facilitate using the motors in various hazardous environments.

We are convincing that the F-resin/G insulation system meets the requirements of the users in various industries.