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RECENT INSULATION SYSTEM FOR HIGH VOLTAGE ROTARY MACHINES

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I. INTRODUCTION

Insulation for rotary machines is being developed through the development of materials, improvement of manufacturing methods, and the development of life tests and other evaluation methods. In recent years, rational insulation systems with higher reliability have been pursued through the approval of various materials and manufacturing methods backed on various evaluation test methods. Since the insulation system used in rotary machines depends on the effects of the stress caused by applying a voltage, of the various stresses applied to the insulation, at high voltage and low voltage, they can be grouped into high voltage insulation systems and low voltage insulation systems. Here, high voltage indicates a high voltage level of a rated voltage of 3 kV or higher, but is substantially effected by the voltage grading and corona discharge of the coil end turn and the insulation design concept with a rated voltage of 6 kV or greater is the basis of high voltage rotary machine insulation. When designing an insulation system, the construction and usage state must be considered from the standpoint of the machine size, electrical specifications, and applications separately from such basic conventions as this voltage grading and thermal class and a manufacturing method which assures minimum costs at actual manufacture must be considered. Resin insulation F resin insulation and Stabilastic insulation are used as the stator winding of high voltage rotary machines, but recently an insulation system best suited to the type and application has come into use by adding the fully impregnated method and resin-rich mold method to these.

On the other hand, rotor windings have different constructions according to the type of machine and applications and there is a low voltage insulation system as the insulation system and attention is mainly being given to thermal resistance and mechanical characteristics and to the effect of thermal cycle, contamination, etc. during operation. These rotor windings can be grouped into synchronous machine salient pole coil, round rotor coil, induction motor wound rotor, etc. These will be outlined below.

II. STATOR WINDING INSULATION SYSTEM

The insulation system of a stator winding uses mica and epoxy resin as the main materials, and the vauum impregnation method and press mold method are employed as the basic manufacturing methods. As previously described, there are four insulation systems, including the recently developed system. These systems are designated F-resin/F insulation, F-resin/R insulation, F-resin/S insulation, and F-resin/G insulation for unification. These insulations range from thermal Class B to Class F and have superior characteristics with almost no significant differences, even though their electrical characteristics and mechanical characteristics may differ slightly. Rather their features should be said to be from the standpoint of the manufacturing method. The features and applicable range of each insulation system are shown in *Table 1*.

Table 1 Insulation systems for stator coils

Insulation system	Features of manufacturing method	Applicable range
F-resin/F insulation	Single coil epoxy vacuum impregnation (all taping)	Large capacity waterwheel generator Turbine generator
F-resin/R insulation	Single coil epoxy press mold (all taping)	Medium, small capacity waterwheel generator Large industrial AC machines
F-resin/S insulation	Single coil epoxy press mold	General AC machines
F-resin/G insulation	Epoxy all impregnation	Large industrial AC machines

1. F-resin/F insulation

F-resin/F insulation is F resin insulation that is resin impregnating insulation for high voltage develped in 1958, to which various improvements have been made and has the longest history as resin insulation. It is mainly used in large capacity machines which use transposition conductors.

The main materials are micasplitting tape and mica paper tape and epoxy resin. When first developed, the mica tape was hand split and both the tape thickness and tape

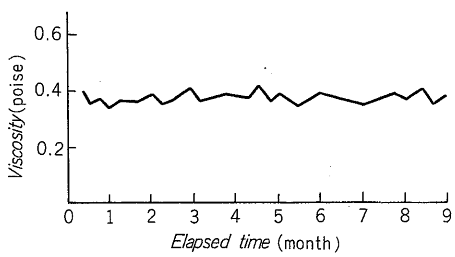

Fig. 1 Viscosity change of impregnating resins

width were small. However, today machine split mica tape is used and it has been improved so that the thickness and width are large, a small number of windings is used and uniform insulation is obtained. Mica tape is wound continuously up to the coil end and then impregnated with epoxy resin under a high vacuum. Both the impregnation method and resin composition have been improved since initial development and today the viscosity of the resin is low, pot life is adequate and the impregnating cycle has been shortened by one-half. The visosity of the resin which influence impregnability is almost constant as shown in *Fig. 1* and stable impregnation is performed. The impregnated coil is painted with high resistance paint having nonlinear characteristics for voltage grading of the core end.

F-resin/F insulation is used in waterwheel generators, pumping up power plant generators, turbine generators, and other large capacity machines and boasts no insulation system trouble up to the present time. An opportunity to investigate an F-resin/F insulation coils that had been operated for several years was recently had and the fact that there was almost no change was confirmed by comparing them against those of initial manufacture as shown in *Fig. 2*.

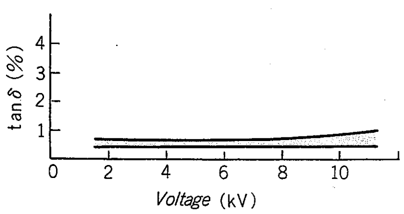

Fig. 2 tan δ vs. voltage characteristics after long operation (F-resin/F insulation)

2. F-resin/R insulation

F-resin/R insulation is an insulation system recently developed and uses an insulation system and manufacturing method incorporating the features of conventional F-resin/F insulation and F-resin/S insulation. The main insulation of F-resin/R insulation is a system in which the slots and end of a conductor formed of glass/mica paper tape is continuously wrapped the prescribed number of times and the set in a heat press and press molded. This system has various advantages over the vacuum impregnation method.

To be specific, since prepreg (resin rich) containing the resin used in advance is used, there is no wasted resin, and since an efficient heat press is used, the loss of energy is small compared with heating in a drying oven and it is superior from the standpoints of resources saving and energy saving. Moreover, since management of manufacturing equipment is simple, quality is improved one full order of magnitude. Furthermore, since there is no impregnation process, the number of processes can be shortened, continuous operation is possible and the working environment is improved.

This insulation system was developed for small capacity waterwheel generator and other single half coil shape machines and its high reliability has been confirmed through various evaluation tests.

3. F-resin/S insulation

F-resin/S insulation is a further improvement based on conventional Stabiliastic insulation techniques and has improved environment resistance, in particular, and is extremely reliable. Stabilastic insulation already has a record of achievements of 10 years and is used in a large number of rotary machines up to 13.8 kV class.

The main insulation material of F-resin/S insulation is mica paper with heat resistant epoxy resin. A voidless, uniform, tough insulation layer is obtained by applying high pressure. Furthermore, since this molding work processes multiple coils at one process, scatters in the characteristics are extremely small and quality is stable. After this main insulation is molded, the tan δ characteristic, corona characteristic, dielectric strength between conductors, and various other characteristics which are a problem with high voltage machines are checked and quality control performed.

The coil end windings are insulated with mica tapes. After the coil has been inserted into the core and connected, it is impregnated with nonsolvent resin and finally a single insulation is molded. Recently, we had the opportunity to measure the characteristics of two (A, B) 3.3 kV Class F-resin/S insulation coils that had been used for 10 years. The tan δ vs. voltage characteristics of these coils are shown in *Fig. 3*. In both cases, the scatter is small and the same excellent characteristics as when new are shown.

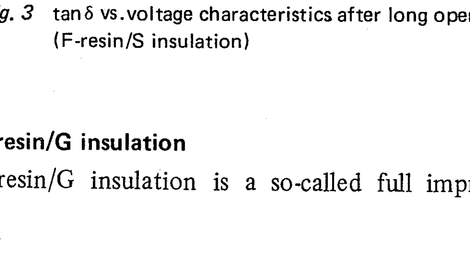

Fig. 3 tan δ vs. voltage characteristics after long operation (F-resin/S insulation)

4. F-resin/G insulation

F-resin/G insulation is a so-called full impregnation insulation system in which the coil is inserted in the core and connected and then the entire coil is vacuum impregnated with resin. This full impregnation system is applicable to low voltage insulation and high voltage insulation, and since resin impregnation is performed with a unit, the mechanical strength of the coil is increased and the coil end windings and connections can be completely filled up with resin. On the other hand, the objective machines is limited because of the size of the equipment and characteristics control in the completed insulation processing state must be evaluated as a complete winding and not just a coil.

With F-resin/G insulation large impregnating equipment is introduced so that it can be used with large machines, the insulation between conductors and the slot insulation, the most important points in a high voltage stator winding are completed in the coil state and quality control is performed stringently.

The main materials of F-resin/G insulation are mica paper and epoxy resin. The conductors are double glass covered plastics film taping wires or mica tape insulated wires which have a high dielectric strength corresponding to high voltage class. The coil is manufactured by measuring the electrical characteristics of between conductors and the slot as a single unit, the same as the common F-resin/S insulation, and inserting it into the core under stringent quality control. Since the surface of the coil is wrapped with special finishing tape to prevent the resin from flowing out after impregnation, there is no drop in characteristics due to resin outflow at curing.

The dielectric strength of the coil end winding in water after being submerged in water is shown in *Fig. 4*. The coil end winding also has as good insulation characteristics as the slot part insulation and is an insulation system resistant to contamination. F-resin/G insulation is applicable to large AC and DC machines and to general AC machines having special specifications.

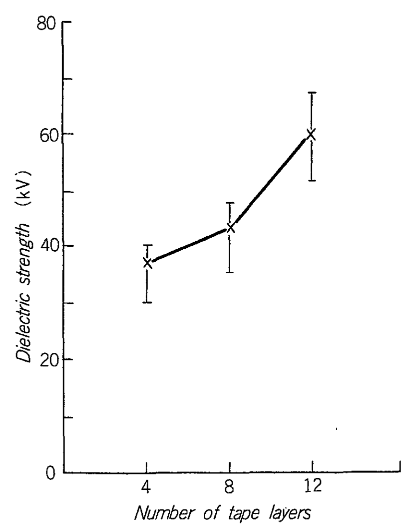

Fig. 4 Dielectric strength of coil end insulation in 3 hours water-submerging (F-resin/G insulation)

5. Insulation characteristics of each insulation system

1) Initial characteristics

A good initial tanδ characteristics and partial discharge characteristics and not changes in state during operation are of maximum importance in a high voltage coil.

The probability distribution of Δtanδ (rated voltage tanδ and tanδ_0 difference) at the time of manufacture of F-resin/F insulation, F-resin/R insulation, and F-resin/S(G) insulation is shown in *Fig. 5*. A typical example of the probability distribution of the maximum partial discharge at the rated voltage is shown in *Fig. 6*. All the insulation systems have a good tanδ characteristic. Moreover, the maximum partial discharge is 10^{-9}C or less and no harmful partial discharge is generated at the normal voltage.

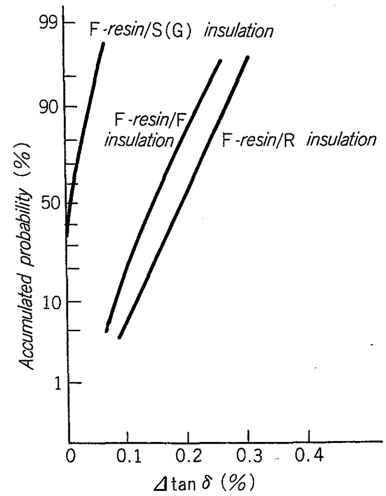

Fig. 5 Frequency percent of Δtanδ (11 kV class coils)

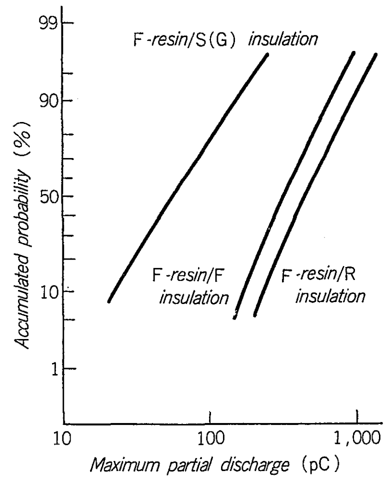

Fig. 6 Frequency percent of maximum partial discharge at rated voltage

2) Voltage endurance characteristic

The voltage endurance characteristic of a coil can

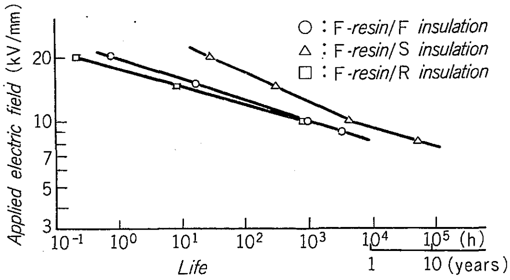

Fig. 7 Voltage endurance characteristics

generally be forecast by *V-t* characteristic test. The *V-t* characteristics (room temperature) of each insulation system is shown in *Fig. 7*.

The characteristic at high temperature (130 ~ 150°C) found at the same time is not much different than that at room temperature and the voltage endurance life of all systems at the operating voltage is extremely long and voltage deterioration is not considered to be much of a problem.

3) Thermal stability

Regarding the thermal stability of coil insulation, the temperature characteristics related to the limit value determined by temperature only and the thermal aging characteristic when heated for a long time at the usage temperature must be considered. Furthermore, the temperaturing distribution when operating or the thermal stress produced by starting and stopping and load changes are important problems. Moreover, the involution action with the thermal and mechanical stress or atmosphere must be considered.

The temperature characteristic of the breakdown voltage is shown in *Fig. 8* as an example of the high temperature characteristic of the insulation layer. F-resin/S(G) insulation has a particular good characteristic. The temperature characteristic of the tanδ vs voltage characteristics after an F-resin/S(G) coil has been heated at 170°C for 3,000 hours is shown in *Fig. 9* as an example of long period thermal stability test. There is almost no change from the initial values. Actually, the characteristic at the operating temperature during long term operation is a problem and the characteristic at high temperature must be found and the thermal resistance studied in this manner.

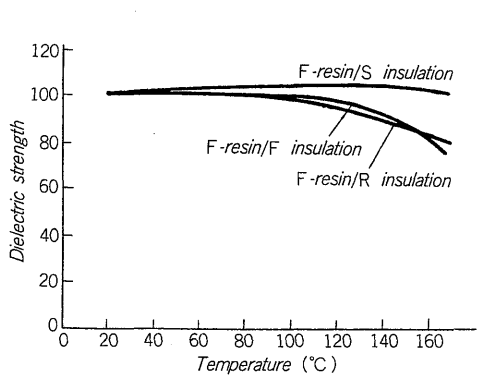

Fig. 8 Dielectric strength vs. temperature characteristics

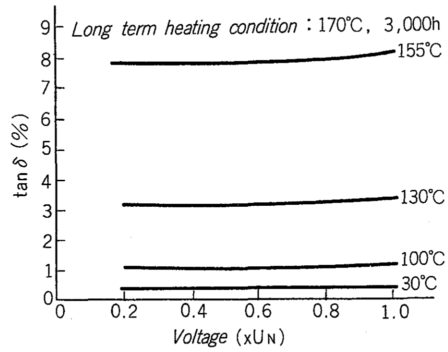

Fig. 9 tanδ vs. voltage characteristics of F-resin/S(G) insulation coils after aging at 170°C for 3,000 hours

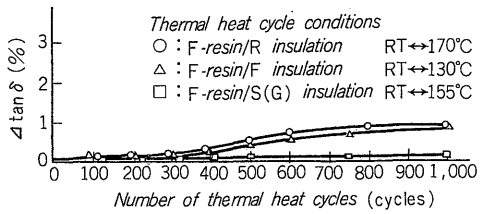

Fig. 10 Change in Δtanδ after thermal cycling

In large machines, the drop in the characteristics due to the thermal cycle is a special problem. An example of the results of a thermal cycle test of each insulation system is given in *Fig. 10*.

4) Mechanical characteristics

When the system is shorted or started and stopped, large mechanical stress is applied to the coil. Repeated stress also acts due to vibration during operation.

The cyclic bending fatigue characteristic showing the time up to fracture by the test voltage (rated voltage x 2 + 3 kV) with applying an amplitude of 2.5 ~ 10 mm both swings to the end of the coil is shown in *Fig. 11*. Various studies related to this mechanical characteristic are performed and the fact that the strength of the coil insulation against the stress applied to the coil has ample design safety is confirmed with the actual machine.

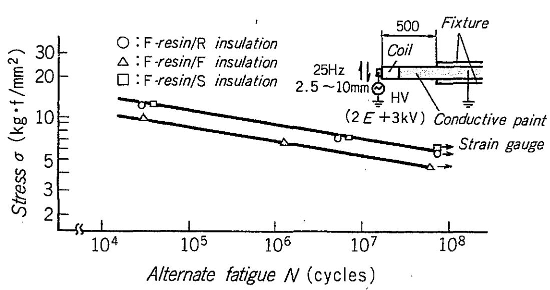

Fig. 11 Characteristics of cyclic bending fatigue

5) Environment resistance

Motors are used in diverse environments and there is the possibility that problems may occur in extremely dirty environments due to high humidity, dust and electrolyte. Extremely severe environments can be coped with by a protection system, but there are many cases where an open type machine is used because of cost and other reasons. Moreover, there is also coping with the demand for maintemance-f.ee machines and we have made both F-resin/S insulation and F-resin/G insulation extremely environment resistant by making improvements stressing environment resistance.

At life tests with a motorette or the actual machines, the performances are checked by pursuring characteristics other than the dielectric check at moisture absorption at each cycle and performing water submerging test conforming with IEEE Std. 429 at each cycle.

An example of the aging change of the insulation resistance at moisture absorption at each cycle of the motorette test of F-resin/G insulation is shown in *Fig. 12*.

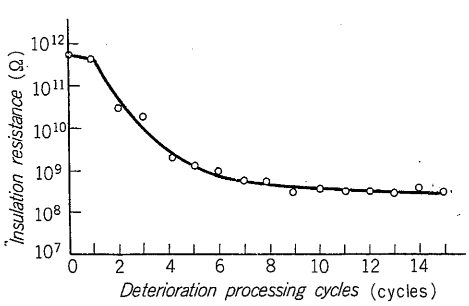

Fig. 12 Change in coil insulation resistance in motorette test

The heating temperature in this case is 210°C and the time of one cycle is 2 days and the mositure absorption conditions are 40°C, RH100% for 48 hours.

An example of the aging change of the insulation resistance in water at the water submerging test after moisture absorption at each cycle of the motorette test, the same as F-resin/S insulation, is shown in *Fig. 13*. The heating temperature in this case is 210°C and the time of one cycle is 2 days. Moreover, the insulation resistance is the value after one hour submersion in water. Both F-resin/S insulation and F-resin/G insulation shows high insulation characteristics even at such extremely severe tests.

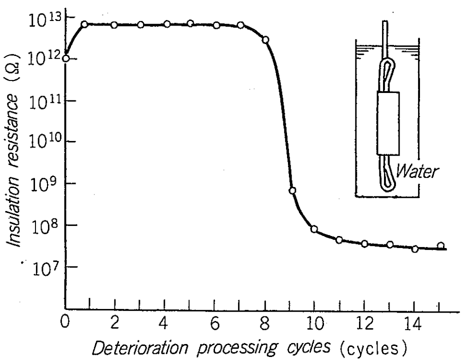

Fig. 13 Change in coil insulation resistance in motorette test

III. INSULATION SYSTEM OF ROTOR WINDING

Since the rotor coil is subjected to centrifugal force by rotation and thermal expansion and contraction due to the thermal cycle simultaneously, the insulation material used must be mechanically strong and mechanical stress, etc. must also be considered in its insulation system. Moreover, recent trends are toward severe machine usage temperature and environments and careful consideration is necessary in insulation design.

1. Salient pole coil insulation

The following points must be considered with a salient pole coil by considering its usage environment and design conditions. In other words, for machines whose surface is severely contaminated by use in severe environments, the surface distance must be protected or the drop in the insulation resistance must be coped with by using a method such as covering the entire surface of the field coil with insulation. Moreover, the thermal expansion and contraction of high speed machines is large and if restrained by the centrifugal force and not elongated at expansion is repeated, creeping will develop. Therefore, consideration is given to slipping by performing special processing on the insulation flange and coil boundary side. Moreover, bonding between the coils is made strong. Furthermore, care must be paid to selection of the material used with high temperature coils and material which does not deteriorate at the usage temperature must be used as the layer insulation inserted between coils.

A general field coil cross section is shown in *Fig. 14*. The coil is made of rectangular copper wire. From various experiments, asbestos with epoxy resin as the adhesive is

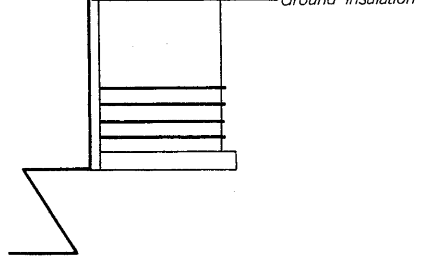

Fig. 14 Cross section of salient pole coil insulation for normal use

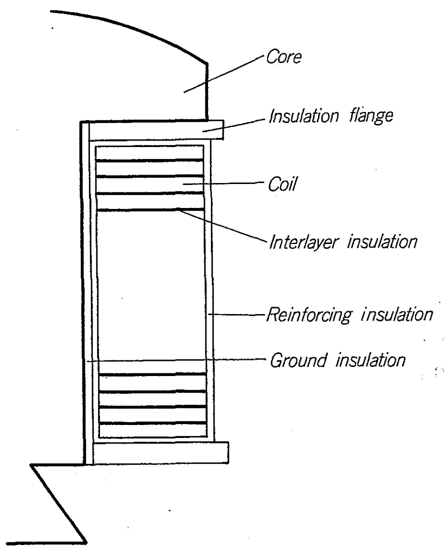

Fig. 15 Cross section of salient pole coil insulation for special use

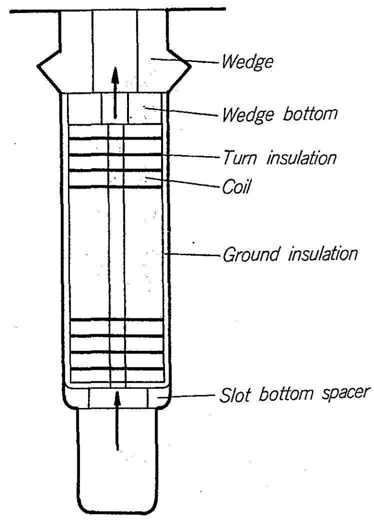

Fig. 16 Cross section of round rotor coil for large turbo generator

inserted and the coil is molded under high temperature and pressure as the interlayer insulation.

Polyester glass laminated plate or epoxy glass laminated plate having superior mechanical strength and thermal resistance is used as the insulation flange. Mica sheet or polyester glass laminated plate is used as the ground insulation and the fact that this insulation system can amply withstand insulation class F has been confirmed.

An example of insulation requiring contamination resistant characteristics such as that of machines installed in chemical plants and coastal areas is shown in *Fig. 15*. In this figure, specially processed mica tape is wrapped around the circumference of the field coil and vacuum impregnated with epoxy resin. A uniform insulation layer is formed at the surface of an insulated coil of this type and its reliability for environment resistance is extremely high.

2. Bound field coil insulation

Since extremely high centrifugal force is constantly applied to a round field coil, the following points are considered in its insulation material and conductors.

Polyester or epoxy glass laminated plate is used as the insulation material. Moreover, since creeping is produced at the conductor, the same as in the case of the waterwheel generator previously described, copper containing a small amount or silver is used as the conductor. A large 2 pole direct gas cooled type is shown in *Fig. 16*. A cooling air hole is drilled in the layer. The layer material is prepreg epoxy glass laminated sheet having powerful adhesion. Since the coil is molded at high temperature and pressure, its adhesion strength is high. The ground insulation is L type epoxy glass laminated plate having high mechanical strength and superior electrical characteristics. In addition, since a large compression force is applied to the wedge bottom insulation, the same kind of epoxy glass laminated plate is used.

3. Induction motor wound-rotor coil insulation

A wound-rotor coil always receives centrifugal force during operation, but it may also be exposed to contamination by an adverse environment. Since a high voltage is inducted in a wound-rotor induction motor at starting, creeping may develop if the winding is extremely contaminated. Therefore, a protected type matched to the contamination is, of course, selected, but an insulation system for these must be considered in advance. Moreover, the coil shape of an induction motor rotor is generally a bar coil and we connect the end by silver brazing to produce a system having a thermal and mechanical reliability higher by one full order of magnitude.

The cross section of a wound-rotor coil used in a high voltage induction motor is shown in *Fig. 17*. The slot insulation of the coil is produced by wrapping with prepreg sheet with a thermal resistant film as the backing material, inserting it into the slot, connecting it, and then heat curing. Special tape is used at the end insulation and the

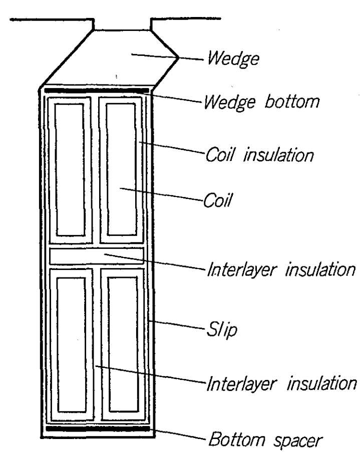

Fig. 17 Cross section of rotor coil for induction motor

end connection part is insulated with mica paper sheet and impregnated with epoxy resin. Since the resin is amply impregnated in the insulator,. the slot insulation and end insulation joint, etc. form a single insulation, mechanical strength and contamination resistance are improved, and reliability is increased one full order of magnitude. An epoxy glass binding is used to support the coil end, considering mechanical strength, etc.

IV. CONCLUSION

An outline of our insulation systems for high voltage rotary machine stator and rotor winding insulation was introduced here. The stator insulation F-resin/F insulation and F-resin/S insulation have a record of achievements of many years, but the system has been complemented by developing F-resin/R insulation and F-resin/G insulation.

Moreover, since the entry of sudden switching surge accompanying the popularity of vacuum circuit breakers is expected, the reliability of the insulation between turns is important and ample consideration is also given to this point.