Third Generation Insulation System in Motors & Generators

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INTRODUCTION

Users of large motors and generators expect their equipment to give 20 to 40 years of reliable performance when properly operated and maintained. The electrical insulation system, composed of nonmetallic materials, must provide electrical isolation and physical support to the electrical conductors for the life of the equipment, even though it is undergoing continuous degradation over time. To better resist this degradation, a third generation insulation system has been developed that enhances the attributes of its service-proven predecessors. This new generation features an improved vacuum-pressure impregnation (VPI) treatment, a corona-resistant enamel as turn insulation, and a Class F insulation system to provide thermal margin in stator windings with Class B temperature rises.

DEGRADATION FACTORS

All motors experience insulation degradation during operation due to such factors as temperature, voltage and mechanical force. These factors are present simultaneously and their overall effect may be greater than the sum of their individual effects. Considered separately, however, their general effects are as follows:

- Temperature causes chemical changes associated with higher reaction rates at higher temperatures. Typically, such changes lead to embrittlement.
- In coils operated above the corona inception voltage, there is some degradation due to ionization in the inevitable voids in the insulation structure. The principal effect is a loss in physical integrity caused by degradation of the organic components, especially the binders used to hold the system together. The effect of voltage on the life of an insulation system is called its Voltage Endurance.
- Insulation systems are exposed to two distinctly different types of mechanical force:
  - Thermal cycling produces strains due to differential expansion, which can cause extensive cracking of the insulation with a consequent loss in dielectric strength.
  - Electromagnetic forces (mainly at twice line frequency) associated with normal operation and transients, such as starting, produce strains in the insulation.

A successful insulation system must maintain its dielectric strength during degradation by these factors. Such a system requires the use of appropriate and compatible materials and fabrication processes. The ultimate proof is in the system's demonstrated service record. Functional tests, conducted when degrading effects are accelerated under controlled conditions, are very useful in assessing the suitability of insulation systems.

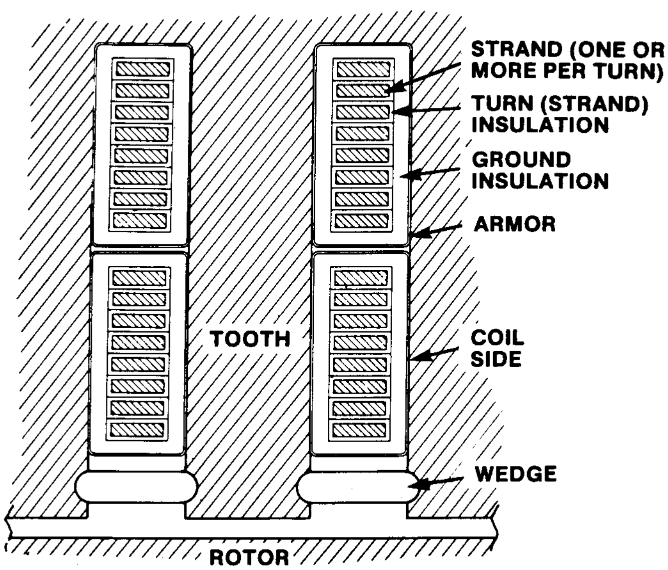


Figure 1. Stator Cross Section (Typical)

RESISTANCE TO ENVIRONMENTAL CONDITIONS

Environmental conditions (such as moisture, chemicals, conducting contaminants or abrasive particles) may have a major effect on the system's performance in particular applications.

- To provide resistance to moisture and conducting contaminants, General Electric builds a "sealed" insulation system into its motors. Industry standards have established the criteria for such sealed insulation systems.
- To prevent attack by chemicals in the motor environment, it is important to choose materials that are resistant to such substances. General Electric uses an epoxy resin in its vacuum-pressure impregnation (VPI) process which provides a high degree of protection against a wide range of chemicals, such as caustics, acids, hydrocarbon and chlorinated hydrocarbon solvents.
- In applications where the motor is required to withstand particularly abrasive atmospheres, the external surfaces of the finished windings are given a protective elastomeric coating to help prevent erosion by absorbing the energy of impacting particles in the cooling air.

STATOR WINDING CONSTRUCTION

As shown in Figure 1, a typical form-wound coil is made up of rectangular strands of copper wire. One or more strands form a turn, and a coil may contain twenty or more turns. The high dielectric strength of enamel-coated wire, such as the type developed by GE engineers, makes it an ideal insulation to keep turns electrically isolated from each other. Conventional enamels, such as polyesters or polyimides undergo substantial degradation from corona activity. The enamel-coated wire used by GE, however, resists such deterioration from corona, while it retains the functional and producibility attributes of conventional enameled wire. These characteristics are described in the referenced paper[1].

While other materials, such as micaceous insulation, also provide effective protection against corona activity, at least twice the thickness of this type of insulation is needed to achieve the required dielectric strength. GE's new corona-resistant enameled wire, on the other hand, makes space available for larger conductors and thus provides greater efficiency.

The enamel may be over-wrapped with glass filaments for additional surge voltage protection. For maximum surge voltage capability, the enamel is over-wrapped with micaceous insulation.

Ground-wall insulation is exposed to line-to-ground voltage during normal operation, and to somewhat higher voltages during transients. For machines of all voltage levels, a resin-saturated micaceous composite is used for the ground insulation with glass and film backers added for strength and protection of the mica. High voltage coils employ still another important feature. A conducting tape covers the slot portion of the coil to prevent corona discharge at the coil-core interface. A conducting material of higher resistivity is then applied at the ends of the conducting slot tape to prevent corona activity at these edges.

The fully-insulated, but as yet unimpregnated, coils are inserted in the stator core. Full-length laminated fiberglass wedges are driven lengthwise into grooves in the inner edges of the slots. A slot filler is placed on the top surface of the coil, with an absorbent felt against the coil. This prevents the wedge from damaging the coil. When finally impregnated with resin, the felt forms a solid blocking for a secure fit of the coils in the slots. Connections between coils are brazed and then insulated with the same micacaeous composite that is used in the ground-wall insulation. The coil ends are braced against movement by GE's Coil-Lock bracing system. The elements of this bracing system include felt blocks, fiberglass roving and rope, glass filled polyester compound, and support rings (Figure 2).

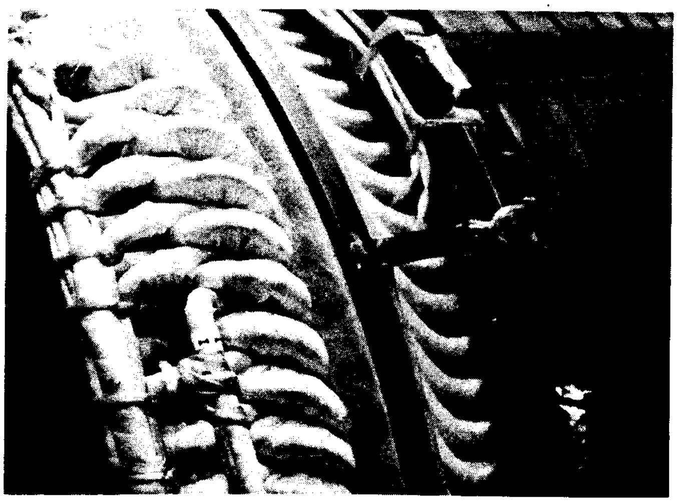


Figure 2. Coil-Lock Bracing Prior to VPI Treatment

The vacuum-pressure impregnation of the complete core and coil assembly fills the coil with epoxy resin, integrating the entire structure. In this process, the strands are bonded together throughout the coil. The insulation becomes filled and bonded, as well, leaving a minimum of voids, and the bracing materials are also filled, solidified and bonded to the coils.

General Electric's third-generation epoxy resin used in vacuum-pressure impregnation of ac motors and generators has been described in the referenced paper[2]. Initially, the first generation epoxy (used throughout the 1960's in Class B machines rated to 7000 volts) was not universally accepted because of limitations it imposed on individual coil replacement. This concern was overcome by the high degree of reliability demonstrated in the performance of thousands of machines in long-term service with minimal maintenance (Figure 3). The solventless thermosetting resin provided a sealed insulation system, and also filled and mutually bonded the supporting structure. It also made the winding resistant to contamination, electromagnetic forces, and the forces of thermal differential expansion. The second generation epoxy which followed (created from controlled-reactivity chemistry) retained these advantages coupled with: lower viscosity to permeate thicker insulation walls; lower dielectric loss to tolerate higher voltage stress levels; and greater thermal stability to upgrade the thermal classification of the insulation system. Thus, Class F motors and generators through 13,800 volts were produced through the 70's. Now, GE's third generation resin (again based on controlled reactivity) offers all the attributes of its predecessors, plus the following characteristics:

- Formulated from commonly available materials, providing the benefits of multiple sources;
- Cures with less heat, for reduced cycle time and lower energy consumption;
- Contains a reactive diluent, allowing viscosity control to ensure penetration and retention of resin;
- Less sensitive to moisture and chemical inhibition of cure, thus simplifying processing controls;
- Improved resistance to thermal embrittlement, resulting in higher temperature capability.

These advantages in performance and processing assure consistent high quality in ac motors and generators.

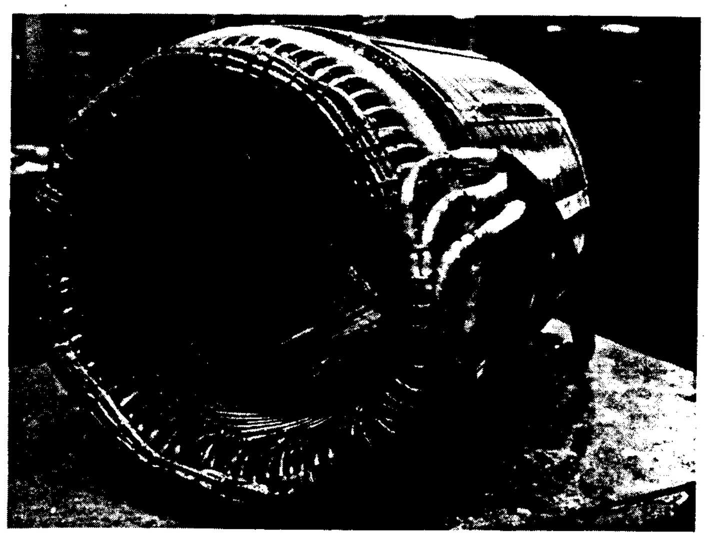


Figure 3. VPI Treated Stator

THERMAL CLASSIFICATION

The IEEE Standard 429, "IEEE Standard Test Procedure for the Evaluation of Sealed Insulation Systems for AC Electric Machinery Employing Form-Wound Stator Coils" is an accelerated cyclic aging test, which predicts the thermal classification for a sealed insulation system. Since this IEEE test is designed as an ***accelerated*** life test, conditions are far more severe than would be expected in normal operation. The duration of these tests is not to be construed as actual insulation life. The test procedure is designed to show the temperature capability of various systems of insulation compared to service-proven systems. The tests are performed on coils, wound in a model stator section and VPI-treated (Figure 4). The deteriorating effects of service on an insulation system can be accelerated by exposure to elevated temperature, as outlined in Figure 5, then to mechanical stress and moisture, followed by a voltage high potential test. In addition, a test of water submersion with high potential applied is used to check the seal of the ground insulation. This testing sequence is repeated until failure occurs.

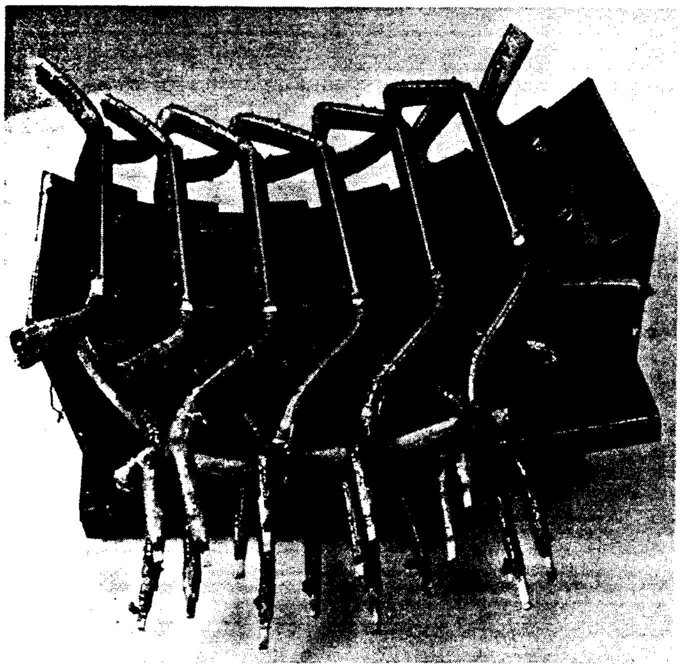


Figure 4. Model Stator Section for Thermal-Classification Testing

THERMAL CLASSIFICATION TEST CYCLE

(IEEE #429 for Sealed Systems)

- Oven Age
- Vibrate
- Humidity Soak (100% and Dew for 2 Days)
- Electrical Proof Test
  - — Turn-to-Turn
  - — Turn-to-Ground
- Water Submersion
- Electrical Proof Test
  - — Turn-to-Turn
  - — Turn-to-Gound

Figure 5

In Figure 6, the X-axis represents inverse absolute temperature. The Y-axis is mean time to failure in hours shown on a logarithmic scale. The upper line shows the performance of GE's third generation VPI insulation system. This line is derived from tests at three specific temperatures, The lower line is based on ten cycles from the time-temperature tables for the testing of Class F insulation and has been confirmed by tests of service-proven systems. Note that the line for the GE system is above and to the right of the base line, with a temperature capability approximately 15 degrees higher and 2½ times longer than the Class F base line at 155°C.

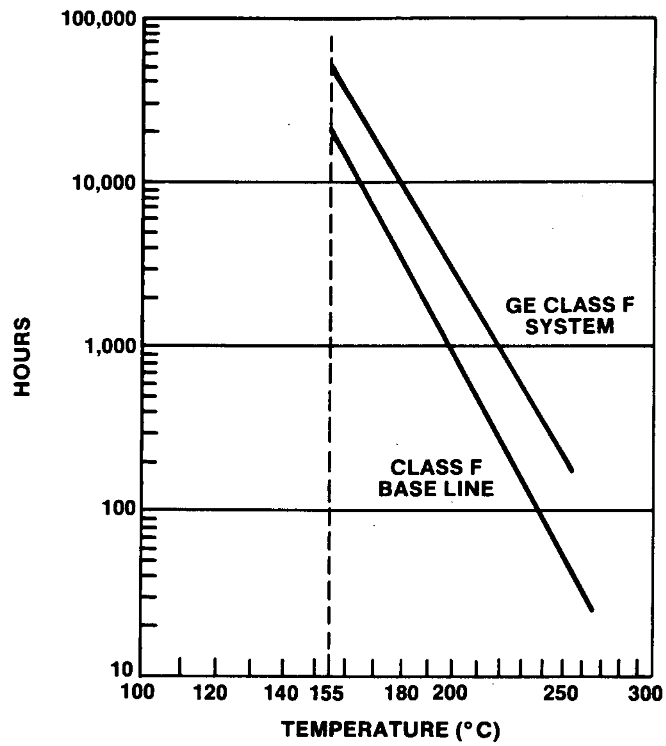


Figure 6. IEEE Std. 429 Time — Temperature Relationship for Sealed Stator Windings

VOLTAGE ENDURANCE

The life of insulation subjected to aging under voltage is an inverse function of the applied voltage stress and frequency. Breakdown is believed due to localized erosion caused by a pattern of corona pulses, which repeats every cycle of applied voltage, and by chemical attack from the oxidation products which results from ionization of air in the voids. In acquiring voltage endurance test data, coils are fitted with metallic electrodes (Figure 7), and subsequently VPI-treated and cured. Voltage is applied continuously between the conductors and the electrodes until insulation failure occurs.

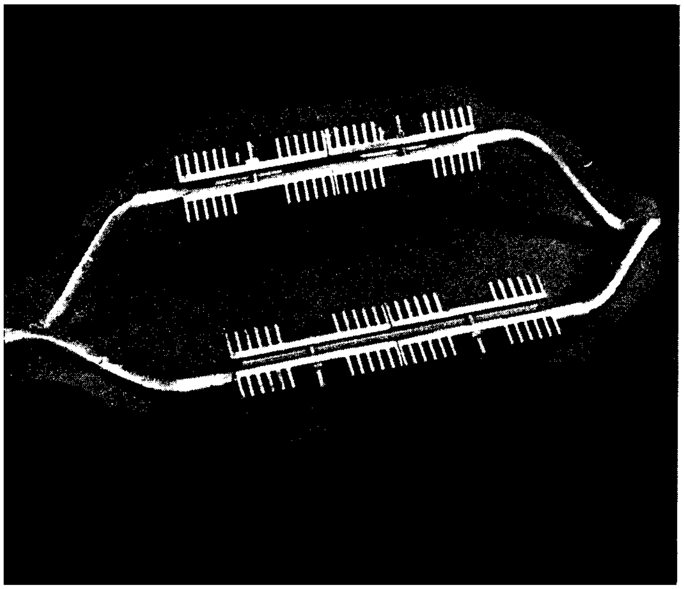


Figure 7. Coil Fitted with Metallic Electrodes for Voltage Endurance Testing

The graph (Figure 8) identifies failure time as a function of electrical stress on form-wound stator coils which contain the vacuum-pressure-impregnated, micaceous ground insulation. The abscissa is life in hours, while the ordinate is electrical stress on the insulation, volts per mil of insulation, 60 Hz RMS. Both scales are logarithmic. Data points for times up to approximately 10,000 hours are obtained using applied voltage at 60 Hz. The longer time points are the result of higher frequency tests (e.g., 3000 Hz failures multiplied by 50 and plotted as the expected life at 60 Hz). Extrapolation to operating stresses in the range of 50 volts per mil of insulation thickness provides an insulation life well in excess of 100 years.

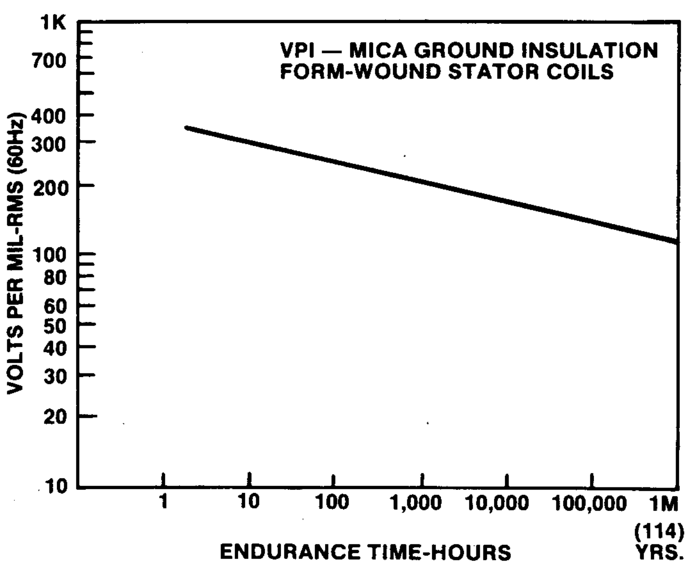
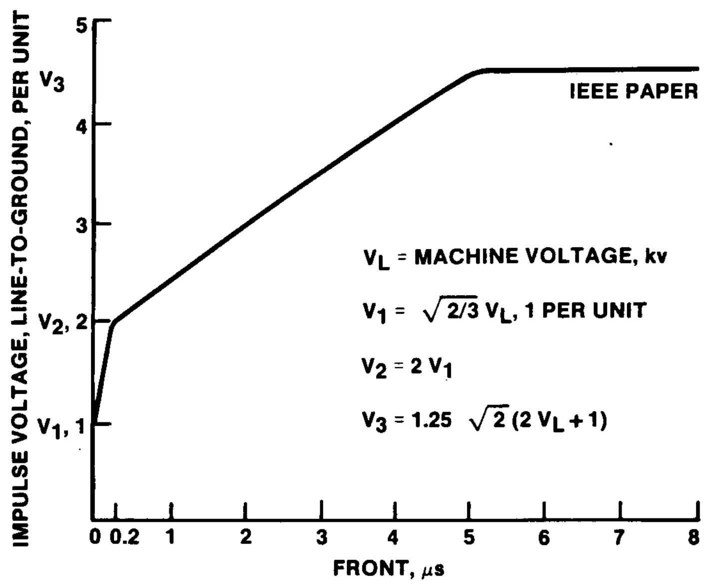


Figure 8. Voltage Endurance

IMPULSE VOLTAGE CAPABILITY

The graph (Figure 9) shows the impulse capability curve[3] established by a Working Group of the Rotating Machinery Committee of the IEEE. The committee concluded that this curve is representative of the impulse capability of ac machines with multi-turn, form-wound coils. For long front waves greater than 5 microseconds, coil and turn voltages are uniformly distributed and ground insulation is limiting. This capability was established at 1.25 times the crest of the 60 Hz ANSI acceptance voltage for finished machines or approximately the dc high potential equivalent of 1.7 times the 60 Hz voltage. In the 0.2 microsecond front range, a large fraction of the incident voltage impulse occurs across the first or terminal coil and, therefore, across the turns in the first coil. The voltage impulse strength is computed at twice the crest of the line-to-neutral voltage or two per unit.



IEEE PAPER 81WM 182-5

Figure 9. Impulse Voltage Capability

Much remains to be learned about dielectric breakdown, such as the type of wave forms encountered, the effects of various wave forms and the cumulative effect of impulse voltage. Some of this work is being done with the support of the Electric Power Research Institute. IEEE Working Group 792 has proposed the trial use of a multi-factor aging test that combines thermal and electrical aging to determine the impulse capability of turn insulation.

A practical, yet positive method to detect faults is needed to proof-test turn insulation in finished stator windings.

Consistent high-quality turn insulation can be assured by proof-testing the turns first in the insulated coil, and again after the coil has undergone the rigors of stator core assembly and wedging (Figure 10). This is done before VPI treatment which increases the dielectric strength of the turn insulation. VPI resin actually doubles the dielectric strength of turn insulation when the turn is wrapped with resin-presaturated mica tape, which has adequate dielectric strength prior to VPI treatment. This result is shown in the probability plot (Figure 11) where the mean direct voltage breakdown of the turn insulation has increased from 12 to 24 KV. VPI treatment also increases the dielectric strength of enameled conductors, but the increase is not as great as in mica-taped conductors. GE's new enamel insulation provides not only a high initial dielectric strength, but also corona resistance, if subjected to repeated voltage impulses. Although the turn insulation is proof-tested for expected voltages, and gains even more capability as a result of VPI treatment, sufficient protection against severe transients should be provided by surge capacitors and lightning arresters.

TURN-TO-TURN PROOF TESTS

(Repeated Surges of 0.1-0.2 Microseconds Front Time)

- Coils after fabrication (prior to insertion in the stator core)
- Coils after assembly in stator core (prior to connection and VPI treatment)

Figure 10

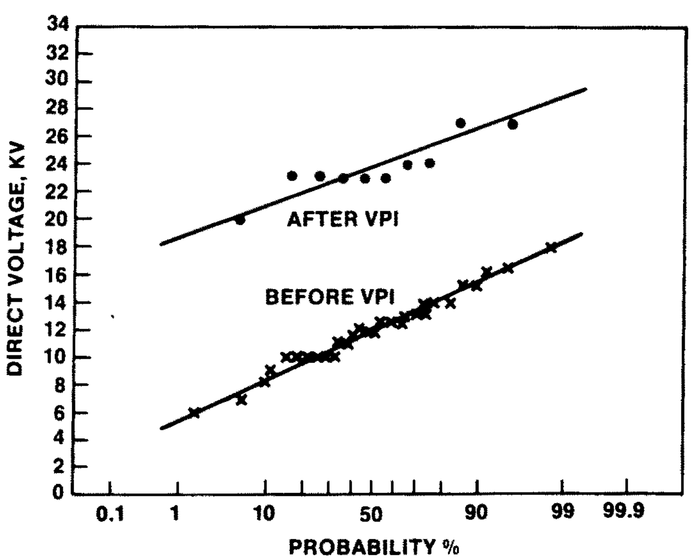


Figure 11. Dielectric Strength Mica Turn Insulation

INRUSH-CURRENT TEST

The Inrush-Current Test was devised by GE and is not covered by any industry standard. Briefly, the test is designed to evaluate the ability of an insulation system to tolerate rapid heating of the conductors, (as in starting a high inertia load) which results in differential expansion of the conductors lative to the iron core.

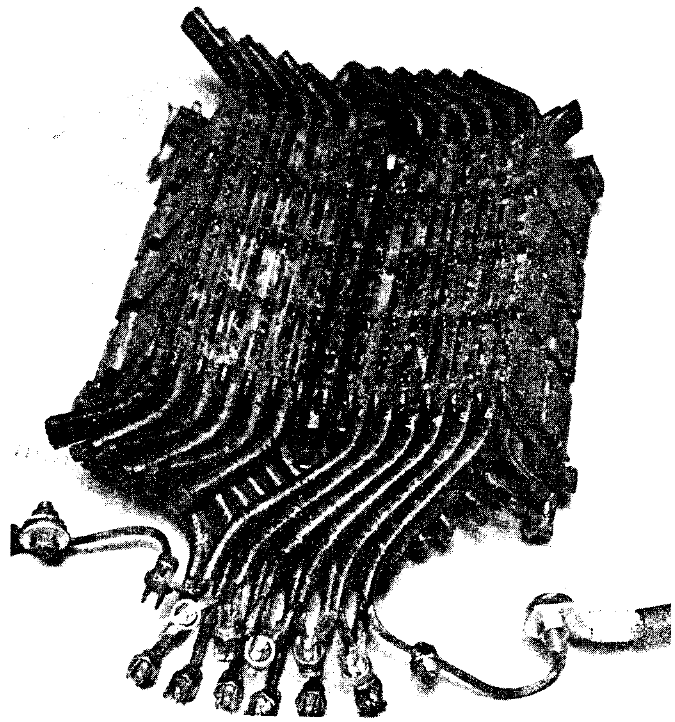


Figure 12. Section of a Stator Winding During Inrush-Current Test

To be assured that new insulation systems are at least equivalent to service-proven systems, coils in a model stator section (Figure 12) are subjected to inrush-current testing. A current density of approximately 25,000 amp/in^2 is imposed on the coils for 20 seconds followed by a cooling period. Due to the duration of the current application period and to the temperature reached by the copper (approximately 190° C), this simulated start-up cycle is more severe that normally found in service. Thermal excursion of the coil relative to the stator core is shown in Figure 13. A test sequence consists of thermal aging the model, followed by inrush-current cycling. While wet from a moisture exposure of 48 hours at 100 percent relative humidity (plus dew), it is electrically proof-tested.

These tests have demonstrated that there is a critical value required in the heat distortion temperature characteristic for any resin impregnant. Above this value, embrittlement, caused by thermal aging, will result in fractures due to the strains of differential expansion. Third generation resin has a heat distortion temperature below the critical value and performs in the micaceous system at least as well as its predecessors in the "inrush-current" test.

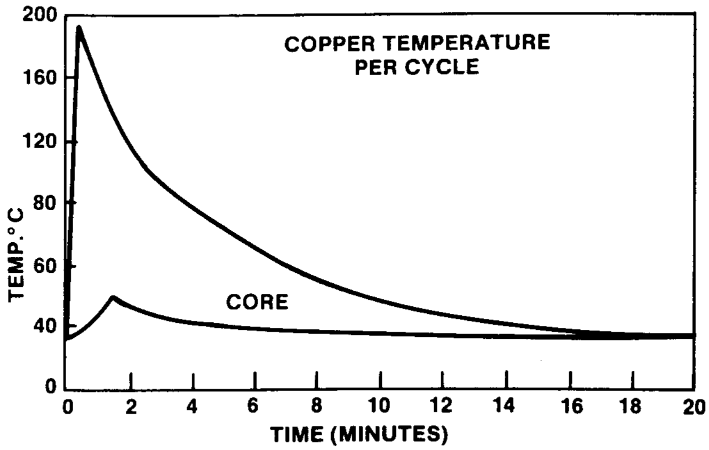


Figure 13. Inrush-Current Test

SYNCHRONOUS ROTOR FIELDS

The thermosetting epoxy compound which has performed successfully for more than 20 years will continue to be used to bond and fill the turns of wire-wound, synchronous-field coils. As in the past, polyester and glass filaments are wrapped around the copper conductors and later impregnated. In addition, an enamel film is applied to the conductor to provide the higher dielectric strength needed to withstand transient voltages imposed on the rotor windings.

A new rotary-curing process, which utilizes solventless epoxy resin, has replaced the previous process of dips and bakes using a solvent-bearing varnish. This provides a more uniform fill of surface irregularities and seals the coil against permeation by contaminants.

WOUND-ROTOR INDUCTION MOTOR

Wound-rotors of induction motors exposed to moisture or conducting dust have a micaceous turn and ground insulation on the coils. The entire winding is bonded and coated with an epoxy in a rotary-curing treatment. This former custom insulation treatment is now the standard offering to provide consistent high quality in the product.

SUMMARY

Factors which can adversely affect the insulation system of motors and generators have been considered in a reassessment of the design and construction processes and in the functional evaluation of model structures. GE's third generation insulation system has evolved from 20 years of experience with VPI-processed stator windings. The latest VPI resin, a modification of proven resin chemistry, assures the consistent high quality of a controlled process. The development of corona resistance in the enamel coating of copper wire provides the voltage endurance characteristic of micaceous insulation. Rotary curing of epoxy resin as the standard treatment for rotor windings on synchronous machines and wound-rotor induction motors provides thorough filling and coating to resist contamination. Thermal endurance testing of Class F stator winding models reinforced by ten years of excellent operating experience, predicts thermal margin versus conventional Class F systems, and assures more thermal margin in stator windings with Class B temperature rises.

REFERENCES

1. A.L. Lynn, W.H. Gottung, D.R. Johnston, J.T. LaForte, "Corona-Resistant Turn Insulation in AC Rotating Machines," (Enclosed).
2. M. Markovitz, W.H. Gottung, G.D McClary, J.R. Richute, W.R. Schultz, Jr., J.D. Sheaffer, "General Electric's Third Generation VPI Resin," (Enclosed).
3. IEEE Working Group Progress Report, "Impulse Voltage Strength of AC Rotating Machines," *IEEE Transaction*, PAS-100, (August 1981), p. 4041.