Guide for Electric Motor Stator Winding Insulation Design, Testing and VPI Resin Treatment

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Guide for Electric Motor Stator Winding Insulation Design, Testing and VPI Treatment

1009700

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REPORT SUMMARY

The Large Electric Motor User Group (LEMUG) has sponsored a number of studies and reports concerning motor repair methods, tiered motor maintenance and now this report on Electric Motor Stator Winding Insulation Design, Testing and VPI Resin Treatment.

Background

Because of the focus by utilities on producing power as efficiently as possible, the reliability of major motors in utility power plants is being examined much more carefully. In-service failures are to be avoided and when motors have to be repaired, plants want to ensure proper repair methods are applied. LEMUG has produced motor rewind specifications to ensure that plants are knowledgeable of motor repair work.

Objective

The objective of this study was to develop a user guide for the vacuum-pressure impregnation (VPI) process for medium voltage stator windings. The guide discusses the principle materials and practices used to manufacture stator windings and include material relevant to random wound stators. The goal was to provide insight into the true role of resin and processing in achieving a proper stator treatment.

Approach

This work builds on the earlier “Guide for Rewinding and Reconditioning Medium Voltage Electric Motors” EPRI EL-5036-V34. Final Report March 1996. The investigation of available VPI resins is placed in the context of the entire winding system: conductors, wire coatings, turn insulation, ground insulation, coil manufacturing and VPI processing.

There is significant new material on epoxy, polyester and hybrid VPI resins as they apply to the process of rewinding medium voltage motors. These resins are an important an ingredient in the production of reliable motor rewinds.

EPRI Perspective

Resins are continuously being improved by the resin manufacturers. Class H resins are common now. It is believed that the increase in resin temperature capability has been derived from the increase in glass transition temperature of the particular resin which extends the important electrical and mechanical properties at higher temperatures. Some resins are designed for multiple-use – form wound motors as well as random wound motors. This is often done in order to increase resin turnover. Resins for 13.2 kV class windings tend to be special with the best of electrical properties and lower viscosity. The maintenance of resin properties while the resin is in storage and in-use continues to be a significant concern.

Key Words

Stator Treatment
Windings, Coils
Resins: Epoxy, Polyester
Vacuum-pressure impregnation, VPI
Form wound, Random wound.

EXECUTIVE SUMMARY

This user guide for the vacuum-pressure impregnation processing of medium voltage stator windings discusses the principle materials, practices and standards used to manufacture, install and test motor stator windings to ensure good quality. The Guide is presented from the point of view of the entire winding system including conductors, wire coatings, turn insulation, ground insulation, insulation qualification, manufacturing, testing and VPI processing.

Key standards and related factors useful in producing a quality and reliable insulation system are brought out in this guide. These are as follows:

1. IEEE Standard 275-1992 *Evaluation of Systems of Insulating Materials for AC Machinery Form-Wound, Preinsulated Stator Coils, Machines Rated 6,900V and Below*: This standard provides a methodology for the qualification of insulation systems for the commonly used Class B, Class F and Class H insulation systems. Basically, insulation systems have to demonstrate 20,000 hour life at the limiting temperature of the insulation Class by sample coil tests at elevated temperatures and by regression analysis.

2. IEEE Standard 1553-2002 *Standard for Voltage Endurance Testing of Form Wound Coils and Bars for Hydro Generators*: To qualify an insulation system, usually rated 13.8 kV or higher, the accelerated aging test is often used to satisfy the purchaser or the manufacturer that the proposed insulation system is of equal or better quality than a previously used system that has passed the test. In this test a higher than rated voltage stress is applied for a standard period of time at a specified temperature to simulate aging during machine operation. For 13.8 kV coils the test is for 30 kV at 100ºC for 400 hours or for 35 kV at 100ºC for 250 hours. This test is conducted on sample coils and is considered to be an objective test.

3. IEEE Standard 522-1992. *Guide for Testing Turn to Turn Insulation on Form Wound stator Coils for Alternating Current Rotating Machines*. For new motors, IEEE Std. 522 calls for an impulse-type test with a fast rise time of 0.1 micro sec. to 3.5 times rated voltage and peaking in 1.2 microseconds at 5 times rated voltage. In general, the coils should have sufficient ground wall and turn insulation to withstand this impulse voltage within the envelope described in Figure 3-2 of this guide. Quality rewound motors must also pass this test. The winding must be totally devoid of moisture when impulse and hipot tested at somewhat lower test values before VPI treatment. The required dryness can be reached by vacuum treatment of the wound stator to remove all moisture.

4. Excerpts from appropriate ASTM Standards that relate to impregnating resins are included for reference and completeness.

5. The description of the chemistry of epoxy and polyester resins along with their evolution is discussed to provide some insight into the complexity of these marvelous liquid solventless compounds which along with the VPI process have vastly improved the reliability and performance of medium voltage electric motors and generators during the past half century.

6. Quality VPI resins used in VPI insulation systems are reviewed from manufacturers published data sheets. The following key technical factors that would identify the best resins were selected:
    - Dielectric Constant @ 150ºC
    - Dissipation Factor @ 150ºC
    - Volume Resistivity, ohm-cm @ 25ºC
    - Helical Coil Bond Strength, lb. @ 150ºC

The rationale for selecting these particular properties is as follows:

Since the stator winding insulation operates with alternating voltage, the capacitance of the insulation is the principal dielectric barrier with mica, fiber glass and resin being the main insulation components. A high dielectric constant of the resin represents the best in the capacitive dielectric property.

A low dissipation factor would indicate a low resistive current loss resin.

Volume resistivity was selected to show which resin would provide the best properties for DC testing, such as megohmmeter, PI, absorption and DC hipot testing.

Helical coil bond strength was selected as being the best measure of mechanical strength which is important for holding the insulation system together at operating temperature including tapes, bracing, blocking, ties, and bonding of coils to the slots. It is also an indicator of the glass transition temperature. A high glass transition temperature shows a resin with good electrical and mechanical properties at elevated temperatures.

7. Key VPI processing steps

Good VPI processing practices are as important as good resin selection. The precise procedure for the VPI process is always defined by the resin supplier. The resin supplier often requires monthly resin samples to verify that the resin is within specifications for chemistry and viscosity. Often, thixotropic resins are used to improve retention of resin within the insulation during the baking process. Key VPI processing steps include preparation, vacuum treatment, pressure treatment and oven cure.

Preparation includes verifying several critical items; resin temperature in the storage tank, resin viscosity, accuracy of the oven temperature monitor and the vacuum gage. Preparation includes applying a release agent to motor parts that should not be coated with resin such as end bell fits, protecting motor lead cables from resin ingress, spot welding one or more thermocouples to the back of the stator to later verify actual stator iron temperature during impregnation and during cure, preheating the oven to a specified temperature and heating the stator to a specified temperature.

Vacuum treatment includes placing the stator which has been preheated to a recommended temperature into the vacuum tank and drawing vacuum to a specified vacuum such as 1.0 mm of Hg or less and holding the vacuum for a prescribed time such as 1 hour. The vacuum is then used to transfer resin from the storage tank to the VPI tank and sufficient resin is drawn to cover the stator by 3 inches. The vacuum is then released and air enters the VPI tank.

The resin is then pressurized to a specified level, such as in an example in this guide of 90 psi per hour per kV of motor voltage. The pressure should be held as long as is reasonably possible such as 8 hours overnight.

The pressure is then used to transfer the resin back to the storage tank and the wet, impregnated and drained stator is placed in a preheated oven with the connection end down so that any resin run-off will coat the connections. The quick application of heat will cause the resin to gel and prevent excessive run-out

The final bake is on the order of 10 hours at 325ºF. One VPI treatment may be sufficient, but often two treatments are used, particularly when the NEMA water submergence test has been specified.

8. Satisfactory resin impregnation can be verified by the one or more of the following tests:
   - Partial Discharge Tests
   - Power Factor Tip-Up Test
   - Capacitance Test
   - Sample Coils
   - Water Immersion Test of Stator
   - Water Immersion Test of Sample Coil

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

The two key elements of this Guide are as follows:

- Provide technical information on commercially available synthetic epoxy, polyester and copolymer resins that are in use for vacuum-pressure impregnation (VPI) of medium-voltage stator windings.
- Provide guidance on the process for using these resins in the VPI treatment of windings.

Beyond this, the objective of this study is to develop a user's guide for the vacuum-pressure impregnation process for medium voltage stator windings. The guide will discuss the principle materials, methods and tests used to manufacture motor stator windings including form wound and random wound windings. This report presents details of synthetic resins that are commonly used for vacuum-pressure (VPI) treatment of medium voltage motor stator windings in electric motor repair shops, and describes in detail the vacuum-pressure processing treatment procedure for using these resins.

1.1 Exceptions

- Nuclear plant, Class 1E qualified, motors should not be repaired to this Guide since it may introduce design changes that negate the qualification. Guidelines on the repair of such motors are provided in EPRI Report NP-6407 Guidelines for the Repair of Nuclear Plant Safety-Related Motors (NCIG-12). However, the material in this document may be useful for providing insight into the process of repairing Class 1E motors.
- While this Guide may contain quality control and assurance requirements it does not attempt to cover all material and workmanship issues. Such issues should be addressed by ensuring that the repair facility has a recognized in-house quality control and assurance program, e.g. ISO 9002, or 10CFR50 Appendix B qualification.

Before presenting information on resin descriptions and VPI treatment procedures, to put the subject matter into perspective, a discussion is presented of the basics of motor insulation including the following items, because there is much more to the successful completion of a stator rewind than the resin and VPI treatment:

- winding temperature standards
- winding temperature measurement

- insulation system temperature qualification
- conductor, turn, and ground wall voltage capability
- insulation systems available in motor repair shops
- coil testing
- coil manufacturing
- advantages of synthetic resins in stator insulation systems
- advantages of the VPI treatment over some other systems
- VPI treatment process

1.2 Insulation Temperature Classes

Motor ventilation, winding temperature, and the capability of the winding insulation to tolerate heat and voltage stress determine a motor's ability to carry its rated load over a long life span. To clearly present the significance of motor temperature it is necessary to introduce the subject of motor insulation systems. Through experience and technology developments, these motor winding insulation system materials are capable of insulating the energized conductors of motor windings from the steel stator core and other metal parts. Not only must the material withstand the applied voltage, it must also withstand the high temperature of conductors, mechanical and electromechanical vibration forces, moisture, chemicals, and abrasion by dust and dirt. With correct winding design and motor application, a 40 year life is realistic. Considering the operating temperature range of 130°C (266°F) for Class B insulation to 180°C (356°F) for Class H insulation and the constant voltage stress, insulating materials for stator windings are very specialized materials.

Class A, B, F, and H are standard insulation classes for induction and synchronous motors[1]. The limiting temperature rises for these insulation classes are shown in:

Table 1-1. The type of insulation used in a motor depends on its operating temperature and, to some extent, its voltage rating and application. Motors are specified by ambient temperature, temperature rise and insulation class.

Insulation systems are classified as follows:

Class A -This insulation system is one that can be shown to have suitable thermal endurance when operating at the limiting Class A temperature specified in the temperature rise standard for the machine.

Class B -This insulation system is one that can be shown to have suitable thermal endurance when operating at the limiting Class B temperature specified in the temperature rise standard for the machine.

[1] References 1 and 2

Class F -This insulation system is one that can be shown to have suitable thermal endurance when operating at the limiting Class F temperature specified in the temperature rise standard for the machine.

Class H -This insulation system is one that can be shown to have suitable thermal endurance when operating at the limiting Class H temperature specified in the temperature rise standard for the machine.

Class A is an older classification. Class A insulation is not used for power plant motor rewinds. Class A insulation is still used for some small motors in portable electrical tools. The Class A insulation system for large motors formerly consisted of such materials as paper, shellac, cotton, and wood, which later gave way to improved materials for higher temperatures and higher electric stress such as fiberglass, Dacron® mica, synthetic resins, and plastic films. With its many years of successful service, Class A insulation system is retained as a reference system for industrial motor insulation systems and as a base of comparison for newer higher-temperature insulation classes.

Class B is the current standard, with F and H used for higher-temperature applications. It is common to specify Class F insulation for motors with Class B temperature rise to achieve a significantly longer thermal life.

The following tables list the limiting temperature rises for these insulation classes.

Table 1-1[2]
Limiting motor temperature rises,°C
Motors with 1.0 Service factor

Stator Winding	Method of Temperature Determination	Class A Insulation	Class B Insulation	Class F Insulation	Class H Insulation
All HP Ratings	Resistance	60	80	105	125
1500 HP and Less	Embedded Detector	70	90	115	140
Over 1500 HP, 7000 V and Less	Embedded Detector	65	85	110	135
Ever 1500 HP, Over 7000 V	Embedded Detector	60	80	105	125

NOTE: The resistance and embedded detector methods of temperature measurement are discussed in Section 1.4.

[2] Reference 1

Table 1-2
Limiting motor temperature rises,ºC
Motors with 1.15 Service Factor at Service Factor Load

Stator Winding	Method of Temperature Determination	Class A Insulation	Class B Insulation	Class F Insulation	Class H Insulation
All HP Ratings	Resistance	70	90	115	135
1500 HP and Less	Embedded Detector	80	100	125	150
Over 1500 HP, 7000 V and Less	Embedded Detector	75	95	120	145
Ever 1500 HP, Over 7000 V	Embedded Detector	70	90	115	135

1.3 Service Factor Rating and its Effect on Motor Performance

Since 1930, induction motors have been available with a 1.15 service factor[3]. The service factor indicates a permissible horsepower loading that can be carried continuously at rated voltage and frequency. The 1.15 service factor infers a l0°C margin for operation above rated maximum temperature for an insulation class. Thus, with a 40°C standard ambient temperature, temperature rises, including hot spot allowance, can be shown for motors with and without service factor for different insulation classes. The maximum temperatures shown in Figure 1-1, sometimes called total temperatures, are theoretical maximum allowable operating temperatures that cannot be directly measured.

[3] Reference 3

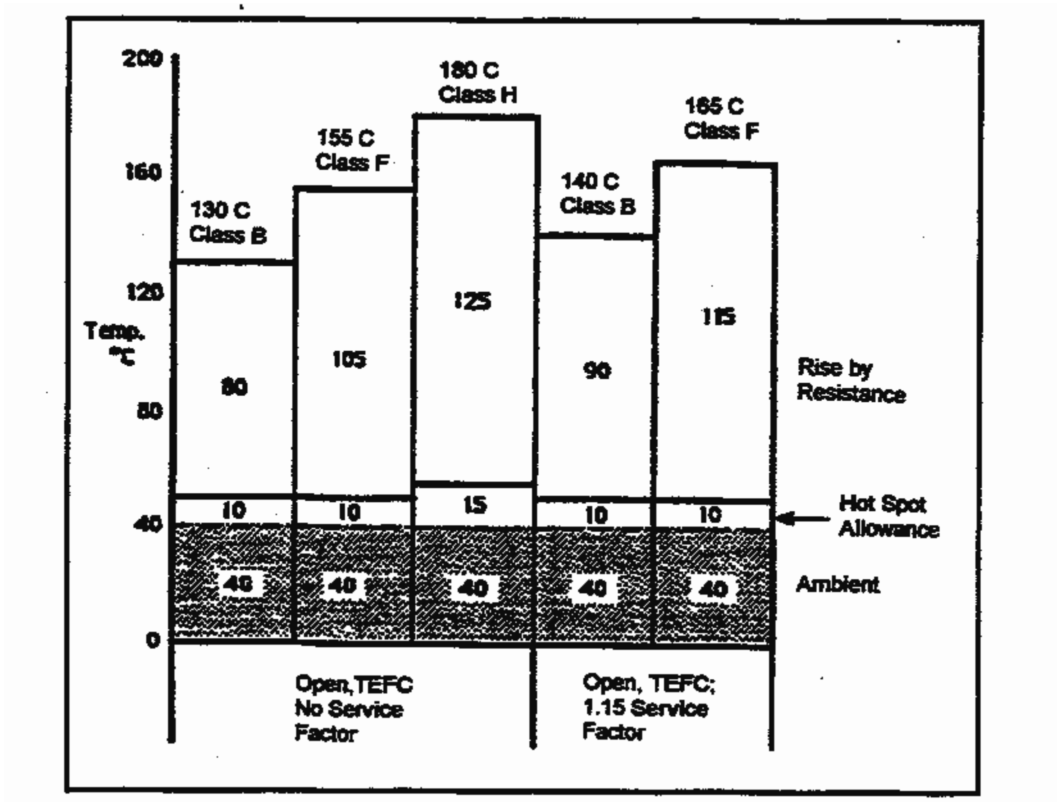

Figure 1-1
Limiting Temperatures for Class B, F, and H
Insulation Systems Showing the Effect of Service Factor

Operation at service factor rating does not imply the same torque margin as operating at rating. For instance, for a 1750 hp motor with a 1.15 service factor rating, a comparison of temperature rise, starting torque, and breakdown torque is shown in Table 1-3.

Table 1-3
Effect of overload operation on available torque
for a 1750 hp motor with 1.15 Service Factor

	1750 HP Load	2000 HP Load
Load, p.u.	1.00	1.15
Temperature Rise, °C	66.00	88.00
Starting Torque, p.u.	0.60	0.53
Breakdown Torque, p.u.	2.00	1.74

The torque values listed in Table 1-3 are shown to demonstrate the concept that operating above original nameplate horsepower rating has an implied effect on the amount of torque margin.

1.4 Effect of Excessive Varnish or Dirt Buildup

The effectiveness of the ventilation system in transferring heat from the copper conductors to the cooling air can be seriously impaired by buildup of additional heat insulating layers of dirt, coal dust, fly ash, or insulating varnish which also become a cooling air restriction. End windings and core ventilation ducts should be kept clean, and periodic dips and bakes of insulating varnish or resin should be used with caution. More dips and bakes are not necessarily better

1.5 Temperature Measurement

The temperature of stator windings of medium voltage motors is usually by resistance temperature detector (RTD) or thermocouple. Six temperature detectors (TDs) are usually located between top and bottom coils in the stator at six locations, and axially, at the center of the core. The TDs are usually distributed two per phase. The RTD is a coil of very fine wire of known resistance. Temperature of the RTD is determined from its change in resistance as the temperature of the winding increases with motor load.

The alternate temperature measurement method is the resistance method. With this method, the resistance of the stator winding is recorded while the motor is not running and is at ambient temperature. It is measured again after the motor has been operating and the temperature is stabilized. The measurement is made from the leads after the motor has been tripped. Temperature is determined from the two resistance measurements, one hot and one cold:

$$t_t = \frac{R_s}{R_t}\left(t_s + k\right) - k$$

where:

R_s = winding resistance, ohms, corrected to specified temperature t_s
t_s = specified temperature for R_s, ºC.
R_t = test value of winding resistance, ohms, at temperature t_1.
t_t = temperature of winding when resistance was measured, ºC.
k = temperature coefficient of resistance: 234.5 for copper.

The temperature measurement by resistance is an average value for the entire winding and may not be close to the hottest part of the winding. The RTD is located on the outside of the coil and thus does not measure the temperature of the copper in the winding. Also, the TD may not be at the hottest part of the winding. To compensate for the difference in TD measured temperature or for resistance temperature determination, and the actual hottest winding temperature, a 10ºC or 15ºC hot spot allowance, depending on voltage, is typically allowed by standards, as shown in Figure 1-1.

2 QUALIFICATION OF INSULATION SYSTEMS FOR TEMPERATURE CLASS

For medium-voltage motors, tests for qualifying a new insulation system for temperature class are given in IEEE Std. 275[4]. It describes standard dimensions for laboratory formette equipment for simulating stator slots used to test models of form coils. Specified times and temperatures are provided for aging the coil samples with temperature. Mechanical, moisture, and voltage-stress exposure of the samples are also specified. Figure 2-1 shows a typical test setup for simulating the slots to hold coil samples for formette testing. The formette sample should include all of the major components of the insulation system to be qualified including slot wedges, mid sticks and end winding bracing.

Test results of the samples of the new insulation system are compared to tests results on a known insulation system to establish that the new system is at least as good as the reference insulation system.

Underwriters Laboratories Standard UL1446 is an accepted standard for the thermal qualification of random wound insulation systems used in low-voltage motors. It is widely used by repair shops, which lack laboratory facilities of their own. Without this standard, or the use of the insulation manufacturer's qualified systems, a repair shop is not capable of qualifying an insulation system for temperature class.

The concern with any electrical insulation system is its operating temperature capability and the degradation of the insulating materials over time when exposed to that temperature.

[4] Reference 4

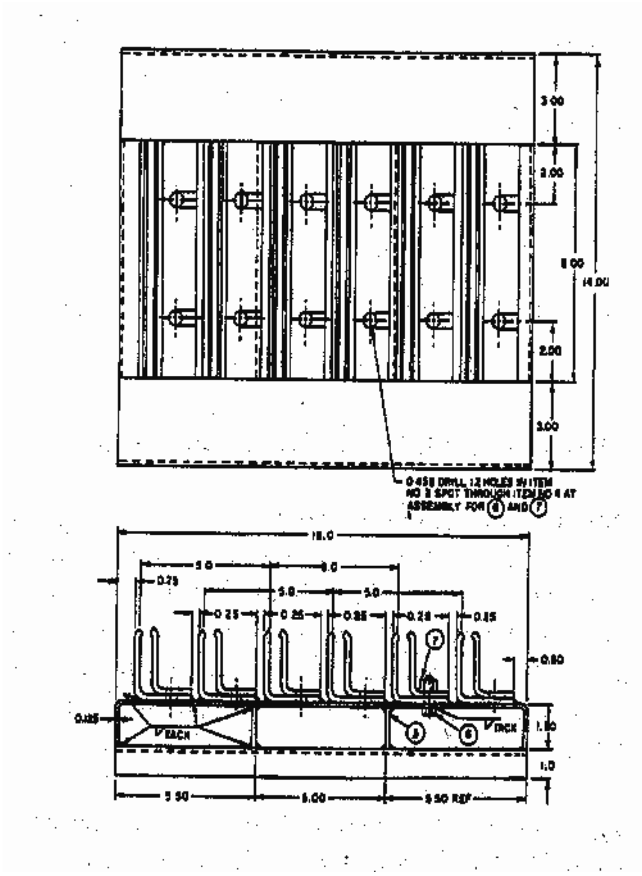

Figure 2-1
Test Fixture for Holding Coil Samples For Formette Testing

2.1 The Arrhenius Equation

Insulation systems are typically evaluated using the theoretical Arrhenius equation, which defines the temperature dependence of reaction rates.

$$Ln(r) = \frac{Ea}{Kb}\frac{1}{T} + A$$

Where:

r = reaction rate
E_a = activation energy (eV)
K_b = Boltzmann's constant (8.617 x 10-5eV/ºK)
T = absolute temperature (OK)
A = constant
Ln = natural logarithm

This equation can also be expressed as:

$$r = Ae^{\frac{Ea}{Kb}\frac{1}{T}}$$

To determine insulation life from aging test data, the Arrhenius equation takes the form:

$$t_1 = t_2 e^{\frac{E_a\left[\frac{1}{T_1} - \frac{1}{T_2}\right]}{{}^oK}}$$

where:
t1= time at aging temperature, hours
t2 = time at service temperature, hours
T1 = aging temperature, °K
T2 = service temperature, °K
°K = 273 + T°C

$$\frac{T_1}{T_2} \text{ must be } <1$$

As a result of experience in testing and qualifying motor insulation systems, a generally used Arrhenius Rule is that remaining insulation life is reduced by 50% for operation for every 10°C increase in temperature. Thus, average insulation life decreases rapidly with increasing temperature above the temperature limit of an insulation class. Consequently, a cool-running motor will have a much longer insulation life.

Typical insulation life versus temperature curves for motor insulation are shown in Figure 2-2[5] for Class A, B, F, and H insulation systems. Insulation life is shown at 20,000 hours. The Arrhenius curve approach is a widely accepted and highly successful empirical method for qualifying insulation. Experience with insulation application, development and qualification has shown that the 20,000 hour extrapolated life, Figure 2-2, qualifies the Class B, F, and H systems to have an equivalent life of a traditional Class A system, which was generally accepted to be 40 years. 20,000 hours is 2.28 years. How does this correspond to 40 year life?

The basis of the 40 year life projection can be from two perspectives.

- Most motors do not operate at full load and full temperature rise continuously. If there is a 10 % margin in horsepower, a 90ºC rise motor with Class B insulation would operate at 73ºC rise. 73ºC rise plus a 40ºC ambient would yield 113ºC winding temperature which would have a 70,000 hour life (7.7 years from Figure 2-2). If the ambient were 30ºC instead of 40ºC, the winding temperature becomes 103ºC and the life becomes 120,000 hours (29 years from Figure 2-2). Thus, considering horsepower margin and ambient temperature margin, there would seem to be some validity to the concept that 20,000 hour qualified life equates to 40 year life.
- In reference 1.8, the authors indicate that they have a tradition of maintaining one full temperature class margin between the operating temperature and the thermal rating of the

[5] Reference 5

insulation. In other words, for a stator operating continuously at the Class F temperature limit of 155ºC, the insulation system is rated for Class H, 180ºC temperature. This provides, Figure 2-2, 34 year life with 40ºC ambient. With a 30ºC ambient, the expected life would be greater than 40 years.

This analysis of the relationship between a qualified 20,000 hour life and an expected 40 year life for the winding shows the logic in many motor specifications that request a Class F rated insulation system with a Class B temperature rise.

Today's insulating materials used in VPI systems are much better than those of older systems, but new motors are designed with closer temperature and voltage margins than older motors. The Arrhenius curve certainly applies, but its relevance to the ability of a particular motor to accept overload is a complicated question. The answer involves the heat capacity of its insulation system and the inherent margin in the motor. However, rewinding an older motor with a new insulation system should provide a motor with a long life expectancy and/or more current carrying capacity.

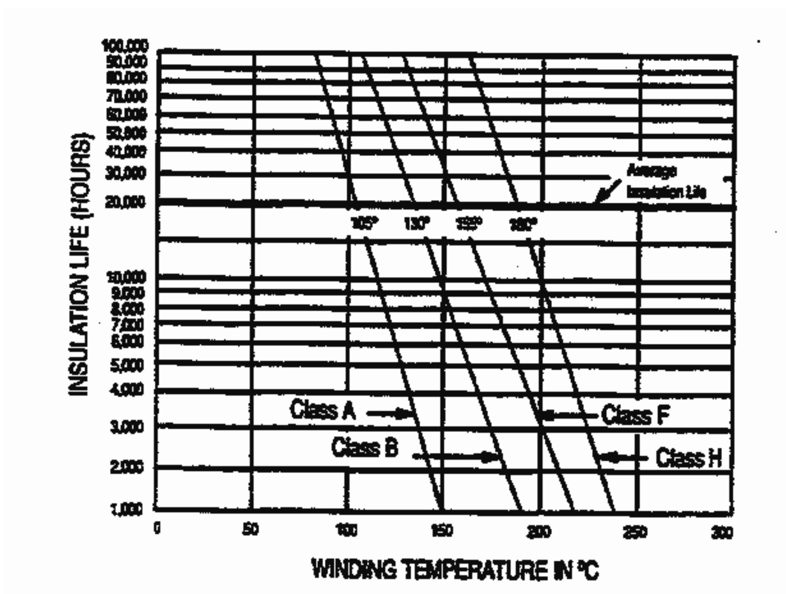

Figure 2-2
Insulation Life vs. Temperature

Reference 6 sheds some light on the complexity of this question of the applicability of the Arrhenius Equation. Synthetic solventless resins have a Tg (glass transition temperature). This is closely aligned with the values of HDT (heat distortion temperature) and FDT (flexural deformity temperature. At this temperature the hard, brittle characteristic of the cured resin changes to a softer more flexible characteristic. The voltage-endurance characteristic improves with higher temperatures but decreases at temperatures above the glass transition temperature. The glass transition temperature can be high or low, depending on the amount of flexibility designed into the insulation system.

Thus, the synthetic resin-impregnated insulation system may or may not follow the Arrhenius curve for expected life at elevated operating temperature, considering the effects glass transition temperature on voltage endurance. The Arrhenius curve applies for temperature degradation of the organic materials in the insulation system, but it appears to be a complex issue -- not as simple as expressed by the commonly used rule of insulation life halved for each 10°C increase in operating temperature above rating.

Organic materials used in stator winding insulation include all man-made materials other than the inorganic materials such as mica and glass fibers. Organics would be Dacron®, Nomex®, resins: epoxy, polyester, copolymer, varnishes and paints. For example, the mica materials used in winding insulation is good for 650ºC maximum, whereas the best organics are good for 220ºC maximum.

For anticipated operation of a motor at an elevated temperature, it is best to check with the motor manufacturer or the insulation system supplier.

3
DESIGN OF INSULATION SYSTEMS FOR STATOR WINDINGS

As indicated in Section 1.0, the design, manufacturing and testing of a coil insulating systems must recognize several things:

- The motor will be subject to heat, rotor vibration, possibly dirt and ash, and oil and/or water.
- Thermal cycling may add mechanical stress to the insulation and reduce its life.
- Starting current produces severe electromechanical forces on the end windings.
- The concentrated electric field in the slots has a potentially degrading effect on the insulation whenever the motor is energized.
- Coils may be subject to switching surge voltages that can cause failure of weak insulation.
- Insulation, if not robustly designed, can be damaged during the coil manufacturing and installation processes.
- Continuous aging parameters such as temperature and partial discharge effects when operating in the presence of oxygen can shorten winding life.

Properly designed coil insulation systems can easily tolerate the manufacturing and installation process and whatever switching surges most likely to occur[6]. Impregnation in solventless resin not only improves the ground wall dielectric and mechanical strength but also improves the turn insulation strength, and the heat transfer capability of the insulation.

Motor manufacturers and their suppliers, starting in the 1950s and continuing through the present, have developed improved conductor, turn and ground wall insulation systems using mica, glass, and synthetic materials along with thermosetting, solventless synthetic resins. The result is windings with excellent dielectric and mechanical strength, heat transfer and thermal capability, and good moisture and chemical resistance.

EPRI has funded considerable research on the impulse withstand strength of motor windings. Results of its work have been published, and are listed in the references to this report. The EPRI work and related work[7] has defined the level of switching surge voltages that are present in electric utility power plants. It has also investigated the surge withstand voltage of commonly used turn insulation systems in motors.

[6] Reference 18
[7] References 11-22

As a result of this work, IEEE Standard 522[8] was revised in 1992 to provide improved turn-testing requirements compared to those that have existed in the past. The basic change was in calling for an impulse test with a fast rise time and a peak of up to 5 times rated voltage.

The impulse-testing requirements called-for in the revised IEEE Standard 522 for turn insulation and the time- proven (2E+ 1,000) V ac hipot test for ground wall insulation provide a sound basis for the manufacturing and installation of quality coils for stator windings of ac motors.

3.1 Materials Used in Stator Coils

This section discusses the materials used in the construction of motor stator coils and the basis for selecting these component materials. Insulating materials are discussed by temperature class such as 220°C and 155°C. While these materials are used in Class B, F, and H insulation systems, they do not modify the basic temperature classification of the system. For example, all components of a Class F system do not have to be rated 155°C if the system has been qualified for Class F temperature. Conversely, if all materials are 155°C class materials, the system is not necessarily a Class F system, unless it has been qualified as such.

3.1.1 Standard Rectangular Wire Sizes and Insulation

Standard rectangular wire sizes for medium-voltage motors are identified in the NEMA Wire Book, MW 1000[9], for manufacturing new motors and for rewinding motors. This publication also provides the following information for wire insulating materials:

- Dimensions
- Adherence and flexibility .Elongation
- Heat shock
- Spring.-back
- Dielectric strength
- Completeness of cure

3.1.2 Bare Wire

Dimensions and corner radii are provided for rectangular bare wire in NEMA Publication MW 1000. The insulation covering is described, the voltage capability of the wire is specified, and flexibility and adherence of the coating is described along with elongation and spring-back requirements. Standard wire dimensions, nominal thickness (in millimeters and inches) and nominal width are provided.

[8] Reference 10
[9] Reference 7

3.1.3 Enameled Wire Breakdown Voltage

Table 3.1 is typical of the information in Publication MW 1000 on the breakdown voltage of different enamel wire coatings and the effect of adding glass and polyester glass +covering to enameled or bare wire. While the enameled wire has breakdown voltage on the order of 1500 to 2000 V ac, it may, according to the standard, also have allowable surface areas with breakdown voltages on the order of 500 to 900 V. The addition of the glass fiber adds 90 V per mil for the added material or something on the order of an additional 540 V in breakdown capability. The applied level of voltage is normally a fraction of the breakdown voltage.

Table 3-1
Wire Coating Characteristics

Enameled Wire Covering	Thermal Class ^{o}C	Min. Breakdown Voltage	Min. Breakdown Voltage (See Note 1)
Polyamide, Heavy	220	1,500	500
Polyamide, Quadruple	220	2,500	900
Polyester (Amide)(Imide)			
Heavy	200	1,500	500
Quadruple	200	2,500	900

Note 1: The higher value is the minimum breakdown voltage for three of four electrodes during a 60 Hz steady ramp of voltage up to breakdown. The lower value is the minimum breakdown voltage for the same test for the fourth electrode.

3.1.4 Glass Fiber Wire Covering Over Bare or Enamel, Breakdown Voltage

Double polyester fiber glass (DDG) over bare wire or DDG over heavy film provides a conservative wire covering for medium voltage motors and it is often used in rewinds, if there is enough space in the slot. The DDG adds about .012 inch of build to the wire, .006 inches for each dimension and adds 90 volts per mil or 90 x 6 = 540 volts breakdown strength of the insulation.

To summarize, a heavy enamel wire coating can have a breakdown voltage rating of from 500 to 1500 volts, a quadruple enamel wire coating can have a breakdown voltage rating of 900 to 2500 volts. DDG can have a voltage breakdown of 540 volts. DDG is a superior mechanical covering for magnet wire and, when used over an enamel coating, it provides a good combination of voltage breakdown strength and mechanical strength. Enamel or DDG coatings are typically used for operating voltages up to 50 volts per turn.

3.2 Turn Insulation

Figure 3-1 shows how wire insulation is integrated into the insulation of a coil. The wire insulation by itself may be adequate to serve as turn insulation, or it may be necessary to provide dedicated turn insulation as in Figure 3-1. In addition to the wire insulation (also referred to as conductor or strand insulation) plus the dedicated-turn insulation, there is the ground insulation. The ground insulation consists of all the insulation components between conductor and the iron of the slot, i.e., conductor insulation, turn insulation, and ground wall insulation.

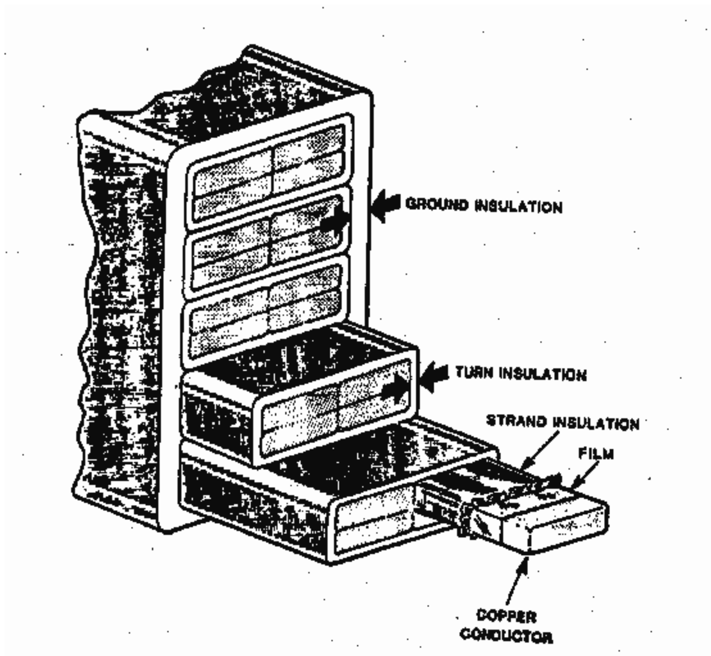

Figure 3-1
Stator Coil Insulation Components

3.2.1 Selection of Turn Insulation

There are three methods for selecting turn insulation. One is based on the operating voltage per turn, the second on core length, and the third on the impulse test voltage per turn.

3.2.2 Operating Volts per Turn Method

An example of the peak operating volts per turn is as follows:

$$\text{Volts per Turn } = \frac{\sqrt{2}}{\sqrt{3}} \frac{V_r}{N k_d K_p}$$

Where:

Vr = rated line-to-line voltage

N = series turns per phase

K_d = distribution factor

K_p = pitch factor

Conductor insulation is specified as DDG. Depending on the calculated volts per turn, dedicated turn insulation is added as follows:

Volts/turn	**Dedicated turn Insulation**
>50	one ½ lap layer mica tape
>80	two ½ lap layers mica tape
>120	three ½ lap layers mica tape

This method is based on a high degree of reliability and many years of experience. It recognizes that there is considerable mechanical stress on the conductor and turn insulation during the coil forming and coil installation procedures. The double polyester glass over heavy film provides mechanical as well as electrical protection.

3.2.3 Specified Core Length Method

Based on experience, and considering machine horsepower and voltage, one successful user specifies that all motors with a core length of 26 in. (660 mm) or longer must have dedicated turn insulation. When dedicated turn insulation is specified applying this rule, use the same criteria as the volts per turn method in 3.2.2 or the impulse voltage method of 3.2.3.

3.2.4 Impulse Voltage Method

For new motors, IEEE Std. 522[10] calls for an impulse-type test with a fast rise time of 0.1 micro sec. up to 3.5 time rated voltage and peaking in 1.2 microseconds at 5 times rated voltage. In general, the coils should have sufficient ground wall and turn insulation to withstand this impulse voltage within the envelope described in Figure 3-2, Figure 2 in Reference 10.

Repair shops generally have impulse testing capability for replacement motor windings. IEEE Std. 522 provides guidelines on the magnitude of surge voltage peak values to be used for individual coils. Surge comparison testing is commonly done to ensure no turn-to-turn shorts. There are no standard test values and practices vary widely. Typically, a reduced repetitive surge peak voltage should be on the order of the reduced dc hipot test voltage for green coils for testing prior to VPI treatment, Section 5.1, and as indicated in Section 6.6 of IEEE Std. 522.

[10] Reference 10

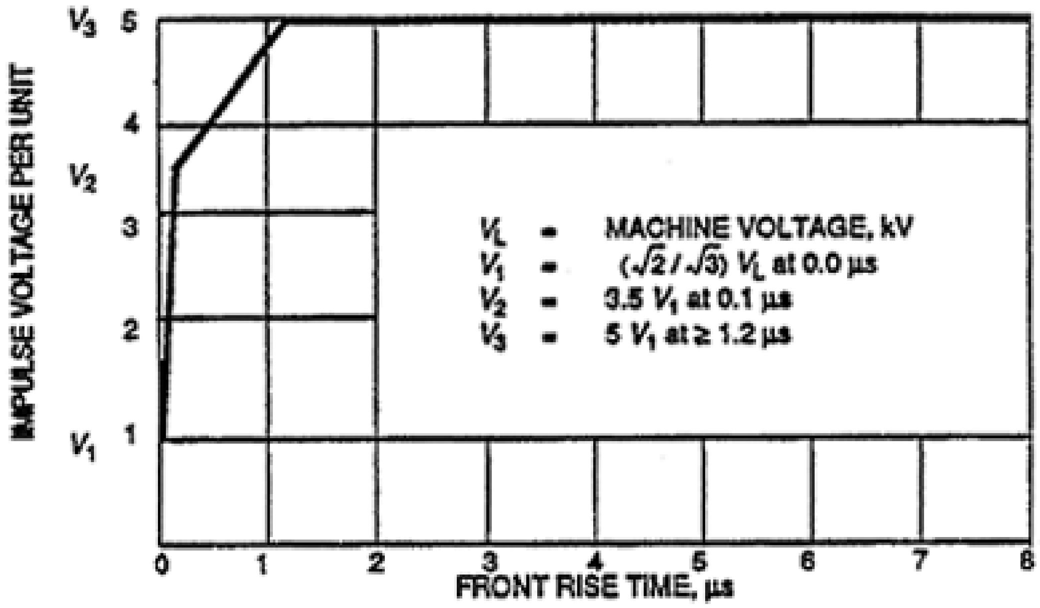

Figure 3-2
IEEE Std 522 Coil Impulse Envelope

3.2.5 Impulse Breakdown Strength

The EPRI published test data[11] for commonly used wire and turn insulation for a 0.2 micro sec rise time surge voltage test follows:

Table 3-2
Impulse Breakdown for Wire Insulation

Wire Coating Material	Varnished = V Unvarnished = U	Voltage , kV
QML = Quadruple polyester amide-imide	U	12.5
QML = Quadruple polyester amide-imide	V	17.0
QML DGG = DDG over QML	U	18.0
QML DGG = DDG over QML	V	34.0
Mica DG = Single Daglas with one ½ lap mica tape	U	12.0
Mica DG = Single Daglas with one ½ lap mica tape	V	32.0

The effect of additional varnish or resin treatment to the QML wire or taped turn is clearly demonstrated from this test data, particularly with the mica tape over single Daglas samples. From this information, one can infer for a vacuum-pressure impregnated system the following impulse withstand voltages:

[11] Reference 11

Table 3-3
Impulse Withstand Voltage for Wire or Turn Insulation

Wire or Turn Covering Rating	Withstand kV
QML	17
QML DDG	34
QML one mica	32
QML two mica (32 + 15)	47
QML three mica (47 + 15)	52
QML DG one mica (34 +15)	49
QML DG two mica (49 + 15)	64
QML DG three mica (64 + 15)	79

Thus there are several combinations of enamel, fiberglass, and mica tape that can be the basis of turn and conductor insulation for coils, depending on the rated machine voltage.

3.3 Ground Insulation

Ground insulation consists of either layers of insulating tape or sheet material commonly called a cell wrapper. These materials usually consist of a backing material, such as glass or polyester cloth, with a thickness of .002 in. (.0508 mm), a layer of mica paper with a thickness of .002 to .004 in. (.0508 to .1016 mm) and another fiber glass or polyester mat or cloth layer. Sometimes a .0005 in. (.0127 mm) layer of polyethylene film is substituted for one of the cloth layers, but this is not acceptable for VPI type coils as the film will inhibit resin impregnation. Total mica tape thickness usually runs .0075 to .008 inches thick.

The mica paper component may be fully cured, or a partially cured (B-stage) condition depending on the final resin processing system. These tapes and cell wrappers are designed for a particular insulation system includes wire covering, turn insulation, ground insulation, an outside protective layer of polyester or fiberglass cloth, and an impregnating resin to bond all of the material together with no voids.

Mica is a mineral silicate appearing in nature in a form that can be split into ever- thinner sheets. It is the best electrical insulating material found. All quality insulating systems for medium-voltage motor coils contain mica and fiberglass since neither material is damaged by partial discharge from voltage stress.

The cell wrapper forms an excellent insulation for the slot cell part of the coil since it has no joints. However, the insulation is tapered at the end of the cell wrapper, and layers of tape are used to insulate the end winding part of the coil. Some object to the scarf joint between the end of the cell wrapper and the tape layers, and prefer that the entire coil be taped. Others are concerned that a long cell wrapper will be difficult to impregnate with resin in the VPI process. With the effective bonding resins available, cell wrapper and fully taped coils have equivalent insulating capability, but the cell wrapper takes up less slot space.

4
AVAILABLE INSULATING SYSTEMS FOR REPAIR SHOPS

Improvements to insulation systems used in the medium-voltage electric motor industry for the past several decades, along with the recent improvement in turn-test requirements for motor coils, have led to high-quality insulation systems for new motors.

For rewound motor stators, the perception of consistent quality may not be so clear and hence this report which attempts to clarify, or at least identify the many issues involved in the quality motor rewind. Along this line, following is a description and discussion of the available insulation systems used in motor repair shops.

4.1 Dry System

The dry system can be used when the motor repair shop is not equipped with vacuum-impregnation facilities. It can also be used by manufacturers who do not have to meet a stringent qualification test or specification. The dry system is not widely used, but, if a machine cannot be removed from the plant to a repair facility, it may be the only practical system.

This system consists of a standard wire covering, such as QML or QML DG, and a ground wall made up of fully cured mica tape, consisting of a bonded layer of 0.0002 in. thick polyethylene film, a layer of .005 in. mica paper and a layer of 0.004 in fiberglass tape. The fully cured tape allows the coils to pass the high potential test, and the wire coating is sufficient to allow the coil to pass the impulse test.

The system, without good VPI in solventless resin, does not have the long-term partial discharge withstand capability and has neither the mechanical strength nor moisture resistance of impregnated systems. Further, while the polyethylene film provides high initial dielectric strength for passing the hipot test, in time, it will disintegrate under the thermal stress and partial discharge, exposing any latent defect from manufacturing.

4.2 Varnish System

Insulating varnishes are widely used in electric motor repair shops to insulate the stator windings of low-voltage motors that have random windings. Insulating varnish consists of a resinous material and a thinner. The thinner reduces the viscosity of the resinous material to improve its coating and impregnation capabilities. During the baking cure of the varnish, the thinner, which is an aromatic, evaporates, leaving a tough insulating film that improves the dielectric, mechanical, and moisture resistance.

Considering solvent evaporation, a varnish with 50% solvent would seem to provide a 50% coating of wires in the slot. In fact, studies of random wound stators have revealed a 12.5% coating of the wire at the center of the slot length. The reason is that solvents deep in the slots do not have a chance to migrate to the surface, and consequently boil in the slot during baking, pushing the resins out of the slot area. Multiple dips and bakes in insulating varnish do little to improve the internal insulation that may contain voids because, at the completion of the first cure, the ends of the slots may be sealed for additional varnish entry.

Insulating varnishes are totally unsuitable for VPI of medium-voltage motor coils or windings. When the thinner evaporates, voids remain in the insulation. These voids can allow internal partial discharge to develop, which can then result in coil failure. Multiple dips and bakes in insulating varnish do little to improve the internal insulation that may contain voids.

4.3 VPI Insulation System

Several developments in the insulating materials industry in the last 50 years have contributed to improvements in motor winding insulation systems:

- Very thin and uniform thickness fiberglass and polyester cloth materials serve as carriers for mica-insulating materials in insulating tapes and sheets.
- Thin paper made of pulverized mica has led to uniform thickness and uniform dielectric strength for mica-insulating tapes.
- Synthetic, solventless epoxy and polyester resins for vacuum-pressure impregnation of motor coil-insulating materials.

Synthetic solventless resins, first introduced into electric machinery manufacturing in the 1950s, have provided a quantum improvement in the dielectric strength, mechanical strength, and moisture and chemical resistance of motor winding systems. All of these properties have led to improved initial and long-term reliability for motors.

The importance of VPI using solventless resin may not be uniformly appreciated. According to Reference 9, the surge voltage withstand of non-impregnated insulation systems is less than one-half that of impregnated systems. Some major repair facilities use solventless polyester resins for winding impregnation, others use epoxy resins. The question asked is which is better - Either system is usually acceptable and both are far superior to a non-impregnated system. The epoxies have traditionally had better bond strength and better moisture and chemical resistance than polyester resins. According to one expert, epoxies have better electrical properties and polyesters have better high temperature properties.

Some epoxy resins can produce serious skin irritations and other nasty reactions after constant exposure to wet resin. Material safety data sheets (MSDS's) should be reviewed with personnel prior to any possible exposure. Polyester resins generally do not produce these reactions, and for this reason are preferred by some shops. Some monomers used in solventless polyesters do have flammability, vapor inhalation and/or excessive shrinkage factors. New polyester-resin chemistry makes their bond strength and moisture resistance characteristics similar to those of epoxies. Each electrical motor impregnating resin is usually designed for a specific purpose or for a set of specific purposes. Accordingly, each resin has its own special properties of dielectric loss, heat-distortion temperature, shelf life, viscosity, and health safety.

The great advantage of the VPI of stator windings is the removal of all air from the insulation layers during the vacuum cycle. All air spaces are filled with resin as resin is introduced into the processing autoclave to flood the winding. Pressure is introduced to force the resin into all unfilled spaces in the insulation and coil structure. The pressure is then used to return the excess resin to the storage tank, and the coils, now filled with resin, are cured at an elevated temperature in an oven. To prevent loss of resin during processing, some resins are modified for “thixotrophy” properties. That is the ability of the resin viscosity to reduce as pressure is increased while in the VPI autoclave and for the viscosity to increase when pressure is removed to retain resin in the coils.

During rewind, many motor windings are made up of dry, uncured mica tapes. These dry or "green" coils are wound into the stator, and the entire stator is treated in the vacuum pressure autoclave and cured in an oven. This system of manufacture and VPI treatment is called the post-impregnation, or global VPI process.

The post-impregnation process results in coils that are well-bonded to the stator slots and provide a well-bonded end-turn bracing system. VPI is preferred for large motors, since it eliminates vibration damage from loose coils in the slots and end windings. For a long core length generator, bonding coils to slots will eliminate coil vibration, but may cause shear stress from differential expansion rates between copper and insulation and insulation and core. The shear plane between copper and insulation can create voids resulting in partial discharges in the region of the turn insulation which may damage the turn insulation. The shear plane between the slot side and coil side can result voids and allowing partial discharges that can cause severe damage to the corona suppression system and ground wall insulation.

4.4 B-Stage or Resin-Rich Insulation Systems

An alternative to the VPI system is the B-stage or resin-rich insulation system. The mica tapes are made with partially cured or B-stage tapes. In the B-stage epoxy has a non-liquid, waxy feel and can be handled without significant problems of dermatitis. The tapes contain a surplus of resin, and hence the term resin-rich.

Coils manufactured with the resin-rich system have their straight sections cured in a hot press to manufacturing tolerances. The temperature of the press is hot enough to cause the resin to flow, hopefully filling all air spaces to eliminate voids or air pockets in the coils. Excess resin usually flows axially into the end winding region of the coil which is usually cured in an oven. This curing of the end winding is done after the coils are wound, wedged, braced and connected to form the three-phase winding. This scheme of manufacturing makes a coil far superior to the dry insulation, type coil, but probably not quite as good as the global VPI-type coil for motors, especially in the end winding. One advantage of the B-stage or resin-rich system is that the resin viscosity needed for good impregnation is not a factor in the design of the insulation system. Such characteristics as dielectric loss and heat distortion temperature can be optimized without regard to vacuum pressure impregnation capability. Another advantage is the elimination of the need to store resin and maintain resin quality for long periods of time.

One manufacturer has been seen to VPI treat a fully cured resin-rich stator winding to improve chemical resistance and improve end winding mechanical strength.

4.5 Brush-on Resin

It is possible to manufacture coils for 2,300 V and 4,000 V motors with resin brushed over the wire bundle and between tape layers. This method produces a better coil than one produced by the dry system or the varnish system, but is not of the consistent quality of a vacuum-pressure impregnation system.

4.6 Why the Concern for Insulation Voids

Vacuum pressure impregnating an insulation system accomplishes several things in one operation. The VPI process seals the windings against moisture penetration. It provides an essentially void-free insulation system if adequate resin penetration is achieved. It bonds the coils to the slot, it forms a solid end winding support system, it improves the electrical strength of the insulation and it makes a very solid mechanical structure of the winding to resist magnetic forces that occur during starting.

A void free insulation system is very important in medium and high voltage motors and generators. When a motor is energized, a voltage stress is present across the insulation. If a void is present, there is a voltage across the void. If the gradient across the void is high enough, electrical discharges will take place across the void. These are called partial discharges because they do not go between conductor and ground. If electric discharge occurs, it causes erosion of organic materials such as resins, polyester fibers, and wire enamel, leaving dry glass fibers and dry mica particles. Without wire enamel or impregnating resin, coil failure will follow.

When this occurs, severe damage may be done to the winding and stator iron. A portion of the stator iron will have to be repaired or replaced depending on the extent of the damage and the machine will have to be rewound or at least partially rewound.

If the voids are small enough, the voltage gradient across the voids is below the corona inception level. Small void size can be accomplished with a B-Stage insulation system or a VPI insulation system.

The goal in the use of a VPI system is to eliminate the voids that occur in most other insulation systems. No manufacturer can produce a totally void free insulation system. There will always be micro- voids. Therefore the VPI insulation system is called an "essentially void free system".

The voltage that appears across the micro-voids is small enough to eliminate the possibility of partial discharges across the voids.

The size of the void and the intensity of the electric field are a concern because electric discharge can occur within the void. The correlation between field intensity and void size is typically given by the Paschen Curve[12], Figure 4-1, which defines the breakdown strength of air for different spacing of parallel plate electrodes at one atmosphere of pressure and 20°C. As can be seen from Figure 4-1, there is a range of void sizes for which air breaks down at relatively low voltage levels.

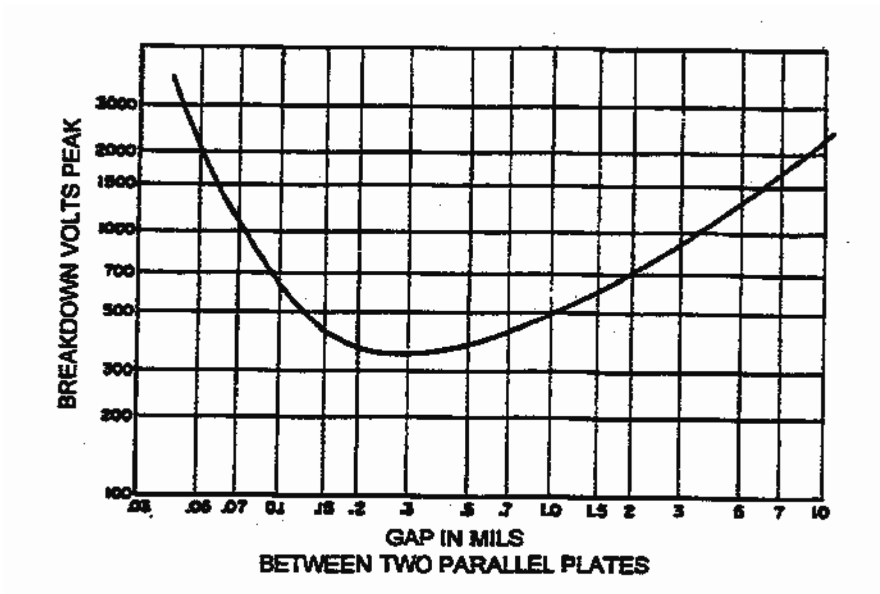

Figure 4-1
Paschen Curve for 1 Atmosphere of Pressure and 20ºC

According to Reference 45, for medium voltage motors, for a dissected sample VPI coil the largest void size in the insulation of the coil's slot section and in first bend out of the slot shall bend greater than 0.012 inches (0.3 mm) in the direction perpendicular to the insulation and 0.118 inches (3.0 mm) in any other direction. These limits may be doubled for insulation beyond the first bend.

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12 Reference 9

5
COIL MANUFACTURING

Part of the overall equation for a good set of coils for a motor rewind is the coil manufacturing technique. The wires should be in tight alignment, that is, the wires should be in good vertical alignment and they should be in close contact with each other. Otherwise, valuable slot space can be wasted. Bends should be gradual. Sharp bends can result in “keystoning”, the build-up of wire thickness on the inside of the bend. Such build-up can result in pressure points that can cause wire-to-wire or turn-to-turn shorts.

If slot space is at a premium, it may be necessary to dip either the coil loop or the spread coil in varnish and hot press the cell to minimize the vertical space between wires and to achieve good wire alignment and strand bonding. Other methods of consolidating the slot section of the coil are the use of B-stage epoxy mica turn tape or B-stage brushed-on resin, either of which is followed by hot pressing prior to applying the ground wall tape.[13]

Turn tape, if used, and ground wall tape should be applied tightly without wrinkles. If it is necessary to press the coil to get it to slot size, it is better to do an inside press with wire bonding before the tape is applied than to press loose tape and develop wrinkles. Wrinkles can result in hipot failures.

5.1 Coil Testing During Manufacturing and During Installation

Coil test levels for green coils prior to VPI vary among manufacturers of replacement coils for medium voltage motors. Repair shops also differ on the values they use for testing green coils during assembly into the stator as evidenced by the values used and recommended in the following table for two coil manufacturers for 4,000 volt windings. Not all shops agree on the test levels to be used when installing green coils. Some test at much lower levels. If any testing is to be done, the winding should be baked or vacuum dried prior to testing to remove any moisture that may have entered the tapes from the atmosphere during the winding period.

[13] Appendix A of Reference 25

Table 5-1
Test Voltage Levels for Green Coils, 4,000 Volt Rating

Test Level, Volts	Factory Hipot DC	Factory Surge	Before Connect Surge	Before Connect DC Hipot	Final Hipot DC	Final Surge After VPI and Cure
CMI	6,900	14,000	2,600	9,500	15,844	11,430
Ken Coil	8,375	8,375	7,100	4,400	13,200	11,430
IEEE 522		6,854-9,139				
Ref. 23		4,000	4,000	4,000	4,000	11,430

IEEE Std. 522 suggests a test of 60-80% of the recommended line-to-line voltage peak impulse level for green coils before impregnation and cure. Recent work by one manufacturer recommends caution for testing green coils[14] because of the possibility of the coils absorbing moisture. This recent study indicates that it is possible to develop partial discharge carbon tracks in the insulation if high impulse test values are used after the coils are inserted into the slots. With this study, an impulse peak level and a dc hipot test level for green coils would be on the order of 1,000 volts per layer of mica tape.

5.2 Background Material Summary

From this discussion of winding temperature standards, winding temperature measurement, insulation system temperature qualification, coil insulation components, available insulation systems in service shops, coil testing, advantages of using synthetic resins in stator insulations systems, and the advantages of VPI treatment, it becomes apparent that synthetic resin VPI systems have advantages over many of the other insulation systems that are available in service shops.

Now follows a discussion of commercially available synthetic resins. This in turn is followed by a presentation on the VPI treatment procedure for motor stators.

[14] Reference 23, 24

6
VPI RESINS

6.1 Solventless Synthetic Resins

The solventless synthetic resin used in vacuum-pressure impregnation systems for stator windings of medium voltage motors is one of the key ingredients of the motor's stator insulation system. The other key ingredients are the wire insulation, the turn insulation, and the mica content of the insulating tape containing glass and Dacron® fibers used in the ground insulation. For winding insulation systems rated 6 kV and higher (sometimes even 4 kV), there is the added coil surface corona suppression system. Corona suppression tapes may slow the flow of resin into the insulation system during VPI processing and require a longer treatment time than normal.

This section of this report discusses the solventless synthetic resins used by motor repair shops. From information presented below supplied by resin manufacturers[15], it becomes apparent that there are key characteristics that have been designed into the resins for suitability for the specific purpose of VPI treatment. In essence, there are general purpose resins and special purpose resins. Cost is always a factor in resin selection. Resin is very expensive and it needs to be maintained such that its properties are not degraded. The wider flexibility of application capability of a resin leads to greater usage, hence the availability of general purpose resins that are suitable for both low voltage and medium voltage VPI to 7 kV ratings. Some of the properties of resin design for VPI resins are as follows:

- dielectric strength
- viscosity
- temperature capability
- thixotrophy
- mechanical strength
- maintainability
- gel time
- cure time
- cure temperature
- heat distortion temperature

[15] References 29-38

- multiple-use capability
- cost

For instance, gel time, thixotrophy, temperature capability, multiple-use, mechanical strength and dielectric strength are important factors in quality resins for motor windings for voltages up to 7 kV. In this case, thixotrophy promotes retention of the resin in the winding after the stator is removed from the VPI tank. Fast gel time allows formation of a semi-cured barrier to hold resin in the winding as the stator is heated to its cure temperature. The combination of thixotrophy and fast gel time prevents resin from running out of the insulation as the winding is processed in the bake oven.

On the other hand, resins for high voltage windings (11 kV and higher) need lower viscosity to penetrate the additional tape layers on the coils, and they need the best in dielectric properties.

6.2 Background on Epoxy VPI Resins

The American Standard for Testing Materials has a standard for classifying epoxy resins according to their chemical nature. A summary of the standard follows as an introduction to epoxy resins.

6.2.1 ASTM D 1763 Standard Specification for Epoxy Resins

Scope

This specification covers totally reactive epoxy resins applied as liquids or solids which can be used for castings, coatings tooling, potting, adhesives, or reinforced applications. The addition of hardeners in the proper proportions causes these resins to polymerize into infusible products. The properties of these products can be modified by the addition of various fillers, reinforcements, extenders, plasticizers, thixotropic agents and cross-linking agents, and they can be combined with other reactive products.

Classification

The resins covered contain no hardeners. Resin types are divided into specific groups by their chemical nature:

Type I-Bisphenol A and epichlorohydrin.

Type II-Reaction product of phenol and formaldehyde (novolac resin) and epichlorohydrin.

Type III-Cycloaliphatic and peracid epoxies.

Type IV-Glycidyl esters.

Type V-Reaction product of epichlorohydrin and p-aminophenol.

Type VI-Reaction product of epichlorohydrin and glyoxal tetraphenol.

These types may be further subdivided by grades:

Grade 1- Resins containing no diluent.

Grade 2- Resins modified with a reactive diluent.

Each class of Grade 2 resin can be made from any class of Grade 1 resin.

6.3 Bisphenol A and Aliphatic Glycol Based Resins

Liquid epoxy resins are complex highly cross-linked hydrocarbons that are used with various curing agents, diluents and modifiers to obtain the desired electrical, mechanical, temperature and processing properties. Two typical basic liquid epoxies are bisphenol A and aliphatic glycol based resins that are converted to a thermosetting resin by the addition of a hardener. Bisphenol A epoxy is manufactured from phenol and acetone. Then it is reacted with epichlorohydrin and the byproduct of chlorine is removed with sodium hydroxide to produce diglycidyl ether of bisphenol A (epoxy).

Basic hardeners are polyamines, anhydrides, polyamides and catalytic types. Aliphatic polyamines are used for resins that cure at ambient or moderately elevated temperatures. Some amine-based hardeners can cause skin and eye irritation. The reactivity rate of some anhydrides with epoxies is slow and an accelerator is often used to speed up gel time and cure time. Anhydride-cured epoxies have excellent electrical properties for VPI systems, but in liquid form they are sensitive to absorption of moisture from the air which tends to decrease gel time and increase viscosity. Polyamides are generally restricted to applications under 65ºC. Catalytic curing agents promote epoxy-to-epoxy or epoxy-to-hydroxyl reactions and do not themselves serve as direct cross-linking agents. Tertiary amines, amine salts, boron trifluoride complexes (BCl_3 –complex), and amine borates are examples of catalytic curing agents.

A reactive diluent is used primarily to reduce resin viscosity. Adding a reactive diluent, allows higher filler loading and gives better wetting and impregnation. Preferably the diluent should react with the curing agent at approximately the same rate as the resin and be non-reactive with the resin under normal storage conditions. Some of the reactive diluents are butyl glycidyl ether, aliphatic glycidyl ether, cresysl glycidyl ether and ethylhexyl glycidyl ether. Two diglycidyl diluents are 1,4 butane diol diglycidyl ether and neopentyl glycol diglycidyl ether.

Resin modifiers are used to improve certain mechanical properties and flexibility. Colloidal silicas and clays are used to obtain thixotropic characteristics.

6.4 Novolac Epoxy Resins

Polyglycidyl ether of phenol-formaldehyde novolac, also known as epoxy novolac is another class of epoxy resins. Novolac resins offer the following advantages over bisphenol-A type resins:

- Improved resistance to acids
- Retention of mechanical, electrical and adhesive properties at high temperatures and under wet conditions
- Minimal shrinkage
- Acceptance of a wide range of modifiers and fillers

Modified amines, catalytic curing agents and some anhydrides provide optimum elevated temperature properties for novolac resins. If heat is used to reduce viscosity, polyamides and aliphatic polyamines will react extremely fast.

Epoxy novolac resins have glass transition temperatures ranging from 126ºC to 255ºC. Generally speaking, the higher the functionality of an epoxy resin - that is, the maintenance of electrical and mechanical properties - the higher the crosslink density of the cured resin. In turn, crosslink density, cure schedule, catalyst concentration and type, curing agent type and resin type, help to determine the glass transition temperature. The higher glass transition temperatures obtainable with novolac resins, determines the maintenance of these properties at elevated temperatures.

6.5 Epoxy Resin Development

The early solventless epoxy VPI resin systems used either an anhydride curing agent or a catalytic type, in the Lewis acid family, known as Boron trifloride-monoethylamine complex. The latter was replaced with Boron trichloride amine complex because this resulted in ten-fold improvement in VPI tank stability. Anhydride cured VPI resin systems have also been improved by this same material, at a much lower concentration, as an accelerator.

Today, the simple Newtonian, non-thixotropic VPI resin system consists of epoxy resin, reactive diluent, modifier and curing agent and/or catalyst or accelerator. This type system generally produces a cured coating thickness of around one mil and this works very well in form coil construction.

The thixotropic VPI resins have gone through even a greater evolution. With some of them having been improved more than 20 times to improve thixotropic stability and performance. Thixotropy, in a VPI resin, today may include a number different materials with each at a certain concentration. The “slightly thixotropic resin” results in a system that will maximize retention and mil build and, at the same time, not restrict the resin’s penetration of multiple layer of VPI type mica tape in higher voltage form coils. The random or mush wound stator can be processed in a Newtonian VPI resin system but the number of process cycles required may increase by a factor of three unless special techniques of coil taping and Dacron felt lined slot liners and phase separators are used.

Thermal endurance of VPI resins are generally established by "thermal indices" that are the results of twisted pair aging results and helical coil aging results. Both at three or more temperatures for each wire type. Another more comprehensive and time consuming method is the Ahrrenius approach. Motors or formettes are constructed using the prescribed insulation system. The samples are aged at three or more temperatures with each aging cycle consisting of time at temperature, vibration (1.5 G for 1 hour), thermal shock (-20ºC for 2 hours) and humidification (48 hours with condensation).

In both test programs the result of average aging life of all points are extrapolated to a 20,000 hour temperature level. If the result is 179ºC, the rating is Class F and if it is 180ºC it is Class H.

6.6 Polyester VPI Resins

Polyester VPI resins are made up of four basic components: the base resin that is held in a liquid solution by the second component, the monomer. The third component is the catalyst and the fourth the inhibitor. The monomer reacts with the base resin during the cure and acts as a solvent at room temperature. The catalyst, with the addition of heat, initiates the chemical reaction that causes the resin and the monomer to go from a liquid state to a solid state. Styrene monomer is an aromatic hydrocarbon which under normal conditions is a clear, colorless, flammable liquid. In VPI resins, styrene has been replaced with vinyl toluene which results in a higher flash point temperature.

Conventional baking polyesters are cured at a temperature above 150ºC.

6.7 Hybrid VPI Resin

There are hybrid resin systems that incorporate properties from both unsaturated polyester resins and epoxy resins. The hybrid is cured under the same conditions as conventional unsaturated polyester resins and epoxy resins. It has good bond strength at elevated temperature and good chemical resistance.

6.8 Glossary of Resin-Related Terms

Bond Strength: The measure of force required to break the bond of varnished helical coils of enameled magnet wire.

Centipoises, cps.: Unit of viscosity. Usually measured by the drag on a turning spindle immersed in the liquid, Brookfield viscosity. A force of 0.01 dyne per centimeter.

Film Build: Average build-up of cured resin on one side of a metal panel.

Capacitance: From ASTM D150. That property of a system of conductors and dielectrics which permits the storage of electrically separated charges when potential differences exist between conductors.

Copolymer: A polymer formed by the inter-polymerization of two or more chemically different monomers with each other.

Deaerate: Remove air from other gasses by vacuum. Note that initial deareation after a tank fill can take from several hours to as much a 3 or 4 days depending on the amount, type and condition of the resin.

Dielectric Constant: The property of a material that determines how much charge is stored per unit volume when unit voltage is applied. The capacitance of a material compared with the capacitance of an equal volume of air or vacuum.

Dielectric Strength: The voltage a material can withstand before breakdown occurs - usually expressed in "volts per mil". Interestingly, a thicker section of material has a higher total breakdown voltage but a lower dielectric strength, i.e., dielectric strength for one mil Mylar may be 3,000 VPM, but for 2 mils, breakdown would be only 5,000 volts (2,500VPM).

Dissipation Factor: From ASTM D150 loss tangent, tan δ, - The ratio of the loss index k" to the relative permittivity k' which is equal to the tangent of its loss angle δ or the cotangent of its phase angle θ. When the dissipation factor is less than 0.1, the power factor differs from the dissipation factor by less than 0.5%.

Flash Point: The temperature at which enough vapor is generated to flash if a spark or flame is introduced. The flash point of polyester resins has been increased by replacing the styrene monomer ingredient with vinyl toluene.

Foaming: An accumulation of frothy bubbles caused under vacuum by the expansion of air and other gasses trapped within the resin.

Gel Time: While undergoing polymerization at elevated temperature, certain materials rapidly increase in viscosity indicating transition from a liquid to a gelled condition. The time required to reach this arbitrary high viscosity is called the gel time. This point is registered by the instrument through the closing of an electrical gap actuated by the torsion exerted on a slowly rotating spindle suspended in the test sample. Example: Sunshine Scientific Instrument Co. 1810 Grant Ave. Philadelphia, PA. Model #22.

Glass Transition Temperature: (Not in data sheets). The temperature at which the resin binder in coils become soft and its dielectric constant and dielectric loss factors change. At this temperature mechanical stresses are released and electrical field strength distribution in the mica layers is displaced.

6.9 ASTM Standards for Insulating Material Testing

Resin manufacturers often refer to results of ASTM tests in their data sheets for resins. To provide some understanding of a few significantly relevant ASTM Standards, the following summaries are presented:

6.9.1 D 150 Standard test methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation

Scope

These test methods cover the determination of relative permittivity, dissipation factor, loss index, power factor, phase angle, and loss angle of specimens of solid electrical insulating materials when the standards used are lumped impedances. The frequency range that can be covered extends from less than 1 Hz to several hundred megahertz.

These test methods provide general information on a variety of electrodes, apparatus, and measurement techniques.

6.9.2 D 257 Standard Test Methods for DC Resistance or Conductance of Insulating Materials

Scope

These test methods cover direct-current procedures for the determination of dc insulation resistance, volume resistance, volume resistivity, surface resistance, and surface resistivity of electrical insulating materials, or the corresponding conductances and conductivities. These test methods are not suitable for use in measuring the electrical resistivity/conductivity of moderately conductive materials.

6.9.3 D 3145 Standard Test Method for Thermal Endurance of Electrical Insulating Varnishes by the Helical Coil Method

Scope

This test method covers the determination of the thermal endurance of electrical insulating varnishes alone or in combination with wire insulation. Changes in the helical coil bond strength are used as the test criteria. The coils can be made from bare aluminum or copper wire or from film- or fiber insulated magnet wire.

Terminology

Definitions of Terms Specific to This Standard:

9. Bond strength: a measure of the force required to separate surfaces which have been bonded together.

10. Magnet wire: a metal electrical conductor, covered with electrical insulation, for use in the assembly of electrical inductive apparatus such as coils for motors, transformers, generators, relays, magnets, etc.

Discussion — The electrical insulation is usually composed of a film covering formed from magnet wire enamel applied over a bare conductor. In some specific applications, fibrous coverings, either taped or linear filament served, are also used as electrical insulation. Electrical insulating varnish: a liquid resin system that is applied to and cured on electrical components providing electrical, mechanical and environmental protection.

Discussion — There are two types of electrical insulating varnishes-solvent-containing and solventless. Solvent-containing types are solutions, dispersions or emulsions of a polymer or a mixture of polymers in a volatile, non-reactable liquid. Solventless types are liquid resin systems free of volatile, non-reactable solvents.

Summary of Test Method

Flexural strength of the helical coils is measured periodically after exposure to several aging temperatures. The time to reach an arbitrarily selected value of bond strength at each aging temperature is determined. The logarithms of these times in hours are plotted as a function of the reciprocal temperature

(1/K) to give an Arrhenius plot.

Significance and Use

This test method is used to determine the effect of exposure to elevated temperatures on the bond strength of combinations of magnet wire insulations and electrical insulating varnishes. The results are used as a guide for the comparison and selection of varnishes and combinations of varnishes and wire insulation for specific applications. Test Methods D 1932, D 3251, and D 3850 describe additional tests for determining the thermal endurance of insulating varnishes.

A comprehensive evaluation of thermal aging should include a comparison of the thermal endurance determined in these different ways. This test method is useful for research and product qualification purposes.

6.9.4 D 2519 Standard Test Method for Bond Strength of Electrical Insulating Varnishes by the Helical Coil Method

Summary of Test Method

Flexural strength tests are made on varnish-treated helical coils to determine the force required to break the coil under specified conditions of temperature.

Significance and Use

Values obtained by flexural tests can provide information with regard to the bond strength of the particular varnish, in combination with a particular wire, when measured under conditions described in this test method.

Apparatus

Tensile Testing Machine-An adjustable-speed drive and a suitable instrument for measuring force should be used in breaking the specimen. This may be in the form of one of the generally available tensile testing machines, or may be simply an accurate spring gage and a separate adjustable-speed drive. To cover the range of load strength values which are commonly encountered it is recommended that a multi-range tester be used.

6.10 Consolidation of Resin Manufacturers

There has been a worldwide consolidation of ownership of resin manufacturers within the past 3 years. The ALTANA Chemie group of companies, a conglomerate based in Bad Homburg, Germany now owns P. D. George Company of St. Louis, MO as well as Rhenatech and Weideking in Germany, Dea Tech Siva, Syntel and Camattini in Italy, Tongling Siva in China and Rembrantin in Austria.

P. D. George Company had previously acquired Sterling Varnish and now controls the products of Epoxylite Corporation (July 17, 2001), Guardian Resin Corporation (June 1, 2002), Viking Products (February 28, 2003, Schenectady International Inc. (June 30, 2003), Ranbar Electrical Insulation (January 8, 2004),). Some idea of the degree of consolidation these acquisitions represent is described in the following:

The Epoxylite package included Epoxylite Corporation, Ripley Resin Engineering Company and Epoxylite International.

VIKING Products, a Division of Underwood Industries of New York, Inc., manufactured electrical insulating varnishes, solventless insulation compounds and epoxy compounds for the electrical and electronics industries.

Schenectady International, Inc. (SII) was a private, family-owned company founded in 1906 with headquarters in Schenectady, New York. It was the world leader in the production of alkylphenols, and a leading global producer of performance resins. ALTANA Chemie acquired Schenectady International's global businesses in wire enamels, which are used to insulate magnet wire; and impregnating resins. During 2002, SII achieved sales in these lines of business of about $90 million. As part of this transaction, ALTANA Chemie obtained 100% of the shares in Schenectady Europe GmbH, Hamburg, as well as 83% of the shares in Schenectady Beck India, a company listed on the Indian stock exchange. In addition, ALTANA Chemie acquired Schenectady International's electrical insulation business in the United States, Great Britain, South Africa, Brazil, Mexico, Canada, and Australia.

The Ranbar acquisition included all of Ranbar's electrical insulating varnishes, solventless resins and epoxy compounds for the electrical and electronics industries. Ranbar had purchased the Westinghouse varnish and resin product range in the mid 90s and then introduced a successful range of water-based varnishes and epoxy co-polymer resin products.

6.11 VPI Impregnating Resin Descriptions by Manufacturer

With the diversity of resins, hardeners, modifiers, diluents and additives available for epoxy resins and the complex chemical nature of these compounds, it is easy to understand why resin formulators hold their formulations as proprietary. Many VPI resins, both epoxy and polyester, are rated for Class H temperatures, have good bond strength, 20,000 hour temperature qualification and other properties desirable for medium voltage motor windings.

Following are data sheet descriptions of resins being used by electric motor repair shops by manufacturer. A glossary of the terms used in these data sheets is in Section 6.8.

6.11.1 Epoxylite Corp.

(Now part of ALTANA Chemie)

Epoxylite 478 is presented as a solventless VPI impregnating resin for use with insulating systems rated 7,000 volts and less. It is offered for both form-wound motors and random-wound motors so that a repair shop does not need two separate resins. Epoxylite 478 is a thixotropic resin, that is, resin viscosity reduces with pressure and increases when pressure is removed. With this feature, there is good penetration during the pressure cycle, but less runout of resin after pressure is released after VPI treatment of form wound and random wound stators. Epoxylite has two other versions of this resin: Epoxylite 477 for form-wound coils with a catalyzed viscosity of 1750 cps, and Epoxylite 477GP for high voltage form-wound coils with a catalyzed viscosity of 550 cps. See Appendix 1 for manufacturer's claims for the 478 resin.

Table 6-1
Epoxylite 478 Properties

	Property	Method	Value
1.	**Viscosity**	Brookfield 2 rpm 20 rpm	6,100 cps
2.	**Thixotropic Index**	Brookfield Ratio	2,800 cps
3.	**Impregnating Viscosity**	Ferranti-Shirley (7 cm cone) 36 seconds-1 360 seconds-1	1650 cps
4.	**Thixotrophic Index**	Ferranti-Shirley Ratio	1.1 (no change after 144 hrs @50^{o}C)
5.	**Fillers**	Proprietary	Small amount for viscosity and flow control.
6.	**Diluents**	Proprietary	Proprietary
7.	**Resin**	ASTM-D-1763	Class 2
8.	**Epoxy Assay**		175-195
9.	**Specific Gravity**		1.2
10.	**Hydrolyzable Chlorine, max.**		0.2%
11.	**Color**	Gardner	5 max.
12.	**Heat Distortion Temperature**	ASTM-D-648 4 Hrs 180^{o}C 16 hrs 160^{o}C	 83^{o}C 90^{o}C

	Property	Method	Value
13.	**Hardness**	Shore D Barcol	85 23/20
14.	**Weight Loss**	1,000 hrs, 180°C	2% max.
15.	**Compressive Strength**	ASTM-695	20,000 psi
16.	**Tensile Strength**	ASTM-638-52TD	8,500 psi
17.	**Tensile Strength**	ASTM-D790-49T	$0.54x10^{6}$ psi
18.	**Elongation to Break**	ASTM-D638	6%
19.	**Coefficient of Thermal Expansion**	ASTM-698	$64x10^{-6}$ cm/cm/°C
20.	**Linear Shrinkage**	ASTM-D-2566	1.6%
21.	**Thermal Conductivity**	ASTM-D-2214	$5.3x10^{-4}$ cal/cm/sec/cm^{2}/°C
22.	**Mechanical Shock**	MIL-I-16923	12 ft-lb
23.	**Shelf Life**	ASTM-D-2471	12 mos. @25°C (77°F) No Replacement. Indefinite with Replacement.
24.	**Cure Time**	@150°C	6 hours
25.	**Gel time @ 150°C**	Sunshine Gel Test	14 minutes
27.	**Lap Shear** **Bond Strength** **Random Wound** **Alum to Alum**	ASTM-D-1002 25°C 150°C	 2700 psi 300 psi
28.	**Bond Strength Helical Coil** **Bond** **Strength Spring** **Configuration**	RE2-1987 (5.2) 25°C 75 °C 150°C	 58.8 lb 9.6 lb 5.2 lb
29.	**Q-Panel Retention**	Cured wt./ Drained wt.	65% -705
30.	**Coil Retention**	Cured wt./ Drained wt.	70%-75%
31.	**Freon Extractables**	Pressure Bomb R-22 HCFC	 <0.5% <1.0%
32.	**Moisture Absorption**	ASTM-9-570	.14%/24 hours .19%/48 hours
33.	**Moisture Vapor Transmission**	MIL-1-16923	0.01 gr/sq ft/24 hrs/in @ 38°C
34.	**Flash Point**	PMCC	220°F
35.	**Dielectric strength**	3 mil coating	2500 VPM
35.	**Dissipation Factor** **25°C** **105°C** **130°C** **155°C** **180°C**	ASTM-D-150	 .0032 .0052 .0182 .0908 .0992
37.	**Permittivity** **25°C** **105°C** **130°C** **155°C** **180°C**	ASTM-D-150	 4.564 4.181 4.614 5.610 10.074
38.	**Volume Resistivity** **25°C** **180°C**	ASTM-D-257	 $>10^{16}$ ohm/cm $1.3x10^{9}$ ohm/cm
39.	**Arc Resistance**	ASTM-D-495	120 sec.

6.11.2 John C. Dolph Company

320 New Road P. O. Box 267
Monmouth Junction, NJ 08852-0267
Tel: 732-329-2333

John C. Dolph Company offers a number of epoxy, polyester and hybrid resins, both thixotropic and non-thixotropic, for the electrical apparatus industry. Shown here are data sheets for their two recommended resins for medium voltage motor VPI systems.

Table 6-2
Dolph's Epoxy and Polyester VPI Resins

Resin ID	**Dolphon CC-1118LV**	**Dolphon CC-1305**
Resin Type	Class H VPI Epoxy Low viscosity, Thixotropic	Class H, VPI Polyester Semi-rigid, High-flash
Purpose	VPI, Dip	VPI, Dip
Color		Clear/ Amber
Weight/Gal.		10
Brookfield Viscosity	6000-9000, 1 rpm, 2000-4000, 10 rpm	1000-2500 Spindle No. 1, 2.5 rpm, 77^{o}F
% Non-Volatile	100% Reactive	100% Reactive
Shelf Life @ 25^{o}C	1 year	1 year
Sunshine Gel Time, minutes	18.0 @ 140^{o}C	110-180 @ 100^{o}C, 20-40 @ 110^{o}C
Film Build, mils	3.0	0.9
Flash Point, ^{o}F	>200	554, Tag Open Cup, >200, Seta Closed Cup
VOC, lbs/gal.		
Shore D Hardness 25^{o}C	85	85
% Water Absorption 24 hrs.		
Chemical Resistance	Excellent	Excellent
Salt Water	Excellent	Excellent
Humidity	Excellent	Excellent
10% Sulfuric Acid	Excellent	Excellent
Oil	Excellent	Excellent
Helical Coil Bond Strength, Lb. ASTM-D-3145	60 @ 25^{o}C' 8 @ 150^{o}C	42 @ 25^{o}C, 20 @ 150^{o}C, 14 @ 180^{o}C
Tensile Strength, psi ASTM D-638	10,100	No Data
Dielectric Strength ASTM	2400 v/mil for 7 mil	3500 v/mil for 1 mil
Dissipation Factor **60 Hz** **25^{o}C**	.0031	0.01

Resin ID	Dolphon CC-1118LV	Dolphon CC-1305
55 °C 90 °C 105 °C 130 °C 150°C	.0053 .0079 .063 .091 .117	 .108
Dielectric Constant 60 Hz 25°C 55 °C 90 °C 105 °C 130 °C 150°C	 2.82 2.98 3.00 3.71 3.87 4.73	 3.35 5.36
Thermal Life IEEE 57 UL	20,000 hr @ 180°C 220°C	20,000 hr @ 180°C 220°C
UL Thermal Endurance, °C Twisted Pair MW-35 MW-16 MW-76	 180 220 180	 180 220 180
UL Thermal Endurance, lb to break, helical coil MW-35 @ 25 °C MW-35 @ 150 °C MW-35 @150 °C		 42 20 14
Volume Resistivity Ohm-cm		7×10^{16} @25°C 1.4×10^{13} @150°C
Cure Time	8-10 hours @300°F 4-6 hours @ 325°F	1-1.5 hr 300°C

6.11.3 P. D. George Co. (now part of ALTANA Chemie)

5200 North 2nd Street
St. Louis, MO 63147

P. D. George Co. offers E-833 epoxy resin for impregnating coils of all kinds including high voltage coils. Its E-833 RT is a slightly thixotropic version of the same resin. The viscosity of the E-833 RT resin can be adjusted for particular applications. The properties of these two resins follow:

Table 6-3
Properties of P. D. George E-833 and E-833 RT Resin

Item	E-833 (Formerly Y-833)	E-833 RT
1. Specific Gravity	1.18	1.20
2. Weight/Gal.	9.8	10.0
3. Color	Amber	Clear, Amber
4. Solids Content	100%	100%

5. Brookfield Viscosity **2 rpm** **20 rpm**	Not tested 350-650	1500 – 2000 cps 1000 – 1500 cps
6. Sunshine Gel @ 130^{o}C	30-55 min	23 – 35 min
7. Flash Point **ASTM-D-93**	>200^{o}F	>200^{o}F
8. Shelf Life	6 months @ 25^{o}C in a dry controlled atmosphere	6 months @ 25^{o}C in a dry controlled atmosphere
9. Care of Resin	Hold in storage tank at 15-20^{o}C with slight vacuum or dry air or dry nitrogen blanket. Resin must be protected against moisture contamination.	Hold in storage tank at 15-20^{o}C with slight vacuum or dry air or dry nitrogen blanket. Resin must be protected against moisture contamination.
10. Dielectric Constant **ASTM –D-150 120 Hz** **150^{o}C** **200^{o}C**	6.3 6.3	6.3 6.3
11. Dissipation Factor **ASTM-D-150** **ASTM –D-150 120 Hz** **150^{o}C** **200^{o}C**	0.2 1.7	0.2 1.7
12. Surface Resistivity **ASTM-D-257**	1.6x10^{11} ohms/cm^2	1.6x10^{11} ohms/cm^2

P. D. George's E-881 epoxy resin system is the former Sterling VIPAK system. This 155ºC system consists of glass backed mica paper tape, a shrinkable polyester armor tape and the resin. In this impregnation system, the epoxy and accelerator are in the tapes and the hardener is in the VPI tank. The hardener has a low viscosity of 300 cps which allows good penetration of the tapes and allows this system to be used on 13.8 kV windings. The accelerator provides a fast gel time of 17 minutes at 100ºC or 7 minutes at 150ºC. The shrinkable armor tape reduces the void content as the coils in the wound stator are cured in the oven. The power factor for this system is .05 at 155ºC and the power factor tip-up is less than 1% at 155ºC between 20 and 80 volts per mil.

6.11.4 RANBAR Electrical Materials Inc.

(Now part of ALTANA Chemie)

RANBAR offers several resins that are appropriate for motor repair shops for medium voltage VPI, dip and bake, trickle treat, high voltage coils and low voltage motors. B-9-116 is not a VPI resin for medium voltage motors, but its properties are listed for comparison purposes. Note the relatively high viscosity. The Ranbar resins are listed in the following table with most of their characteristics and properties:

Table 6-4
RANBAR Resins

Resin ID	RanVar 2003	RanVar 2003T Thixotropic	Trirez TSR-190	B-7-373 (B-7-373T Thixotropic)	B-7-619 Thixotropic	B-9-116
Resin Type	Co-Polymer Resin with Catalyst, Viscosity Reducer, Inhibitor Solution	Co-Polymer Resin with Catalyst, Viscosity Reducer, Inhibitor Solution	Epoxy	Polyester Resin with Catalyst, Viscosity Reducer, Inhibitor Solution	Epoxy	Epoxy
Purpose	VPI, Dip, Trickle	VPI, Dip, Trickle	H. V. Form wound Coils	VPI and Dip Class H	VPI Harsh Environment incl. Radiation and Steam	VPI and Dip
Color	Light Amber	Light Amber	Amber Clear	Light Amber	Clear	Light Amber
Weight/Gal.	8.9	8.9	9.9		9.4	9.6
Brookfield Viscosity @ 25°C, cps **2 rpm** **20 rpm**	 450-750	5000±500 2300±200	 500 ± 150	 900-1200	4000 2000	12,000 4,000
% Non-Volatile	100% Reactive	100% Reactive		100% Reactive	100% Reactive	88-90% Reactive
Shelf Life @ 25°C	3 months	3 months	3 months	>3 months	12 months	6 months

6.11.5 vonRoll Isola USA, Inc.

One West Campbell Road
Schenectady, NY 12306
(vonRoll Isola USA, Inc's parent company is vonRoll Isola of Switzerland)

vonRoll Isola offer solventless polyester, solventless polyesterimide, and solventless epoxy resins for medium voltage motor windings:

Table 6-5
vonRoll Isola Resins

Product ID	Diluent	UL System Max Rating	Viscosity 25°C	Gel Time/ Temp.	Cure Time/ Temp	Application
707	Vinyl toluene (VT)	220	900	15 min/ 120°C	2 + hr 150°C	Polyester VPI Resin
711	VT	220	14000/ 5000	15 min/ 120°C	2 + hr 150°C	Thixotropic version of 707 polyester VPI Resin

Product ID	Diluent	UL System Max Rating	Viscosity 25^{o}C	Gel Time/ Temp.	Cure Time/ Temp	Application
3309	VT	240	225	2 min 150^{o}C	2 + hr 150^{o}C	Polyesterimide VPI Resin OK for 17.5 kV
74035		180	8000/3000	10 min 150^{o}C	4 hr 150^{o}C	VPI Epoxy Resin, Motors to 7 kV
74038			900	30 min 170^{o}C	8 hr 150^{o}C	VPI Epoxy Resin for use to 15 kV

6.12 Comparison of Key Resin Properties

To compare key properties of cured impregnating resins, the following have been selected:

- Dielectric Constant @ 150ºC
- Dissipation Factor @ 150ºC
- Volume Resistivity, ohm-cm @ 25ºC
- Helical Coil Bond Strength, lb. @ 150ºC

The rationale for selecting these particular properties is as follows:

Since the stator winding insulation operates with alternating voltage, the capacitance of the insulation is the principal dielectric with mica being the main insulation component. A high dielectric constant of the resin would seem to enhance the dielectric properties of the mica.

A low dissipation factor would indicate a low loss resin.

Volume resistivity was selected to show which resin would provide the best properties for DC testing, such as megohmmeter, PI, absorption and DC hipot testing.

Helical coil bond strength was selected as being the best measure of mechanical strength which is important for holding the insulation system together at operating temperature including bracing, blocking, ties, and bonding of coils to the slots. It is also an indicator of the glass transition temperature. A high glass transition temperature shows a resin with good electrical and mechanical properties at elevated temperatures.

The following table compares these properties for some of the resins presented:

Table 6-6
Comparison of VPI
Impregnating Resins

	Epoxylite 478	**Dolphon CC-1118LV**	**P.D. George E833**	**Ranbar B-7-619**	**Ranbar B-7-373T**	**vonRoll Isola 707/711/777**
Property	**Epoxy for use to 7 kV**	**Epoxy VPI Motors**	**Epoxy VPI Motors**	**Epoxy Harsh Envir.**	**Polyester VPI**	**Polyester VPI**
Dielectric Constant @ 150^{o}C	9.7	4.73	6.3	12.5	6	2.5
Dissipation Factor @ 150^{o}C	0.0908	0.117	0.2	0.437	5	2.1
Volume Resistivity Ohm-cm @ 25^{o}C	$1x10^{16}$	$7.9x10^{15}$	$3.3x10^{9}$	$5x10^{13}$	$6x10^{13}$	
Helical Coil Bond Strength, lb @ 150^{o}C	5.2	8	Not Avail-Able	6	1.5	8

While comparison of these properties is significant, it does not include such important properties as viscosity, gel time, and degree of thixotropy which are important for processing during manufacturing or motor repair, and thus may help to achieve these electrical and mechanical properties.

7
THE VPI PROCESS

Following are two procedures[16] 7.1 for VPI processing of a medium voltage stator using a thixotropic epoxy resin and 7.2 for prosessing of a medium voltage stator using a thixotropic polyester resin. First, preparation of the stator for VPI, and second, the VPI process itself. The procedures are typical of the care that needs to be taken when carrying out the VPI process. The processes will have variances if a different type of resin is used.

7.1 Part 1 – The VPI Process for Thixotropic Epoxy Resin

7.1.1 Preparation of Stator for VPI

11. Record the Repair Shop Job #, motor manufacturer, model number and serial number on the data sheet.

12. Record the temperature of the resin in the holding tank. The acceptable temperature is 68°F to 70° F for form wound motors.

13. Visually inspect the stator and windings for handling damage, cleanliness, and missing or inadequate end turn blocking. Visually inspect the test coils to insure that they are correctly prepared.

14. For motors requiring 2 or more VPI cycles, 2 test coils must accompany the stator, one each for the first of 2 cycles.

15. Record the results of the last penetrating viscosity test on the resin and the date of the test. The penetrating viscosity limits for the resin are 2500 centipoises maximum and 1200 centipoises minimum.

16. Apply release agent to all machined surfaces, motor leads, RTD leads, bolt holes, studs, etc. Apply masking grease to all threaded surfaces and any locations where resin might accumulate.

17. Inspect the stator to insure that it is properly masked.

18. Record the instrument number and calibration due date for the oven temperature monitor, the VPI tank temperature monitor, and the VPI vacuum gauge.

[16] Reference 39

19. Spot weld 2 type J thermocouple to the back of the stator iron 180° apart (if the back of the stator iron is accessible) so that one thermocouple will be at the bottom of the stator.

    – a as it sits in the oven. Attach additional thermocouples to the stator if directed. Attach male type J thermocouple plugs to the end of the thermocouple leads.

20. Weigh and record the stator's weight.

21. Preheat the oven to 325ºF.

7.1.2 The VPI Process

The VPI process in itself is not complicated, but it is exacting, and involves the following steps:

1. Heat the stator to 300ºF. Reduce oven temperature to 250ºF. Allow the stator temperature to drop to 275ºF.

2. Attach motor lead cables and seal each end of each cable with room temperature cure epoxy resin to prevent VPI resin ingress during impregnation.

3. When the stator temperature reaches 140ºF, place the heated stator in the VPI processing tank.

4. When stator temperature reaches 130ºF draw a vacuum (1.0 mm of mercury or less).

5. Hold the stator in the vacuum for a minimum of 1 hour to evacuate all air and all volatile compounds such as oils, solvents, etc.

6. Flood the chamber to a level that is a minimum of 3 inches above the stator coils and lead cables. The resin will be heated by the stator making it less viscous and easier to penetrate the insulation. With the insulation system now void of gasses, it will soak-up resin.

7. Release the vacuum and allow air to enter the processing tank.

8. Pressurize the processing tank to 90 psi. The pressure aids in forcing the resin further into the insulation system. The pressure is maintained for a minimum of 1 hour per kV of motor voltage (or layer of mica tape) or until it is determined or specified by other means (such as capacitance measurements) that the insulation system has absorbed as much of the resin as it can. If there is sufficient time available, maintain the stator in the pressurized resin for 8 hours.

9. By this time, the stator will have given up most of its heat to the surrounding resin. Once the stator has cooled sufficiently to 95ºF, the pressure is released. The reason for ensuring that the stator has cooled, is to be sure that the viscosity of the resin within the insulation has increased sufficiently to prevent the resin from running out.

10. The stator is then placed in a 325ºF pre-heated baking oven. The stator is placed vertically with the connection end down. It is very important that the oven be pre-heated. The quick

application of heat will begin to gel the resin on the surface of the coils before the internal heat lowers the viscosity of the resin within the coils. If the oven were not preheated, resin would flow out of the coils as the heat builds up and lowers the viscosity of the resin within the coils.

11. Once the resin has gelled, the stator can be removed from the oven and either processed through another VPI cycle or have the machined surfaces cleaned.
12. The stator is returned to the oven for a final 10-hour cure. The oven time will depend on the curing temperature, voltage and the type of resin used.
13. Megohmeter test, surge test, and hipot the stator winding at (2E + 1000) volts.

7.2 Part 2 — The VPI Process for Thixotropic Polyester Resin

The following procedure is for VPI of a stator in thixotropic polyester resin courtesy of TVA:

1.0 PURPOSE

The purpose of this procedure is to provide the instructions for vacuum pressure impregnation of electrical windings.

2.0 REFERENCES

2.1 Material Safety Data Sheet (MSDS) for 708 solventless polyester varnish

2.2 MSDS for 709 solventless polyester varnish

2.3 MSDS for 777 solventless polyester varnish

2.4 PSS-n 3.14, "VPI Solution Testing and Maintenance"

2.5 PSS-QAP 2.3, "Quality Assurance Records"

2.6 PSS-QAP 6.5, "Control of Measuring and Test Equipment"

2.7 PSS-QAP 8.1, "Corrective Actions"

2.8 VonRoll Isola (VRI) Application Data -708 solventless polyester varnish

2.9 VRI Application Data -709 solventless polyester varnish

2.10 VRI Application Data -777 solventless polyester varnish

3.0 PRECAUTIONS

3.1 Avoid breathing varnish vapors. Respiratory protection is not necessary unless the Threshold Limit Value (TL V) is exceeded or overexposure is likely. If exposed to high vapor concentrations, leave the area at once. If breathing becomes difficult, get medical attention.

3.2 Avoid varnish coming in contact with skin and eyes. Safety glasses, neoprene gloves and a rubber apron should be worn when handling varnish. If accidental contamination takes place, remove contaminated clothing and launder before reuse. Wash with soap and water. In case of contact with eyes, immediately flush eyes with plenty of water a for at least fifteen (15) minutes. In either case get medical attention if irritation persists.

3.3 These mixtures are considered combustible liquids. Keep away from heat, sparks and open flames.

3.4 Follow standard shop practices as outlined in the "Employee Safety Handbook"

3.5 This procedure applies only to motors with Class F or Class H insulation systems. Because the cure temperature exceeds the temperature rating of other class systems, other class systems cannot be included in this procedure and will be addressed on a case by case basis.

3.6 Use special caution to prevent damaging the windings by contact with slings used to lift the component or by contact with the VPI tank, oven, transfer car or other devices.

4.0 PREREOUISITES

4.1 Measuring and test equipment shall be controlled in accordance with PSS-QAP 6.5.

4.2 Resin temperatures should be between 66°F and 70°F during the VPI process. (The optimum resin temperature is 68ºF)

4.3 Turn on Shop 4 roof fans and open truck doors as needed to provide mechanical ventilation when VPI tank is open and VPI fumes are present.

5.0 INSTRUCTIONS

NOTES:

1. Steps may be performed out of sequence if necessary to facilitate work; however, no step may be performed out of sequence if it compromises the performance of steps designated as a hold point (such as a QC or Foreman hold point).
2. Steps can be N/A 'ed only when allowed by this procedure or with approval from all individuals that approved the procedure (or their designated representatives).
3. Harsh environment random wound components shall be VPl'd using VRI 708/709 resin.
4. Harsh environment form wound components shall be VPl'd using VRI 777 resin.

5. Non-harsh environment safety related and non-safety related components may be VPI'd using either VRI 708/709 or VRI 777 resin.
6. The oven should be on and at temperature (300°F to 325°F) prior to inserting the component in the oven for curing.
7. Unless otherwise noted, the craftsman performing the step should initial and date in the space provided adjacent to the step number.
8. For safety related components, use calibrated M&TE to monitor temperatures. Temperatures should be recorded on chart recorders and the chart included in the work package. In lieu of a chart recorder, record the temperature at 15 minute intervals on a Time-Temperature Data Sheet similar to Attachment I Initial/Date.

5.1 For form wound components only, prepare a sample coil for processing in conjunction with the component A means of simulating the slot portion of the iron should be provided. This can be accomplished by attaching a length of steel bar to each side of the slot portion of the coil. The steel bar should be of sufficient mass, or additional steel should be added to insure the sample coil maintains sufficient temperature to facilitate resin penetration representative of the coils installed in the stator.

5.1 Initial/Date_____/________

5.2 Verify electrical testing has been performed to insure the electrical integrity of the winding. Electrical testing should be performed in accordance with applicable PSS Job Instructions. Recommended tests include winding resistance, insulation resistance at 500 VDC, surge comparison test at the voltage rating of the machine and high potential test at the voltage rating of the machine. The VPI process should not be performed if the winding fails any of the above tests.

5.2 Initial/Date_____/________

5.3 Verify imbedded temperature detectors (RTD's or thermocouples) are operational, or install a temperature detector (RTD or thermocouple) mounted as close as practical to the center of the component.

5.3 Initial/Date_____/________

5.4 Verify the temperature indicating device (meter or recorder) and the temperature detector (RTD or thermocouple) are compatible (i.e. the meter or recorder is configured for the specific type RTD or thermocouple being used).

5.4 Initial/Date_____/________

5.5 QC HOLDPOINT Verify the resin has been tested in accordance with PSS-JI-3.14 requirements.

5.5 Initial/Date_____/________

5.6 QC HOLDPOINT Verify the resin temperature is between 66°F and 70°F.

Resin Temperature of ___________ºF

5.6 Initial/Date_____/________

5.7 Place the component to be VPl'd, and the sample coil, in an oven and preheat to 250°F ± 10°F for a minimum of one hour after the component reaches temperature for random wound components, or for four hours after the component reaches temperature for form wound components.

5.7 Initial/Date_____/________

5.8 Move the component and sample coil to the VPI process tank. Position the ends of the leads above the resin fill line. (Be sure to connect an in-tank thermocouple to the component to enable monitoring the component temperature while in the process tank.)

5.8 Initial/Date_____/________

1_{st} VPI

Initial/Date_____/________

2_{nd} VPI

5.9 Allow the component to cool to 140°F.

5.9 Initial/Date_____/________

1_{st} VPI

Initial/Date_____/________

2_{nd} VPI

5.10 Evacuate the VPI process tank to between 3 and 5 mm Hg. (This is the dry vacuum). Maintain dry vacuum for 30 minutes for random wound components or 2 hours for form wound components. If the component temperature falls below 120°F and a minimum dry vacuum time of 30 minutes has been achieved, proceed immediately to the next step in the process.

5.10 Initial/Date_____/________

1_{st} VPI

Initial/Date_____/________

2nd VPI

5.11 Flood the process tank with sufficient resin to cover the component and sample coil.

5.11 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.12 Continue evacuation of the process tank for 60 minutes. (This is the wet vacuum cycle.)

5.12 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.13 Release the vacuum on the process tank by venting with nitrogen.

5.13 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.14 Pressurize the process tank to between 85 and 95 psi. Maintain this pressure for a minimum of 1 hour for random wound components and 1 hour per half-lapped layer of insulating tape (mica and glass) on form wound components. A minimum of2 hours is required for any form wound component. (This is the pressure cycle.)

Half-lapped layers of mica tape __________________

Half-lapped layers of glass tape__________________

Total half-lapped layers of tape__________________

Total hours at pressure (1st VPI)________ (2nd V PI)_______

NOTE: Preheat the curing oven to between 300°F and 325°F in preparation for the curing cycle.

5.14 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.15 Return the resin to the storage tank and agitate the resin for approximately 30 minutes using the in-tank agitator.

5.15 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.16 Allow excess resin to drain from the component. If possible, the component should be held in a horizontal position during the draining process. Clean excess resin from the component. Separate the leads and wipe off any resin present on the leads. Clean, dry, compressed air at 20 to 30 psi may be used to remove resin from the vent slots if necessary. (Safety related components and RCP stators must have the vent slots cleaned prior to curing.) Drain time should be limited to the minimum time necessary to clean the vent ducts.

5.16 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

Sample coils should be cut open to check for resin impregnation to the conductor stack before the first bake cycle.

5.17 Place the component in an oven preheated to 300°F to 325°F for 2 hours on the first VPI cycle, 2 hours on subsequent VPI cycles, and 8 hours on the final VPI cycle. If the component is cured with the bore horizontal, it should be oriented with the leads at the 3 o'clock position for the first VPI cycle and rotated 190 degrees during subsequent cycles (i.e. 9 o'clock for second cycle, 3 o'clock for third, etc.) If the component is cured with the bore vertical, the connection end should be down on the first VPI cycle and alternated for each additional cycle. Time and temperature shall commence after the component temperature reaches 300°F.

5.17 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.18 PLANNER/ENGINEER/PROJECT MANAGER HOLDPOINT Determine if additional VPI cycles are required. This determination should be based on resin build achieved on the previous VPI cycle, the component's operating environment and the component's failure history. Harsh environment components require a minimum of 2 VPI cycles.

Second VPI required [ ] Yes [ ] No

Basis for omitting second V PI cycle_____________________________

____

____

5.18 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.19 QC HOLDPOINT Inspect the leads following the curing process to insure the leads are not excessively coated with VPI resin. The leads are considered acceptable if they retain their flexibility, and are not stuck together. If excessive resin is present, remove it by it using sandpaper or a rasp being careful not to damage the lead insulation.

QC Inspector. Initial/Date _____/_______

5.19 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.20 Repeat steps 5.8 through 5.19 for subsequent VPI cycles, or mark N/A the initial and date blanks on those steps if only one VPI cycle is to be performed.

5.20 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.21 Clean the components bore COD's on rotors), machine fits, and bolt holes to ensure they are clear of all interference.

5.21 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.22 Inspect vent ducts for blockage and clean if necessary to prevent restricting component cooling air flow.

5.22 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2nd VPI

5.23 ENGINEERING HOLDPOINT Dissect the sample coil and inspect for degree of impregnation. Sample coils with impregnation less than 100 percent will be documented and evaluated by engineering.

Engineer. Initial/Date _____/_______

5.23 Initial/Date_____/________

1st VPI

Initial/Date_____/________

2_{nd} VPI

6.0 ATTACHMENTS

6.1 Attachment 1, "Time -Temperature Data Sheet

ATTACHMENT 1

Time – Temperature Data Sheet

8
TESTS TO CHECK THE QUALITY OF RESIN IMPREGNATION

There are a number of tests[17] that can be used as a quality check of the effectiveness of the resin impregnation from the VPI process. The final AC or DC test can be an expensive way to demonstrate if the impregnation is sufficient. It is also expensive when windings that have passed these tests have failed in a relatively short period of time after going into service. These tests to demonstrate impregnation quality are described in the following without any particular order. The utility can select which test to use.

8.1 Partial Discharge (PD) Tests

PD testing can be used as a quality check for impregnation and bonding of ground insulation in new windings after impregnation and cure, but there are no recognized standard values of pico-coulombs for these tests, rather comparisons are used for similar machines with the same insulation systems. Both on-line and off-line measurements are suitable, but it is important to note that the values for these two types of PD test will be different because, in the on-line tests the voltage is distributed between the line and neutral ends of each phase, whereas in the off-line test the complete winding/phase is at the same potential. Also, off-line tests should, if possible be performed on individual phases, and with the other two grounded, so that any significant phase-to-phase PD activity, that can result from inadequate coil endwinding or connection spacing, can be identified. Also, sample coils are used for these tests. Further information on PD testing can be found in IEEE Std. 1434-2000 “Trial-Use Guide to the Measurement of Partial Discharges in Rotating Machinery.

The type of test used is a function of PD measuring instrument availability. PD test instruments[18], which test machines at the manufacturing plant, are becoming more popular with motor and small generator manufacturers. This test is appropriate for motor and generator stator windings with voltage ratings of 6.0 kV and above. However, some utilities are starting to use this test for 4 kV motors.

The specification of acceptance criteria for factory or repair shop test will help ensure that a well-impregnated and bonded ground insulation system has been provided. Peak PD magnitude acceptance limits are somewhat dependent on the following:

- the instrument used to measure PD

[17] Reference 40
[18] Reference 41

- the type of sensors used
- the machine voltage

Therefore, acceptance criteria should be based on the results of tests on well-consolidated windings of similar voltage rating, the same type of cooling and with a particular instrument and sensors. Acceptance criteria must be based on data collected on similar windings using well defined test procedures and equipment. Sources of such data for stator winding acceptance are as follows:

Purchaser Data Base: In this case the purchaser of the winding has a data base of PD data collected on similar stator windings using a well defined test procedure. The purchaser can then specify that the new stator winding PD levels, according to the exact same test procedure, used by them are at or below those for a winding known to be well consolidated. This philosophy can be applied to both on- and off-line tests.

Vendor Data Base: Both OEM's and PD Measuring Equipment suppliers have PD data bases that reflect what the levels in a new, well consolidated winding should be. These can be used to establish both on-line and off-line test acceptance criteria using a well-defined test procedure. The Purchaser can then specify that a new winding should have PD levels in each phase that are (say) a value below the average PD level found by the Vendor for that type of stator winding plus (say) two standard deviations. This is essentially a statistical Process Control procedure, that is commonly used in manufacturing. Again it is important that the test procedures used by the vendor for the new stator winding should be the same as those used in collecting their database.

Baseline PD levels should be obtained on new windings since trending of PD levels is the most effective way of applying this monitoring technique to detect winding ground insulation degradation, loose windings, degradation of corona suppression system coating, phase-to-phase PD and winding contamination. It should be appreciated that, even in well consolidated windings, the PD levels tend to reduce, due to further resin curing, after a few months of operation and therefore it is best to start trending after an operating period of about 6 months.

8.2 Power Factor Tip-Up Test

This test[19] which is sometimes called the dissipation factor tip-up test, is only meaningful if performed on individual coils or from the stator winding terminals. This test is applicable to form-wound coils and windings with voltage ratings of 2.3 kV and above.

This test can be used to check the quality of ground insulation in new fully processed coils and in particular it can be used to check sample global VPI coils that are processed along with the stator winding.

This test can also be specified to be performed on fully-processed complete windings and, if possible, it should be performed on each phase. For quality epoxy-mica or polyester mica

[19] Reference 42

insulation systems, the power factor should be in the range of 0.01 to 0.02 and the power factor tip-up ≤ 0.005.

8.3 Capacitance Test

This test can be used as a quality check for new stator windings.

Capacitance can be used during global VPI winding processing as an indication that resin impregnation is complete. A capacitance bridge is connected to the winding and during the resin impregnation process the capacitance increases with time. If capacitance versus time is monitored, complete impregnation is indicated when the capacitance stops increasing. However, this method is not full-proof since flattening out of the capacitance versus time curve may be an indication that no more resin can penetrate the winding, but that there may still be voids in it.

Capacitance can also be used as an acceptance criteria for new VPI windings. Again, if possible, individual phases should be tested. A capacitance tip-up test is the best indicator of the quality of winding ground wall insulation VPI resin impregnation. The capacitance values at 20% and 100% of winding rated line-to-ground voltage and the difference between the two values are compared using the following equation:

$$\Delta C = [(C_{lv} - C_{hv})/C_{lv}] \text{ x } 100\%$$

For a quality epoxy or polyester VPI impregnated mica system, Δ C should be less that 1% and this can be used as an acceptance criteria.

8.4 Sample Coils

It is recommended that for all windings at least 2 sample coils be put through the VPI process. The leads of the sample coils should be connected and taped with full insulation to simulate coils in the stator. The sample coils should have steel or aluminum channels to simulate a stator slot. The channels provide a more restrictive path for the penetration of resin into the slot cell ground wall insulation. One of these sample coils should be removed from the channels and cut open after the first VPI while the stator is still in the VPI tank, before the first oven cure to confirm resin penetration to the conductors. If inadequate resin penetration is found, additional VPI processing is recommended. This test coil should be retained for inspection by purchaser. (From EPRI 1000897, *Repair and Reconditioning Specification for AC Squirrel-caged Motors with Voltage Ratings of 2.3 kV To 13.2 kV*).

8.5 Water Immersion Test for Complete Stator

NEMA MG 1 Part 20.18 *Machines with Sealed Windings* describes a water submergence test that can be specified to demonstrate that the winding has a good impregnation.

For motors that can be submerged, the stator is submerged in water containing a wetting agent with the leads having enough length to avoid creepage to the terminals. With a 500 volt megohmmeter, the 10 minute insulation resistance in megohms should be greater than the machine rated kV + 1, according to NEMA. However, experience has shown that while submerged, the 10 minute insulation resistance, corrected to 40^{o}C[20], should be at least 100 megohms in order to pass the test. The winding should then pass a 60 Hz 1-minute AC hipot test at 1.15 times rated line-to-line voltage. The ac hipot test is followed by another megohmmeter test.

For motors that cannot be submerged, the stator can be sprayed with water containing the wetting agent for one half hour, and the same test sequence can be undertaken.

8.6 Water Immersion Test for Sample Coils

An effective test to check on the quality of the impregnation is to use a sample coil that has been through the impregnation and cure cycle along with the rewound stator. The sample coil is tested for PD and for AC breakdown while immersed in water. The coil leads are separated from the coil by a one inch layer of transformer oil on top of the water to prevent flashover. AC breakdown voltages on the order of 20 to 25 kV for 2300 volt and 4000 volt coils demonstrate a quality VPI treatment. PD measurements on the order of 600 to 2000 pico-coulombs are seen as reasonable for this test. T.C. Garg of Mirant Energy developed this test. He reports that he uses a James G. Biddle Co. off-line PD detector Catalogue No. 6611057 for the pico-coulomb measurement. Other means of measuring PD for this test could be the Adwel PDA Premium tester and the Iris Power Engineering TGA-B tester each of which measure mV.

[20] Reference 44

9
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10
LOW VOLTAGE WINDINGS

Low voltage motors generally use random wound coils. The stator has semi-open slots into which insulating sheet material is laid as a slot liner. Coils are made up of the necessary numbers of conductors and turns of insulated round magnet wire. Coils are placed into the slots through the slot opening a few wires at a time. The wires are in no particular arrangement as far as beginning and ending wires of the coil are concerned and hence the term used to describe these windings – random windings. Top and bottom coils are separated by a phase separator of the same material as the slot liner. The slot liner is folded over the top coil side and a top stick is driven into the slot over the folded-over slot liner. Phase separation insulation in the end winding, if used, is by flexible glass cloth sheet material laid between the coils of different phases.

Class H insulation systems are available for random wound machines. The wire enamel coatings of Table 3-1 are available for the round magnet wires use in random wound motors. Slot liners and phase separators can be Dacron-Mylar-Dacron (DMD) or Nomex. The latter is the preferred material. Class H varnish can be used to dip and bake the random wound winding, but a Class H solventless VPI synthetic resin is preferred, such as a polyester, epoxy or hybrid. Thixotrophic resins are particularly designed for random windings so that a single application of resin will suffice. The principle function of the resin is to bond the wires together in the slot and in the end winding to prevent vibration of the wires from the alternating magnetic field of the motor. Another function is to improve heat transfer between the coils and the core and between the coils and the cooling air. A third function of the resin is to seal the winding against the atmosphere: moisture, chemicals or dirt.

For harsh environment duty motors, the portions of the windings in the slots and in the end windings are often taped with fiber glass woven tape to help in containing the impregnating resin into the wire structure. Liberal use is made of Nomex felt material in the slots and in the end windings to absorb resin. This greatly improves the moisture and chemical resistance of the finished winding.

In addition to impregnating resins, random wound motors can be treated with trickle resins which are poured from a can of resin onto the end winding of a partially energized stator as the stator is rotated end for end in a fixture. This process provides excellent penetration into the slots and provides excellent sealing of the end windings.

If the low voltage motor uses form wound coils, the material in this Guide on form wound coils applies except the numbers of tape layers is only one or two layers.

11 CONCLUSIONS

This user guide for the vacuum-pressure impregnation processing of medium voltage stator windings discusses the fundamentals of the engineering of coils, allowable temperatures, insulation qualification and the principle materials and practices used to manufacture motor stator windings. The investigation of available VPI resins is presented in the context of the entire winding system including conductors, wire coatings, turn insulation, ground insulation, manufacturing and VPI processing.

Updated material on the testing of green coils was included which is based on recent experience in the industry by both a manufacturer and by repair shops. Significant new material has been included on epoxy, polyester and hybrid VPI resins as they apply to the process of rewinding medium voltage motors. These resins are important ingredients in the production of reliable motor rewinds. Resins are continuously being improved by the resin manufacturers as evidenced by the availability of Class H resins which are common now and by the increasing voltage stress levels being used. The increase in temperature capability has derived from the increase in glass transition temperature of the particular resin. Raising the glass transition temperature extends the important electrical and mechanical properties of the resin binder to higher temperatures. Some resins are designed for multiple-use – for form-wound motors as well as for random-wound motors in order to increase resin turnover. Increased resin turnover requires the addition of new resin which helps to maintain the resin's properties. Resins for 13.2 kV class windings tend to be special with the best of electrical properties and lower viscosity. The maintenance of resin properties while the resin is in storage and in use continues to be a significant concern. VPI processing procedures are vital and have been discussed in detail.

A significant finding of this study is the importance of the glass transition temperature in identifying the best of the resins. This property which applies to both epoxy and polyester resins is not defined in manufacturers data sheets. Evidence of high glass transition temperature is in the maintenance of good electrical and mechanical properties such as dielectric constant, dissipation factor (tan δ) and helical coil bond strength at elevated temperatures. To select the best of the resins as represented by the data sheets presented by the resin manufacturers is difficult because rarely do they list comparable test data. The best resin would be the one with the best elevated temperature electrical and mechanical properties such as highest dielectric constant, the lowest dissipation factor, the best helical bond strength. But, it must be remembered that the processing features such as thixotropy and viscosity must also be factored into the evaluation.

Resin cost was not in the scope of work of this report. One resin manufacturer reported that epoxy resins were most expensive, hybrid resins which are a combination of epoxy and polyester resins less expensive than epoxy resin, and polyester resin the least expensive.

A
RESIN DESCRIPTION, USE, MAINTENANCE AND QUALITY CONTROL

The following is taken from the manufacturer's description of Epoxylite #478 resin. The material is presented here because it provides a tutorial on the description, use, maintenance, and quality control of thixotropic resins, whether they are epoxy or polyester.

1. The resin system is composed 100% of resins, modifiers, and hardeners. The resin is 100% epoxy with a small percentage of a viscosity modifier.

2. The viscosity of the uncured compound is of such a range as to provide effective penetration for VPI on form wound stators without allowing excessive runout before and during the curing process. On random wound equipment it provides effective penetration and adequate build-up on end- turns without the use of restraining tapes.

3. Physical properties. The cured compound cures to a tough solid with high bond strength and good thermal and mechanical shock resistance. These properties are not excessively degraded by thermal aging.

4. Electrical properties. The cured resin has excellent dissipation insulation resistance and dielectric strength. These properties are not excessively degraded by thermal aging and by exposure to humid atmospheres.

5. Temperature classification. The cured compound is capable of continuous operation as a NEMA Type EV180/35, /16, /73, and /GC per RE-2.

6. Compatibility. The cured compound is compatible with cured insulating varnishes and magnet wire coatings, such as ML, epoxy, nylon and two-stage polyester. It is non-corrosive to iron, steel, copper and aluminum.

7. Safety. Under normal use and severe conditions, neither the uncured nor cured resin presents an unusual flammability or toxicity hazard provided that common sense, safety and handling procedures are followed.

8. The resin build obtainable by using the Epoxylite #478 system is double, or triple that obtainable by conventional systems.

9. Chemical resistance. The cured compound has good moisture, oxygen and ozone resistance and is not attacked by commonly used cleaning compounds and solvents. In formulating a solventless resin impregnating system, certain basic requirements must be met, as noted:

1. The viscosity must be sufficiently low to allow penetration into the most minute openings. (Pressure is generally used to help force the resin into these openings once the air has been pumped out of the slots and windings.)

2. The viscosity must be sufficiently high to provide sufficient build for the required environmental and electrical protection.

3. The resin catalyst system must be stable, allowing only a minimum of polymerization to take place at ambient temperature. At the same time, it must bring about polymerization according to a reasonable cure schedule.

Solventless impregnating resins have been in use sufficiently long enough to reveal that windings can be satisfactorily impregnated with resins having viscosities of from a low of 100 cps to a high of 10,000 cps depending on application and voltage, and if handled properly. Proper handling includes:

1. Preheating the unit. This assists in driving out moisture and lowers the viscosity of resin during impregnation.

2. Placing the unit in a vacuum chamber and reducing pressure to assist in drying out the unit and pull the air out of the windings.

3. Introducing the resin only when the temperature within the windings has cooled to 43-49ºC (110-120ºF).

The optimum resin storage temperature is between 18-21ºC (65 - 70ºF). Below about 18ºC, the resin becomes quite viscous and difficult to move from the storage to the treating tank. At the same time, some refrigeration is desirable to prolong resin usefulness.

Between the temperatures of 18ºC and 21ºC, the ideal resin storage temperature, resin viscosity in a properly controlled system can vary from 3000 cps to 7500 cps. To impregnate properly, the resin must be thinned and this is done by allowing the resin to be warmed by preheated stator windings.

Not only is 478 resin's viscosity a function of temperature, but it is also a function of pressure. When a conventional system is subjected to pressure, the resin is forced into the voids. When pressure is released and the unit is cured at 121-150ºC, much of the material is free to run out of the unit and it does. In contrast, the Epoxylite #478 system, although seemingly more viscous, is also forced into the voids, because it is thinned not only be being warmed, but also by the applied pressure. When the pressure is released, the viscosity increases to its original value and the resin stays put, retention being 50-100% greater than with conventional systems. This behavior known as thixotropy, is a characteristic of greases, which flow under pressure, but remain in place when pressure is released. Epoxylite 478 resin system has the additional degree of freedom --control of thixotropy in controlling build.

These factors --control of viscosity and control of thixotropy --are matters which should not be left to chance. They are matters which require expertise; something which Epoxylite furnishes as a partner in the operation to assure optimum results.

The user of 478 resin must do the following:

1. Maintain the resin at temperature of from 18-21ºC during storage. This requires that the storage tank be provided with external cooling.

2. After wound stators are baked in an oven to remove moisture, they must be cooled to a temperature between 43-54ºC. Unless these temperatures are conscientiously controlled and monitored, there can be no guarantee of resin stability.

3. Make regular additions to the resin tank. The amount would merely approximate a normal replenishment rate of the amount used during ordinary operation.

4. Coordinate with Epoxylite, furnishing a resin sample each month and fill in the Resin Control Sheet with the appropriate information. A copy of the customer's Control Sheet should be furnished with each sample forwarded for testing.

5. The Epoxylite Corporation will upon receipt of each resin sample run the control check and furnish the customer with a copy of the data to inform him of the tank condition and advise him of any steps necessary to maintain the tank in usable condition. This will be done as soon as possible after receipt of the sample.

6. From time to time, particularly during slow periods, when little resin is being added to the tank by way of make up, it may be necessary to add a viscosity-controlling version of Epoxylite #478. This is Epoxylite #477. While it is effective in thinning the resin in the tank, it also reduces thixotropy. If it should become necessary to use Epoxylite #477 regularly and over extended periods of time, because of infrequent additions of make-up resin, eventually the non-Newtonian character of Epoxylite #478 would diminish and the system will have to be built up again with a heavy dosage of thixotropes. In extreme cases, it may be necessary if there is no replenishment for long, long periods to withdraw a portion of resin from the storage tank and replace it with fresh resin. The resin withdrawn can be stored at 0ºC (32ºF) with little increase in viscosity until it is feasible to return it to the resin tank.

With regard to parent viscosities, only a few generalizations are possible and these are not very powerful. Some systems with viscosities well below 2,000 cps give higher pickups and retentions than other systems having viscosities in excess of 3,000 cps. For a given basic formulation, increasing the amount of filler above some optimum value will give too high wet pickup, as will all the thicker systems we have looked at (i.e. those with viscosities in the 10,000-20,000 cps range). Too high wet pickup leads to excessive oven drain. In previous RID and testing, optimum "as manufactured" viscosities appeared to be below 4,000 cps. Above that value, with systems tested prior to New improved Epoxylite #478 had encountered a combination of too much oven drain coupled with an inability to penetrate and saturate form coil constructions, when recommended procedures were not followed (i.e., preheat unit to 150ºF; begin processing at 110º-120ºF).

The more common method of measuring impregnants is the Brookfield. However, the value produced only indicated a shear value and relative thickness, commonly referred to as viscosity; and using the ratio for two RPM factors, a T.I. (Thixotropic Index) can be determined resulting in a suggested Coating Thickness.

A less common method of measuring impregnants is the Ferranti Shirley, we have used this technique for about 20 years. The value of this method is extremely important, as it measures Penetrating Viscosity.

These two properties -Coating Thickness and Penetrating Viscosity would appear to be mutually exclusive, however, in the design of a universal impregnant for Random Wound and Form Wound Motors up through 7,000 volts, the impregnant has to have the ability of penetrating tightly wound taped coils and at the same time, deposit a uniform coating of a given thickness on the surface of the tapes, or on an enamel coated conductor.

A.1 System Stability

Epoxylite #478 can overcome most of the problems associated with storage life of large quantities of resins in V.P.I. Systems based on the following:

1. The resin is designed for stability at 77ºF (25ºC) for twelve (12) months with no replenishment.
2. Periodic testing is recommended for at least every month of the resin.
3. Training is recommended for correct management of your system.
4. Procedures are available for treating assorted electrical equipment.

A.2 Mechanical Properties

It has always been our belief that these properties are the singularly most important in an impregnant. In the most simple terms, the primary reason why an impregnant is used is to bond and hold steadfast all of the components used in electrical equipment, whether electric motors; transformers; field coils, etc. The secondary benefits are that of electrical insulation, moisture and chemical protection. It goes without saying that if the basic insulation required for a specific voltage is not designed into the electrical component, prior to impregnation, No impregnant will perform as a replacement. The necessity of the impregnant is that of mechanical bonding of all active members of the total insulation system, from room temperature through the operating temperature of the equipment.

A.3 VPI Processing Procedure - Responsibility, Training, Precautions

1. Establish responsibility of shop management, engineering, and quality control for correct operation of the VPI system at all times including when in use and when not in use.

2. All personnel involved in the VPI processing of motors shall be trained and qualified in procedures.

3. All instrumentation used in the process shall be calibrated.

4. When not in use the resin temperature shall be maintained at 50ºF. When use of the resin is anticipated, raise the resin temperature to 70ºF at least 40 hours prior to use.

B
CORONA SUPPRESSION SYSTEM NOTE

The following is from a paper presented at the 2000 IEEE Electrical Insulation Symposium in Anaheim entitled *Anti-Corona Protection of the High Voltage Stator Windings and Semi-Conductive Materials for its Realization*. The authors, R. Malamud, Consultant, MI. USA, and I. Cheremisov of Electrotyazhmash, Kharkov, Ukraine, discuss how effective anti-corona semi-conductive tape and paint coatings are designed:

As the electrical stress or volts/mil of the ground wall is increased (as is the case for new, present-day manufactured machines), the current to be carried by these coatings increases, perhaps doubling, as compared to older machines. With high electric stress, it is necessary to design lower resistance coatings for the slot section and the paint or tape used has to be capable of higher temperatures. More complete contact is needed between the conducting surface of the coil and the grounded core tooth than previously. This Ukrainian firm increases the concentration of carbon black in the paint system from 3.5 -5.4% to 14% by volume and use a finer grade of carbon black as a way to increase the concentration. The carbon black is carried in a high temperature baking enamel or a baking type epoxy .Their newer semi-conducting tape for the slot section uses copper and silver oxides impregnated into fiberglass tape, suitable for 1800ºC. It is cured when the ground wall of the coil is cured. For a grading paint, they use a silicon carbide powder mixed with epoxy resin, which is cured along with the ground wall and the slot semi-conductive coating system.

From these comments and papers, it is apparent that the grading system must be able to tolerate high temperature. The components of temperature are the winding temperature rise, the ambient temperature, and the heat generated by current flowing through the corona suppression coating.

Most shops dealing with 13.2 kV class of machines use semi-conducting tape for the slot section and grading tape for the coil outside of the slot with the latter extending about six inches out from the end of the core. The grading tape overlaps the semi-conducting tape by about one inch. These tapes are vital to the reliability of the 13.2 kV class of machine, but may require longer vacuum and pressure cycle time to assure good impregnation through the corona suppression system.

It should be stressed that 11 kV, 13.2 kV, and 13.8 kV windings are a different class of windings as compared to 4 kV and 6 kV windings. It has been pointed out in this report that many VPI resins used for 4 kV and 6 kV motors are not rated for the higher voltages. Then there is the corona protection issue just discussed. Care should be taken in selecting a rewind facility for higher voltage motors. Experience and reputation are certainly important factors in selecting a rewind shop for motors with the higher voltages.

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