INSULATION TESTING

Insulation testing of high voltage generator stator coils covers many different tests that are performed at various stages of coil production and stator winding. It is normal practice to separate the coil electrical tests into production tests, quality assurance tests, and winding tests. Another important category is development tests, which are special tests performed on coils and insulation systems that are under development. This article covers all the electrical tests usually performed on high voltage stator coils from the early stages of coil fabrication to final machine testing. Insulation testing of all high voltage stator coils is done at three points during the coil manufacturing and winding operations of the stator winding. In addition, quality assurance coils are always part of a coil production run and special electrical tests are performed on these coils, which are identical to the coils in the production set. In addition, when new coil designs are implemented into the manufacturing process and when trial prototype coils are fabricated in the manufacturing facility, special qualification tests are conducted. Insulation testing is a series of electrical tests that are conducted on coils and are identified as conductive electrode and voltage grading electrode test, power factor tests, voltage withstand tests, strand to strand test, voltage breakdown test, and, in special cases, voltage endurance tests. After the coils are placed in the core slots, additional resistance tests and high voltage withstand tests are conducted using high potential alternating current (ac) or direct current (dc) voltages. The described electrical tests are applied to water cooled, air inner cooled, gas inner cooled, and conventional cooled coils.

TYPICAL HIGH VOLTAGE COIL CONSTRUCTION

A typical cross section of a generator high voltage coil is shown in Fig. 1. Each individual strand is insulated using a dacron-glass or enamel coating insulation. The main conductor is made up of strands to reduce the eddy current loss that would be quite high if a solid bar conductor were used. The bar construction is fabricated as a separate component and is formed and bonded in a hot press. After the bar is formed a glass-backed mica paper insulation system is applied to provide a high voltage insulation between the copper conductors and the core of the machine. Insulation systems are normally the resin-rich or vacuum-pressure-impregnation type. A conductive layer is applied to the outer layer of the insulated coil to provide a ground plane. In addition, special voltage grading is applied to the end bars of the coil. There are full coils and half coils depending on the generator size and rating.

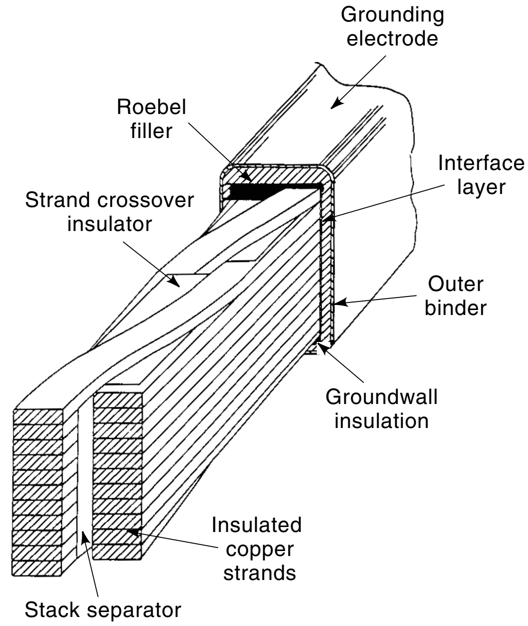

Figure 1. Typical generator high voltage coil showing the major components.

THREE MAJOR METHODS OF INSULATING AND PROCESSING HIGH VOLTAGE STATOR COILS

There are three major methods of insulating and processing high voltage stator coils:

- *Global Impregnation.* Dry insulated stator coils are fabricated and installed in a stator slot and the complete wound stator is vacuum impregnated with a liquid resin. The insulated coils conform to the slot size and configuration. The complete stator is then cured at elevated temperatures.
- *Fully Loaded Tape (Resin-Rich Tapes).* The coils are formed and bonded in a pre-press and then taped with a resin-loaded mica tape. Each taped coil is placed in a hot press, where it is pressed to size and heat cured.
- *Vacuum-Pressure Impregnation.* The coils are formed and bonded in a pre-press, dry taped with a mica tape, and then sent through a vacuum-pressure-impregnation (VPI) cycle. After the VPI cycle, each coil is placed in a heated press and pressed to size and cured in a large oven.

PRODUCTION COIL TESTING

Stand-to-Stand Test

The stator coils are fabricated, placed through a form-and-bond cycle, and then prepared for a strand-to-strand electrical test. The resistance between strands, cooling tubes, and between strands and tubes is measured with a 250 Vdc to 500 Vdc megger. The resistance between strands must be greater

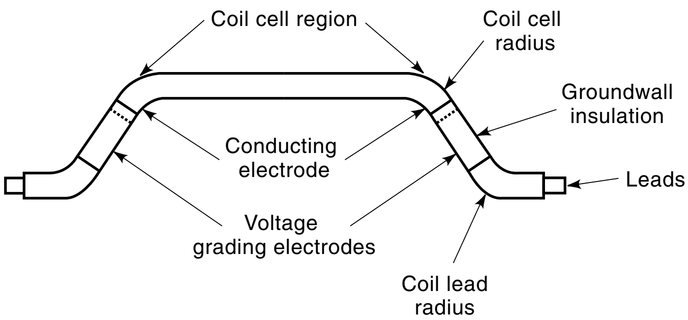

Figure 2. Stator coil outer electrodes.

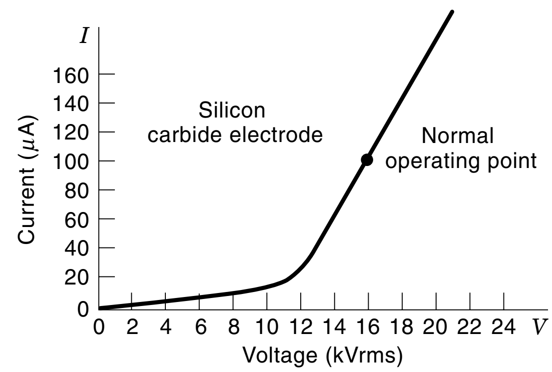

Figure 4. Voltage–current characteristic curve for voltage grading electrode.

than 20 MΩ at the test voltage level. The voltage is applied for 3 s. Resistance is checked between each coil strand to every other strand in the Roebel bar stack. All production coils are tested. No strand-to-strand shorts are allowed in the coil. If a strand-to-strand short is found, the short is cleared and the coil is retested. If a strand-to-strand short were allowed in a coil, a hot spot could develop in the coil during operation, which could lead to early failure of the affected coil. The hot spot is developed due to circulating currents that involve the shorted strands.

Conductive Electrode and Voltage Grading Electrode

Outer coil electrodes are applied to the stator coils before placement in the core. The electrodes are shown in Fig. 2. The purpose of the external electrodes is to grade the voltage along the length of the coil.

Conductive Electrode for Coil Straight Part

As shown in Fig. 2, a conductive electrode is applied to the outer surface of the stator coil. Its function is to provide the electrical contact between the outer surface of the coil insulation to the stator core to prevent any potential buildup caused by the generator field cross-flux. If potential buildup is allowed to occur, slot discharges can occur and over time erode the groundwall insulation, which will result in electrical failure of the coil groundwall insulation. The conducting surface is applied by using conductive paint after coil processing, or using conductive tape during coil processing. The resistance of the finished conductive surface has to be high enough so as not to short out the stator core laminations, low enough to short out the gaps between coil surface and core, but not low enough to cause excessive current flow in the outer conductive layer. For most high voltage generators, the outer electrode resistance is designed to be between 375 Ω/sq to 15,000 Ω/sq.

Voltage Grading Protection for Coil End Turns

Voltage grading paint or tapes are applied to coil end turn regions to reduce the voltage stress placed on the groundwall insulation at a point where it exists the core. See Fig. 3 for a plot of the voltage versus distance along coil end turn. The grading of the voltage minimizes the level of corona activity at the coil cell radius during machine testing and operation. Both the paint and the tape are usually silicon carbide loaded and exhibit a nonlinear voltage–current response, as shown in Fig. 4. A normal operating point is established by electrode design to be in the linear portion of the *VI* curve. For correct design on coils of different voltage ratings, the voltage grading electrode is configured to meet requirements through adjustments to its thickness and surface area.

Testing of Electrodes

The surface resistance of the conductive layer, tape or paint, is measured on each production coil. As illustrated in Fig. 5, copper wire is wrapped around the perimeter of the coil in

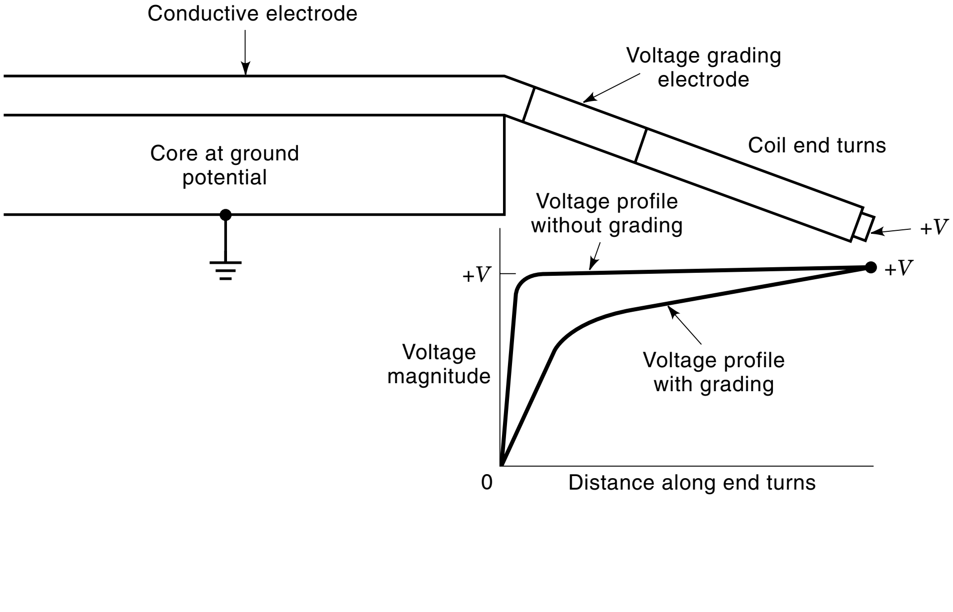

Figure 3. Voltage grading electrodes applied to a stator coil.

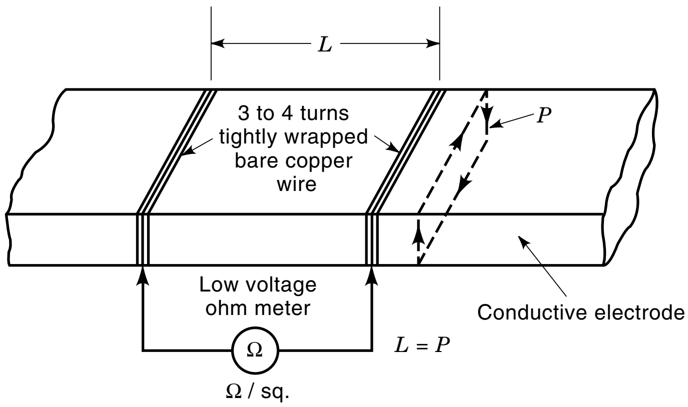

Figure 5. Testing electrode arrangement for measuring the surface resistance of the conductive electrode.

two locations. The length (L) between the two copper wire wraps is set equal to the coil perimeter (P). Setting $L = P$ results in a surface area of the electrode equal to a square. A low voltage ohmmeter is then connected between the two copper wire wraps and the resistance reading is recorded. The resistance reading has units of Ohms per square. The measured resistance must fall between a low limit such as 375 Ω/sq. and an upper limit of 15 kΩ/sq.

After application of the voltage grading tape or grading paint to the coil end turns, the voltage grading material is tested using a high voltage dc test set. Conducting bands are placed around the grading material as illustrated in Fig. 6 and a high voltage dc power source is connected between the two connections. The dc supply voltage is increased to obtain a known current level, such as 2 μA per inch of coil perimeter. The resistance is calculated from

$$R(\Omega/\text{sq.}) = (P/L) \times (V_{\text{dc}}/I_{\text{dc}})$$

where P = coil perimeter, and $I_{\text{dc}} = (2\ \mu\text{A}) \times (P)$. The measured resistance must fall between a specified value, for example, 2000 MΩ/sq. to 6000 MΩ/sq. In most cases L of the electrode is less than P of the coil and therefore L is usually set equal to $\frac{1}{2}P (L = \frac{1}{2}P)$.

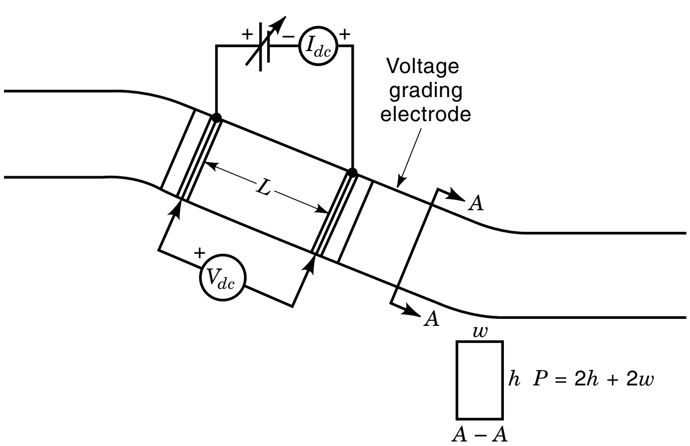

Figure 6. Testing electrode arrangement for measuring the surface resistance of the voltage grading electrode.

POWER FACTOR TEST

To obtain long electrical life from high voltage stator coils, good consolidation of the total coil insulation is required. Low void content is required to minimize the partial discharges (PDs) within the insulation system, which can lead to insulation failure. As illustrated in Fig. 7, internal partial discharges can occur within the insulation system if the insulation contains air-filled voids. The internal discharges cause localized heating and represent a power loss equivalent to power loss in a resistor. Power factor tip-up measurements are done to obtain a measure of the extent of void content by measuring the degree of power loss in the insulation system.

Theory of Power Factor Measurements

The power factor versus voltage characteristic of coil insulation is the net result of several phenomena occurring in the insulation structure. Ionization of gaseous inclusions (voids) in the insulation structure causes an increase in power factor with voltage increase as the critical voltage gradient is exceeded. Void ionization is a form of partial discharge (PD) or corona. The energy dissipated by the partial discharge is represented by a resistor in series (or parallel) with the coil capacitance. A typical coil with a small void content will exhibit a measurable level of power factor tip-up with the resistance having a finite value. A coil with high dielectric loss exhibits a large value of series resistance, caused by the higher level of PD, and exhibits a much higher level of power factor tip-up.

Dielectric absorption and conductive losses in the insulation structure will also cause an increase in power factor with voltage. Refer to Fig. 8.

The energy associated with a single PD event is minute (1). The cumulative effect of many PD events can degrade the insulation. For this reason it is important to quantify the level of PD activity in the insulation system.

The power factor tip-up is defined as the difference in the power factor measured at two voltages. When testing an individual bar or coil, this change in power factor with the test voltage may be caused by a variation in the power factor values associated with the dielectric or partial discharge losses or both with voltage. The power factor component arising from the dielectric losses generally changes very little with voltage; however, with some defects in the solid insulation, such as uncured resin sections or contamination due to ionic impurities, significant space charge losses may arise, leading to an increasing or decreasing tan δ value with voltage. For example, pronounced dielectric losses would be expected to

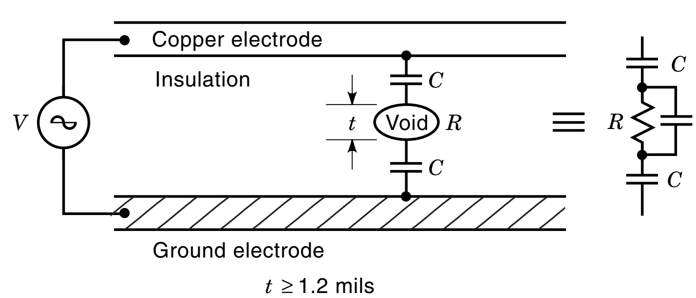

Figure 7. A schematic of a void that can be present in the insulation system.

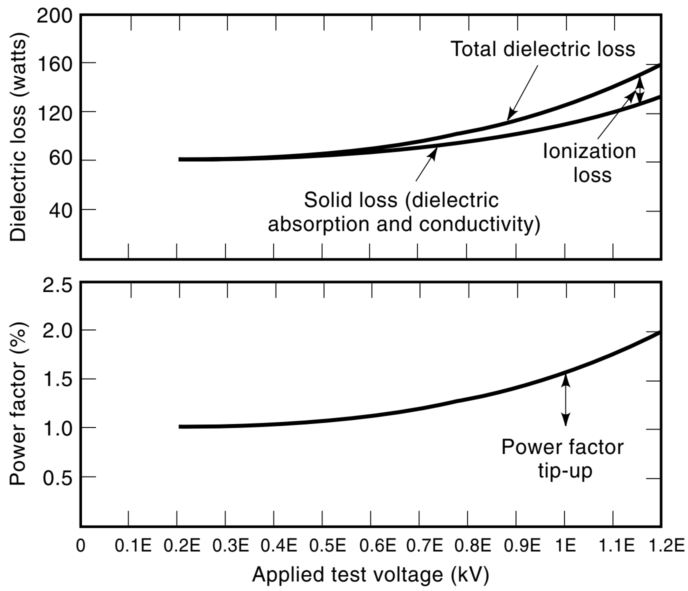

Figure 8. The power factor tip-up is the difference in the power factor of the insulation measured at two different voltage levels. When testing an individual coil, the change in power factor with test voltages is caused, in part, by ionization losses in voids within the insulation.

occur due to space charge accumulation at interfaces of contiguous tapes, having different conductivities as a result of different degrees of contamination. It is difficult to analyze the effect of space charges upon the tan δ value as a function of voltage without the introduction of a number of disposable constants. However, the dependence of tan δ on partial discharges is relatively easily accounted for in terms of partial discharge rate and pulse magnitude as a function of voltage.

The total power loss, P, for the entire insulating system may be expressed as

$$P = P' + \sum_{j=1}^{n} \Delta P_j \tag{1}$$

where P' is the power loss within the solid dielectric portion of the bar and ΔP_j is the power loss due to the jth discharge. If is δ' taken to represent the dissipation factor value of the dielectric loss contribution whose change with voltage is assumed to be negligible, then Eq. (1) may be rewritten as

$$\omega CV^2 \tan\delta = \omega C'V^2 \tan\delta' + C'' \sum_{j=1}^{n} n_j \Delta V_{cj} V_j(t) \tag{2}$$

where ω is the radial frequency term, C is the capacitance of the bar specimen measured at an applied voltage V, and tan δ is the total dissipation factor value in the presence of both the dielectric and partial discharge losses. Here C' represents the capacitance of the specimen bar under the occurrence of only the dielectric losses, while C'' denotes the specimen capacitance in the presence of discharges at the applied voltage V. The voltage $V_j(t)$ is the instantaneous value of the applied voltage at which the jth discharge pulse of amplitude ΔV_{cj} takes place with a repetition rate of n_j pulses per second. The tan δ of the bar insulation in terms of Eq. (2) thus becomes

$$\tan\delta \cong \frac{C'}{C} \tan\delta' + \frac{C''}{\omega CV^2} \sum_{j=1}^{n} n_j \Delta V_{cj} V_j(t) \tag{3}$$

Hence on the assumption that tan δ', which is determined by the dielectric losses, remains unchanged with voltage, the overall tan δ value of the bar insulation will vary with the second term on the right-hand side of Eq. (3), which represents the discharge power loss contribution to the dissipation factor. As long as the applied voltage is rising, an increasingly larger number of voids begin to undergo discharge, and the value of tan δ will continue to increase. Once all voids become ionized and are discharging, the tan δ value after attaining a maximum will commence decreasing with voltage. This behavior is manifest when the power loss due to all the partial discharges is increasing at a lower rate than the square of the applied voltage term, V^2, in the denominator of the second term on the right-hand side of Eq. (3). Consequently, a negative tip-up value of tan δ (if it is caused by partial discharge losses) occurs when all the existing voids become ionized and begin discharging at some lower voltage and a further rise in applied voltage does not result in any additional discharging voids.

Each production coil is power factor tested following the guidelines of IEEE Std. 286-1975 (1). The voltage is set at steps of $0.2E$, starting at $0.2E$ up to $1.2E$, where E is the rated coil voltage. Power factor tip-up is calculated between any two selected voltage levels and must be below specified limits. Cell capacitance is also measured and compared to the calculated value based on the coil geometry.

The initial value of tan δ, measured at $0.2E$, is checked to be certain sufficient coil cure has resulted from the manufacturing process. Each production coil must pass the power factor requirements in order to be used in the stator winding.

COIL POWER FACTOR TEST PROCEDURE

See Fig. 9 for a typical equipment setup for performing power factor measurements on high voltage stator coils.

1. All coil strands are connected together at both coil ends.
2. Bare copper wire is wrapped around the coil's outer electrode. This forms the ground electrode for the coil.
3. Foil guard electrodes are applied to both coil ends at the end of the ground electrode and the start of the voltage grading. The guard electrodes isolate the coil section under test.
4. The coil is connected to an automatic bridge circuit and a high ac voltage supply.
5. The test voltage is set to $1.2E$ for 4 min for presoaking. The presoak conditions the coil by polarizing the dielectric and establishes a steady-state temperature for the dielectric. After the 4 min, the cell capacitance and tan δ are measured and recorded.
6. The test voltage is then set to $0.4E$, $0.6E$, $0.8E$, $1.0E$, and $1.2E$ and cell capacitance and tan δ are measured and recorded at each voltage level.
7. The Δ tan δ is calculated by subtracting tan δ at $0.2E$ and $0.8E$.

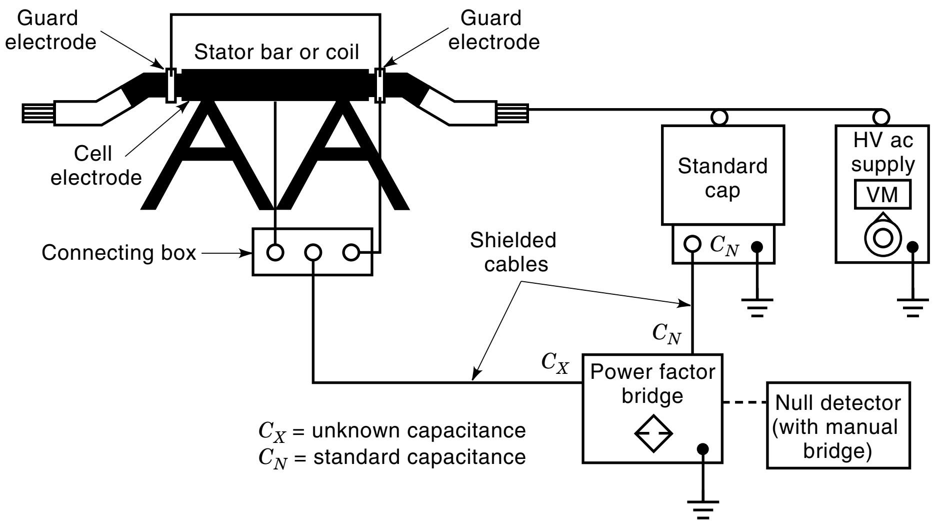

Figure 9. Typical test setup for measuring power factor of individual coils.

8. The cell capacitance is compared to the previously calculated cell capacitance. The value of Δ tan δ is compared to the specified limit for the particular coil design.

VOLTAGE WITHSTAND TESTS

Each production coil is voltage ground tested. The equipment setup is shown in Fig. 10. The coil and the voltage grading system must withstand a specified test voltage for 1 min. Each coil is separately tested. The test voltage level is based on the insulation thickness and the operating volts per mil stress. The 1 min. test voltage level is typically measured at either $1.35(2E + 1\text{ kV})$ kVrms or $1.30(2E + 1\text{ kV})$ kVrms depending on the insulation thickness level. The value of E is the generator line-to-line voltage, which is the rated coil voltage. The coil is not to fail and the voltage grading shall not burn and no corona activity is permitted. The voltage is ramped up to the test voltage level at a 500 V/s rate and remains at the test level for one full minute.

Testing Associated with Stator Windings

High voltage tests on generator stator windings should only be performed by experienced personnel qualified to work with high voltages and testing procedures. Physical damage can occur to the components being tested if extreme care is not taken. It is important to follow normal safety practices when doing high voltage testing to prevent possible injury or death to personnel associated with the testing.

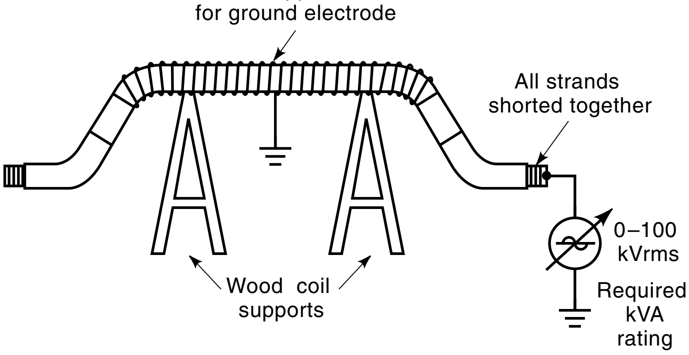

Figure 10. Typical test setup for performing voltage withstand tests on high voltage coils.

DC WINDING RESISTANCE

The purpose of this test is to check the quality of the many connections that are present in the winding. It is usually performed after the winding has been completely assembled. Most electrical connections are either brazed or soldered. This resistance test is performed by using an ohmmeter device or low resistance bridge, capable of measuring accurate low resistance values down in the milliohm range. The test will detect open or high resistance connections, open circuits, and possibly incorrect connections. The readings are usually taken on a per phase basis and the initial factory data are recorded and retained for future reference when tests are repeated later in the life of the winding. The difference readings between phases (three phases) should be within 0.5% from the average of the three. Normally, the readings are taken at room temperature. If temperature is other than room temperature, then temperature correction should be applied to the readings. Additional details can be found in Refs. 1 and 2.

DC INSULATION RESISTANCE

Before and after each voltage ground test, the insulation dc resistance of the winding or portion of the winding is measured using a 2500 V megger for a full minute. Resistance must be above 1000 MΩ after 1 min before proceeding with the voltage ground tests. In addition, before each voltage ground test, the polarization index is measured per IEEE Std. 43-1974 (2). The winding insulation resistance must meet the Standard before a voltage ground test is performed.

AC VOLTAGE GROUND TEST

After the bottom stator coils are wound into the stator slot, the coil voltage ground test is conducted on a maximum of one-half of the coils at one time. While one set of bottom coils are being tested, the other remaining bottom coils are connected to ground. After the top coils are installed, another voltage ground test is conducted on a single phase while the others are connected to ground. These tests are conducted prior to wedging. The level of test voltage is $1.05(2E + 1\ \text{kV})$ kVrms and the winding must withstand this voltage for 1 min.

DC VOLTAGE GROUND TEST

After the stator is fully wound and is finished, and prior to shipment, a final dc high potential test is conducted on each of the separated phase groups. The dc test voltage is set to $1.7 \times 1.05(2E + 1\ \text{kV})$ kVdc and the test is for 1 min.

COIL QUALITY CONTROL ELECTRICAL TESTS

Usually TWO coils from a production set of coils are randomly selected from the production run and tested. The tests performed are power factor of cell, power factor test of end turns, strand insulation voltage breakdown, 60 Hz voltage breakdown of groundwall insulation, and voltage endurance testing of sections cut from the coil straight part. In addition to the electrical tests, chemical and mechanical tests are conducted on the groundwall insulation.

POWER FACTOR TEST

The same test as described for the production coils is applied to the two QC coils. In addition, a 6 inch long electrode is

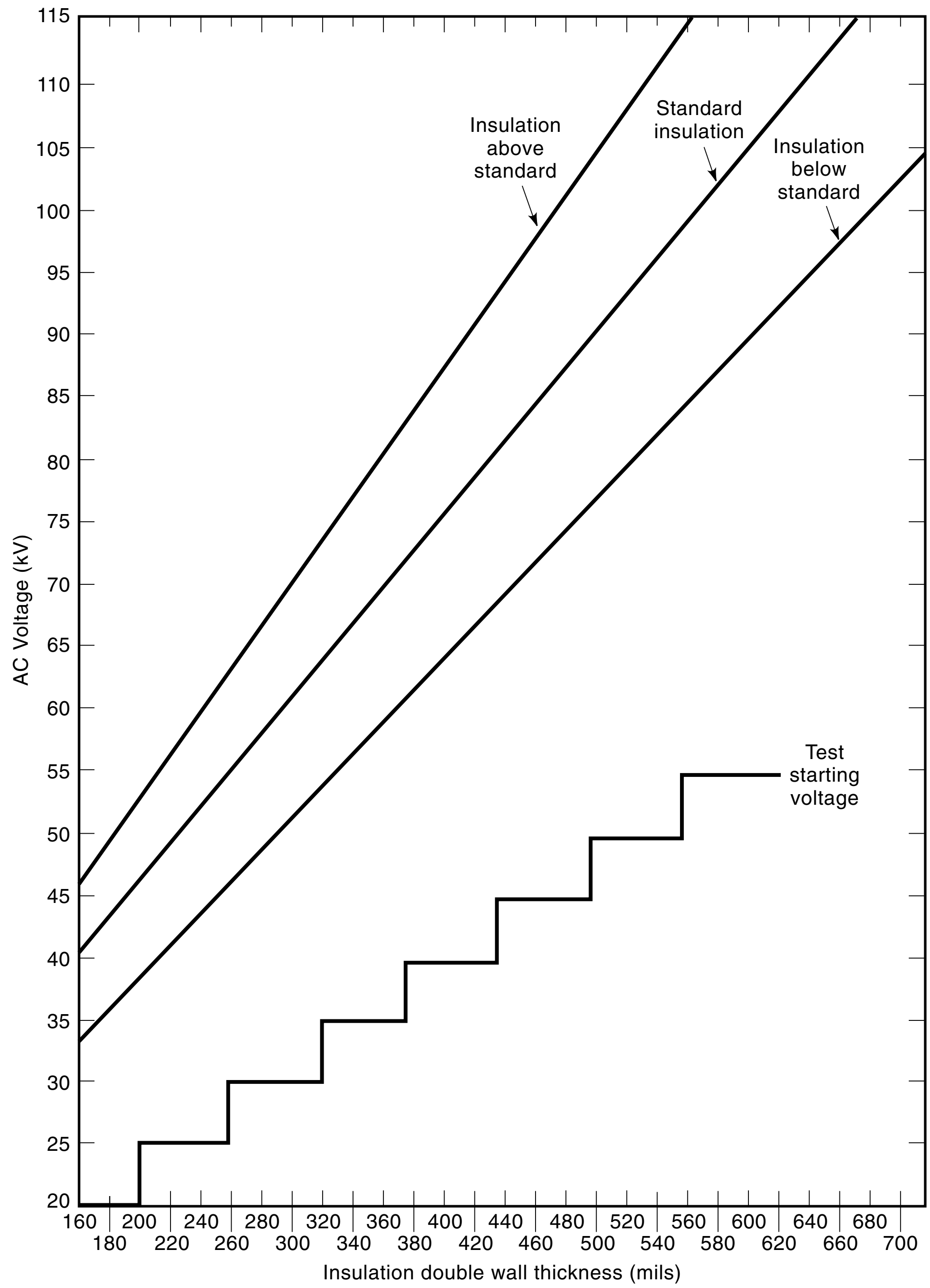

Figure 11. Average voltage hold values and limits for typical epoxy–mica high voltage coil insulation.

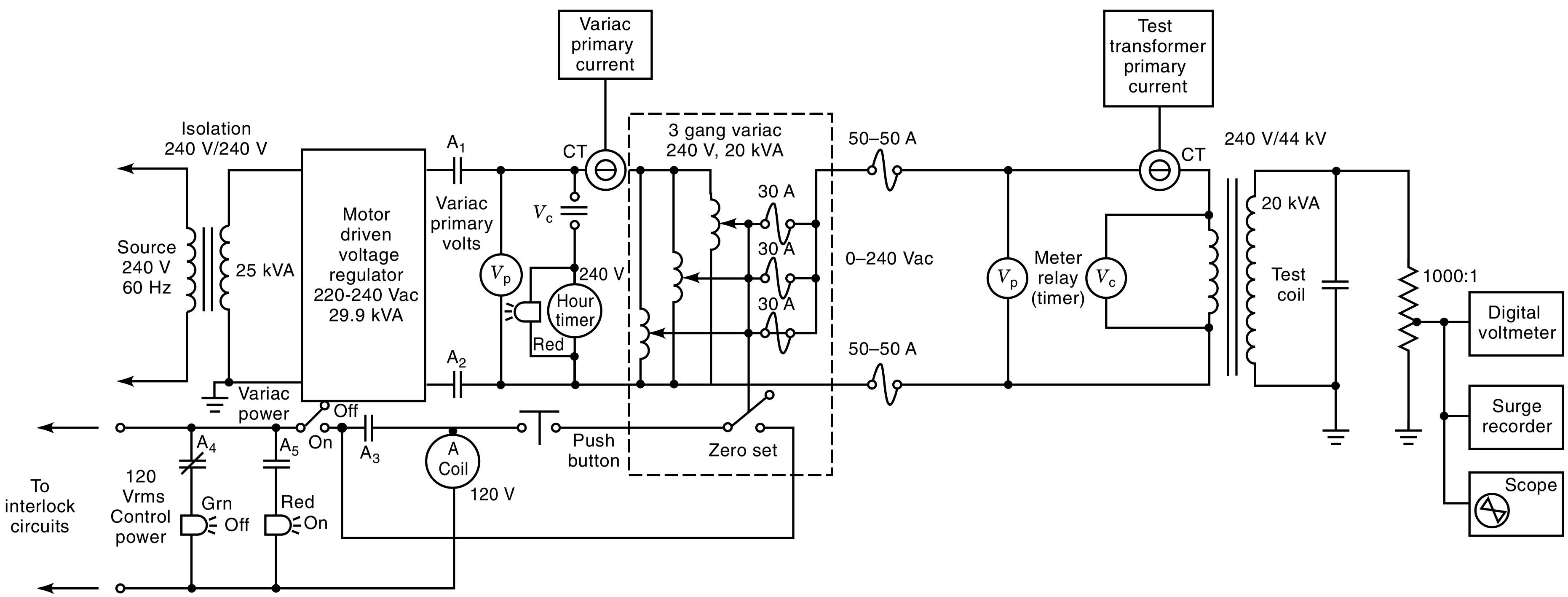

Figure 12. Typical high voltage power supply system designed for voltage endurance testing of high voltage coils.

applied to each coil in the involute region and the power factor test is performed. This test is to check on the consolidation of the end turns to be certain the requirements are met.

STRAND INSULATION BREAKDOWN TEST

A variable ac voltage source, up to 2 kV, is applied between adjacent strands and is increased until dielectric failure occurs between strands. A minimum breakdown voltage is required in order to pass the test. A minimum of 10 pairs of strands are tested per coil.

60 HZ VOLTAGE BREAKDOWN OF GROUNDWALL INSULATION

Voltage breakdown of the groundwall insulation is measured on TWO coils from the production run. These two coils are then used for additional tests designed to keep a status on the insulation system. The coil under test is prepared for the voltage breakdown test and a test starting voltage is selected from a plot based on the coil's insulation thickness. Usually this test starting voltage is about 30% of the expected failure voltage. The applied voltage is increased in 5 kV steps at 1 min intervals until failure of the groundwall insulation occurs or when coil end turn flashover occurs. The breakdown voltage and time (in seconds) at this voltage are recorded. The hold value is calculated based on the time the coil was at the failure level of voltage. The measured hold value is compared with expected values that were derived over many years of accumulated data. The measured hold value should be above the Standard Insulation Curve as shown in Fig. 11. The exact point of failure is recorded. As a general rule, the voltage hold value is about four times the coil rated voltage.

VOLTAGE ENDURANCE TEST

Samples cut from the failed QC coils are voltage endurance tested following the guidelines of IEEE Std. 1043-1996 (3). Major programs are in place to update coil materials and improve manufacturing processes. Therefore, voltage endurance testing of QC production coils has become quite common. Normally, the electrical lifetime of the coils' insulation system is on the order of 40 years, when operated at designed voltage stress levels. Increasing the voltage stress level or reducing the insulation thickness or both will result in insulation failure in a matter of hours, weeks, or months depending on the test parameters. These data are used to predict the electrical life of the insulation when operated at the designed stress level. Voltage endurance testing of high voltage coils involves placing elevated voltages on the coil sections at an elevated temperature. A typical power supply system designed for performing voltage endurance testing of high voltage stator coils is shown in Fig. 12. The voltage stress levels are usually four to six times the normal operating stress levels the coil sees in service. Because a large number of coil samples are tested, the test stress level generally used is in the 12 kVrms/mm range, resulting in short failure times. Voltage endurance testing is used to test new designs, upon customer request, whenever coil materials are updated, to evaluate competitive designs, to test voltage grading techniques, and to maintain control during production. A typical voltage endurance curve is shown in Fig. 13. The actual plot is obtained from testing many samples of good insulation systems. Individual tested coil data are then plotted on this curve to determine the coil's electrical life with respect to the standard curve. The operating voltage stress point can be placed on the plot to estimate the electrical life of the insulation system.

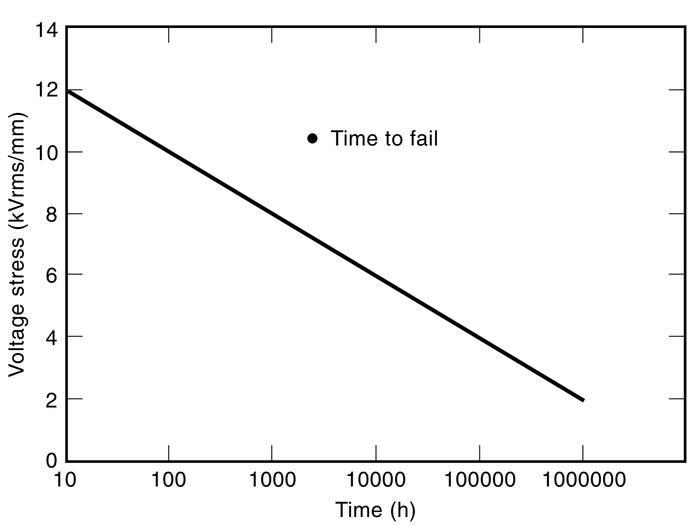

Figure 13. Typical voltage endurance curve for high voltage coils. For a coil to pass the voltage endurance test, its time to failure has to be to the right of the plotted curve. This particular curve is for coils insulated with epoxy–mica insulation.

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3. IEEE Std. 1043-1996, *IEEE Recommended Practice for Voltage Endurance Testing of Form Wound Bars and Coils.*

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INSULATION TESTING. See IMPULSE TESTING.
INSULATION, TRANSFORMER. See TRANSFORMER INSULATION.
INSULATION, VACUUM. See VACUUM INSULATION.
INSULATOR CHARGING. See TRIBOELECTRICITY.
INSULATORS, OUTDOOR. See OUTDOOR INSULATION.