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IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10 000 kVA and Larger)

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Foreword

[This foreword is not a part of IEEE Std 56-1977, IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10 000 kVA and Larger).]

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1. Purpose

The purpose of this guide is to present information necessary to permit an effective evaluation of the insulation systems of large alternating-current rotating electrical machines. Such an evaluation can serve as a guide to the degree of maintenance or replacement which might be deemed necessary, and also offer some indication of the future service reliability of the equipment under consideration.

2. Scope

This guide is intended to apply in general to large alternating-current rotating electrical machines rated at 10 000 kVA or more, and operating at voltages of 6000 V and above.

3. Significance of Maintenance

Rotating electrical machines are complex structures which are subjected to mechanical, electrical, and thermal stresses of varying magnitude. Of the various components, the insulation systems are the most susceptible to aging or damage due to these stresses. The service life of an electrical machine will, therefore, largely depend on the serviceability of the insulation systems.

Where reliability is of concern, adequate inspection and testing programs are advocated to assure that the equipment is maintained in satisfactory condition to minimize the possibility of in-service failure.

The experience and data obtained from regular maintenance inspection and testing programs can, in addition to providing an evaluation of the present condition of the equipment, give some indication of long-term trends and probable need for future repair or replacement.

The extent to which a maintenance program is pursued will depend largely on the operator's own experience and philosophy, but should also take into account the importance of service reliability of the equipment. Where high service reliability is required, a regular maintenance program involving periodic disassembly and knowledgeable visual examination of the equipment, together with the application of electrical tests of proven significance, is strongly recommended.

It should be recognized that some overpotential tests may be damaging to insulation in marginal condition. Where there is uncertainty, consultation with the manufacturer is recommended. This is implicit in setting up any maintenance testing program.

4. Service Conditions Reducing Insulation Life

As has been stated, electrical machines and their insulation systems are subjected to mechanical, electrical, and thermal stresses which give rise to many deteriorating influences, the most significant of which are the following.

4.1 Thermal Aging

Gradual aging caused by temperatures due to normal operating loads.

4.2 Overtemperature

Unusually high temperature from causes such as overload, high ambient temperature, restricted ventilation, and loss of cooling liquid.

4.3 Overvoltage

Unusually high voltage such as from switching or lightning surges.

4.4 Contamination

This deteriorates electrical insulation by actually conducting current over insulated surfaces, or by attacking the material reducing its electrical insulating quality or its physical strength, or by thermally insulating the material forcing it to operate at higher than normal temperatures. Included here are:

Wetness or extreme humidity

Oil or grease

Conducting dusts and particles

Nonconducting dusts and particles

Chemicals of industry

4.5 Physical Damage

This contributes to electrical insulation failure by opening leakage paths through the insulation. Included here are:

Physical shock

Vibration

Overspeed

Unusual electromagnetic forces

Erosion by foreign matter

Damage by foreign objects

Thermal cycling

4.6 Partial Discharge (Corona) Effects

Partial discharges which may occur at higher operating voltages may be accompanied by several undesirable effects such as chemical action, heating, and ionic bombardment.

5. Insulation Systems in General Use

5.1 Insulated Parts

Insulation is present in various machine components, but the complexity of the structure is such that only a general description can be given here. However, detailed information on the structure of insulation systems and modes of insulation failure are important to evaluation.

5.1.1 *Stator Winding*.

The stator winding with its associated leads is the main current-carrying winding of the machine. The coils of the stator winding have strands and ground insulation and may have turn insulation.

Wedges, blocks, and other insulated mechanical supports are a part of the stator winding assembly.

5.1.2 *Rotor Winding*.

The rotors of ac machines are either salient pole or cylindrical type. In all cases, they have turn and ground insulation, insulated mechanical supports, and lead insulation and may have collector rings with insulation.

5.1.3 *Brush Rigging*.

Machines with collector rings will have insulated brush rigging.

5.1.4 *Core Assembly.*

The principal insulation components in this assembly are the insulation between laminations in the core and insulation on through bolts (when used).

5.1.5 *Other Parts*.

Insulation is sometimes used on bearings and other mechanical parts such as hydrogen seals, oil seals, and piping Temperature sensors may be applied, and these usually incorporate insulation. Refer to the manufacturer's instruction book.

5.2 Stator-Winding Insulation

5.2.1 *Strand Insulation*.

The individual strands of stator-coil conductors are usually insulated with organic films, fibers bonded with resins, or mica in various forms bonded with resins. Fibers may be such materials as paper, cotton, asbestos, glass, polyester, or combinations thereof.

5.2.2 *Turn Insulation (Conductor)*.

In a coil with more than one turn, groups of strands forming a single-turn (conductor) may be held together and insulated. Individual strand insulation, as described in Section 5.2.1, may also serve as turn insulation.

5.2.3 *Ground Insulation*.

Ground insulation is generally defined as that insulation intended to insulate the current-carrying components (such as the coils, the collector rings, and connections thereto) from one another and from the noncurrent-carrying components which are usually considered to be grounded (such as the core iron, the shaft, and other structural members).

Ground insulation takes on many different forms depending on the type of machine and the manufacturer's practices.

Ground insulation is generally a dry-type, multilayered system comprising various insulating materials bonded and filled. Mica or micaceous products are generally preferred in high voltage machines for at least a part of the ground-insulation system.

5.2.4 *Insulation Grading System*.

The surface of slot portions of stator coils, including several inches of the coil beyond the core, is normally semiconducting. The semiconducting characteristic is accomplished by the application of conducting varnish or by the use of semiconducting tapes.

5.2.5 *Support Insulation*.

Supports may be nonmetallic or metallic in design. Nonmetallic supports are made of insulating material such as wood, molded parts, or compressed laminates of cotton, asbestos, glass, or synthetic fibers. Where necessary, metallic supports are insulated.

5.3 Rotor Winding Insulation

5.3.1 *Turn Insulation (Conductor)*.

Turn insulation on wire-wound coils usually incorporates a thin insulating layer on the strand itself: for example, various materials such as asbestos, cotton, fiberglass, papers, micas, and synthetic materials.

Turn insulation on strap-wound coils of both salient-pole and cylindrical-type rotors usually incorporates various forms of tape or strip material with resin bonding.

5.3.2 *Ground Insulation*.

Various types of ground insulation are used on the rotating field coils of synchronous machines (salient pole or cylindrical type) and on the wound rotor induction machines. A variety of organic and inorganic materials are used.

5.3.3 *Collector Insulation.*

The insulation used on collector rings and leads must be adequate both for support and creepage to the grounded shaft. The insulation usually consists of laminated fibers or mica suitably bonded or impregnated.

5.4 Brush-Rigging Insulation

The insulatd Components on brush rigging are generally molded compounds, laminates, or tubes made from paper, cotton, glass, or synthetic fibers suitably bonded and impregnated.

5.5 Core and Frame-Assembly Insulation

5.5.1 *Stator-Core Interlaminar Insulation.*

Stator cores are built up from thin steel laminations insulated from one another to reduce core losses. A variety of thin insulating films are used, such as varnish, water-glass, chemical deposits, or chemical treatments.

5.5.2 *Core-Tightening Through-Bolt Insulation.*

The core-tightening through bolts are insulated from ground throughout their length with insulating materials suitably bonded. Bolt-end hardware, such as nuts and washers, must also be insulated from ground. Key bars or bolts, used at the outer diameter of the core for tightening, usually require no insulation.

5.6 Stator-Winding, Embedded, Temperature-Detector Insulation

Stator-winding, embedded, temperature-detector elements are encapsulated in insulating materials. Insulated leads complete the connections from the elements to a terminal board.

6. Visual-Inspection Methods

To achieve maximum benefit from a visual-inspection program, it should be directed initially to those areas which have been shown by previous experience to be most prone to the forms of damage or degradation caused by the influences listed in Section 4 of this guide.

The most significant items to which inspection should be directed are the following sections.

6.1 Stator Windings

6.1.1

Inspect for deterioration or degradation of insulation resulting from thermal aging due to cumulative time-temperature effects. Coils may reveal general puffiness, swelling into ventilation ducts, or a lack of firmness of the insulation, suggesting a loss of bond with consequent separation of the insulation layers from one another or from the winding conductors or turns.

6.1.2

Inspect for girth cracking or tape separation of the ground wall. This is most likely to occur on machines having one-turn stator coils greater than about 3 m in length and having asphaltic-type bonds. Particular attention should be paid to the areas immediately adjacent to the ends of the slots. Where considerable insulation cracking is observed, it is recommended that the wedges at the ends of the slots be removed, if possible, for inspection, as dangerous cracks may also have occurred just within the slots.

6.1.3

Inspect for contamination of coil and connection surfaces by substances which adversely affect insulation surface electric strength, the most common being carbon dust, oil, or moisture contamination.

6.1.4

Inspect for abrasion or contamination of coil and connection surfaces from other sources, such as chemicals, abrasive, or conducting substances. Such effects are aggravated in the case of machines used in adverse-atmospheric industrial applications, such as chemical plants, rubber mills, and paper manufacturing facilities.

6.1.5

Inspect for cracking or abrasion of insulation resulting from prolonged or abnormal mechanical stresses. In stator windings. looseness of the bracing structure is a certain guide to such phenomena and can itself cause further mechanical damage if allowed to go uncorrected.

6.1.6

Inspect for eroding effects of foreign substances embedded or lodged against coil insulation surfaces. Particularly damaging are magnetic pieces (even small particles) which vibrate under the influence of the magnetic field in the machine.

6.1.7

Inspect for insulation deterioration due to partial discharges (corona) in the body of the machine or end windings in the higher voltage ratings. These are evidenced by tightly adhering deposits of white, gray, red, brown, or black color. These deposits are particularly noticeable in areas where the insulation is subject to high electrical stresses. Experience is required to distinguish these effects from powdering which can occur as a result of relative vibratory movement between hard surfaces as can be caused by loose end-winding supports.

6.1.8

Inspect for loose slot wedges or slot fillers, which, if allowed to go uncorrected, may themselves cause mechanical damage or reduce the effectiveness of stator coil retention against normal operating or fault-condition forces.

6.1.9

Inspect for looseness in the parallel-ring or phase-connection supporting structure. Slight looseness of some elements could, if allowed to go uncorrected, lead to more serious problems due to progressive wear.

6.1.10

Inspect bushings for leaks or cracks.. These and other terminal components should be clean to avoid extraneous leakage paths which might affect overpotential tests, especially dc, which may be performed.

6.2 Rotor Windings

In addition to insulation degradation from causes similar to those listed in Section 6.1, close attention should be paid to the following in rotor windings.

6.2.1

Inspect for distortion of coils and coil-to-coil connections due to the effects of abnormal mechanical, electrical, or thermal forces. Such distortion might cause failure of insulation between turns or to ground.

6.2.2

In salient-pole rotors, inspect for shrinkage or looseness of field coil washers. This permits coil movement during periods of acceleration and deceleration with the probability of damaging turn or ground insulation and breaking or loosening of connections between coils.

6.2.3

In cylindrical rotors inspect for evidence of heating or current between retaining rings, wedges, and the rotor body. Heating may be caused by high circulating currents due to generator motoring, phase-current imbalance, or sustained single-phase faults.

If evidence of overheating or burning is discovered, ultrasonic or other nondestructive tests should be made to determine whether thermal cracks (which might propagate into catastrophic failures) are present. Hardness tests are often desirable to detect possible changes in metal characteristics or properties after exposure to excessive temperatures.

The rotor body should be checked for loose or cracked slot wedges and loose balance weights.

The condition and tightness of end-winding blocking, signs of deterioration, or movement of the retaining ring insulating liner due to the above effects, and any other looseness should be noted. Powdered insulation in air ducts may be evidence of coil movement. Red oxide at metallic joints is evidence of movement of metal parts.

Inspect to determine that insulation migration has not closed off cooling passages.

To investigate extraordinary conditions exposed by inspection or operation, removal of retaining rings may be required.

The tightness of field-lead connections and condition of collector and collector-lead insulation should be noted.

6.3 Brush Rigging

Insulation supporting the brush rigging should be inspected for evidence of carbonized leakage paths or contamination which may lead to flashover.

6.4 Core Assembly

In the core assembly, the following items are considered to be the most significant.

6.4.1 *Stator-Core Laminations*.

Inspect for failure of interlaminar insulation. This failure first appears as localized darkening of the insulation, paint, and varnish in an area of the stator bore and can lead to complete machine failure.

Interlaminar insulation failure usually results from mechanical damage, such as from abuse during assembly and disassembly or from foreign objects in the air gap or from electrical arcs during a winding failure.

Whenever several laminations have become short circuited, excessive local heating might arise, resulting in enlargement of the faulted area.

Where such damage is widespread and concern might be felt regarding the adequacy of subsequent repairs, a loop (or ring) test is recommended. This test is detailed in Section 8.1.10.

Inspect for looseness of core laminations. Loose core laminations at the air-gap side of the core (teeth), especially at core ends, will vibrate, abrade interlamination insulation (and ground insulation), short circuit laminations, and cause heating. Also, vibrating laminations may fatigue, crack, break off, and contaminate the machine with iron particles. Iron oxide powder deposits are an indication of loose core iron or loose wedges.

6.4.2 *Ventilation Ducts*.

Inspect for loose or broken ventilation duct separators (or fingers). These can cause core looseness. Also, these can break off, resulting in mechanical damage to the coil insulation and the interlaminar insulation.

6.4.3 *End Fingers*.

Inspect for overheating of the end fingers, which is evidenced by discoloration of the paint or components in the areas affected. Abnormal overheating can lead to thermal degradation of the insulation between laminations with consequent short circuiting of laminations, overheating, and damage to the adjacent coil insulation.

6.4.4 *End Flux Shields*.

Inspect for overheating of the end flux shields (when present) which is evidenced by discoloration of the paint or components in the areas affected. When these shields are insulated, abnormal heating can lead to thermal degradation of the insulation.

6.4.5 *Insulated Stator-Through-Bolts*.

When these are used, inspect the insulation components (washers, tubes, etc) at the ends of the through-bolts for evidence of distress. Verify that the nuts are tightened and locked.

6.4.6 *Bearing, Hydrogen-Seal, and Other Insulation*.

Whenever bearings and other mechanical parts are disassembled, inspect their insulation for signs of deterioration. Pitting in the bearing material may be evidence of bearing-insulation failure. Refer to IEEE Std 115-1965 , Test Procedure for Synchronous Machines, for electrical test procedure.

7. Cleaning

7.1 General

Care and good judgment must be used in any program for cleaning of electrical machinery and windings. Excessive cleaning and unwise use of solvents can do more damage than good, and result in expensive rewinding or repairs.

The need for cleaning may be indicated from:

1) Previous history of machine
2) Equipment application
3) Visual inspection
4) Low insulation resistance
5) Overheating

Once the need for cleaning is established, the cleaning method can be tailored to the type of contamination and the severity of the contamination buildup.

After cleaning (and drying if necessary) the insulation surface condition should be checked for surface cracks, porosity, or the effects of harsh cleaning methods. The desired surface insulating finish should be reestablished by the application of suitable varnishes, paints, or resins. Depending on accessibility or size, surface treatments may be applied by dipping, spraying, flooding, or brushing.

7.2 Cleaning Techniques

The method of cleaning can be adapted to the type of contamination and the buildup of contaminants. The methods listed in the following section are in increasing order of severity and possible damage to windings.

7.2.1 *Vacuum Cleaning*.

Dry contaminants such as carbon dust, coal dust, and fly ash can be removed with a vacuum cleaner. Contaminants can be dislodged for vacuum pick-up by:

1) Rubbing with dry cloths
2) Brushing with a bristle brush
3) Scraping with soft wood or fiber scrapers
   (Wire brushes or metal scrapers should not be used because of possible damage to the insulation and the dangerous possibility of introducing magnetic or other metallic particles into the winding or core assembly.)
4) Nozzle shapes should be varied as required to enable directing the vacuum cleaning into hidden, difficult to clean areas.

7.2.2 *Air-Lance Cleaning.*

After vacuum cleaning, additional cleaning can be done employing shaped nozzles to direct high-velocity clean dry air to dislodge trapped contaminants. It is recommended that air pressure be limited to avoid damaging the insulation.

7.2.3 *Solvent Cleaning.*

Care must be exercised in the choice and application of cleaning solvents from the standpoint of worker safety, and risk of damage to the insulation. The manufacturer should be consulted to select a solvent and method of application which is noninjurious to the winding.

7.2.3.1 *Personnel Safety.*

The persons who will carry out the cleaning should be instructed on the safe use of the solvents. Among those instructions should be the following:

1) Use personal protective equipment such as respirators, goggles, and gloves. Avoid skin contact with solvents, particularly the chlorinated solvents.
2) Use small quantities of solvent at a time to minimize exposure to vapors.
3) Determine that adequate ventilation exists.
4) Rotate cleaning personnel to minimize exposure.
5) Have fire extinguishers, for solvent fires, available to use.
6) Do not smoke around solvents.
7) Use safety containers of the kind prescribed by appropriate regulations.
8) Make certain the machine is cleared electrically and the windings are grounded. Ground spray equipment also, if used.
9) Keep ignition sources out of the cleaning area. Such sources are sparks, flames, welding, open lamp, heaters, and switches.

7.2.3.2 *Types of Solvents.*

Petroleum solvents of the safety type can be used for removing oily and greasy contaminants from asphaltic or synthetic-resin types of insulation. These solvents should be used sparingly. Quite often a lint-free cloth, dampened in solvent, is adequate for rubbing off the contamination. Saturation of asphaltic-type insulations should be avoided to prevent softening of the insulating materials.

Where a stronger or faster-drying solvent is required. a chlorinated safety solvent can be used on asphaltic and synthetic-resin types of insulation. For recommendations on specific solvents to be used with each given insulation the manufacturer of the machine should be consulted. Here, again, solvent-dampened cloths are often sufficient for wiping off contaminants. Refer to Section 7.2.3.3 for risk of damage.

Mixtures of petroleum solvents and chlorinated solvents can be used with better cleaning capability than the petroleum solvents alone. Such mixtures must not be considered nonflammable, even though in some proportions they might be. Differences in evaporation rates can change characteristics of the blend.

Carbon-tetrachloride and benzene are highly toxic solvents and are not to be used for cleaning. Gasoline, naphtha, and similar liquids are not to be used for cleaning because of fire and explosion hazards.

7.2.3.3 *Risk of Damage.*

Liquid solvents are effective in removing oily contaminants. but there are risks involved, particularly from spray applications of solvents. The solvents may carry contaminants into cracks, crevices, or inaccessible areas and cause the insulation resistance to decrease to unsafe levels.

Chlorinated solvents *must not* be used on stainless steel components unless agreed upon with the manufacturer because of the possibility of stress corrosion caused by the chlorides. Examples of stainless steel components are: (1) nonmagnetic retaining rings and wedges on turbine-generator rotors, and (2) stator cooling oil or water systems on turbine-generators. Chlorinated solvents must not be used on aluminum or copper components because of chloride attack.

Solvent cleaning of cylindrical rotors should be avoided. Cleaning of cylindrical rotors should be limited to vacuuming, blowing with dry compressed air, wiping with dry or solvent dampened cloth, or combinations of these three methods. The need for more extensive cleaning may involve retaining ring removal to provide access to areas where contaminants are trapped. Carbon brushes should not be allowed to absorb solvents, particularly the chlorinated types.

Neither petroleum solvents nor chlorinated solvents should be used on silicone insulated windings because of the degrading effect on this type of insulation.

7.2.4 *Abrasive Blasting.*

Another method for removing contaminants utilizes an air blast of ground corn cobs or ground nut shells. This method is often successful for removing oily contaminants. The air-abrasive blast must not be held too long on any one area or the insulation will be damaged by abrasion. Care must be exercised to avoid blowing the abrasive material into inaccessible areas where it cannot be completely removed and may block ventilating passages or cause mechanical imbalance during operation.

7.2.5 *Steam Cleaning.*

The steam-jenny method of cleaning utilizes a high-velocity jet of steam and water containing a mild nonconductive detergent. The detergent spray is followed by multiple steam and water sprays without detergent to provide adequate rinsing. The machine must then be dried or baked to remove all moisture from the windings and to obtain an acceptable insulation resistance value. If an overvoltage test is applied after steam cleaning, there is a risk of insulation failure if all moisture has not been removed or the insulation is defective.

Regardless of the procedure used for drying insulation systems, initial dryout temperatures should not exceed 75 to 85°C (reached at a maximum rate of 5°C/h). In exceptional cases, where insulation resistance does not respond to this limit after 24 h, the maximum temperature may be carefully increased to 100–105°C. At temperatures of 100°C or higher, the possibility of insulation rupture (as water changes to steam) should be a prime consideration in the time-temperature schedule selected. Ventilation is required to remove the water vapor during the heating cycle.

The steam cleaning method is effective on heavily contaminated windings and windings subjected to flooding or salt contamination.

The steam cleaning method usually can be used on silicone-insulated windings.

7.2.6 *Cleaning By Water Immersion or Water Hose.*

The machines involved in this guide are generally too large for immersion, but heavily contaminated or flooded machines can be washed with a hose. Baking and drying precautions noted under steam cleaning would also apply for water immersion or water hose cleaning.

Silicone-insulated windings can be generally cleaned using the water hose method with a nonionic, nonsudsing detergent.

8. Maintenance Tests

The tests listed below have been used generally either to establish the long-time trends in parts of the insulation structure, or to detect specific types of flaws which may develop in portions of the insulation.

The common tests normally used for maintenance evaluation are directed at determining the condition of the ground insulation. These are direct-current, insulation-resistance tests, and overvoltage proof tests. It is customary to make one or more of such tests at each inspection.

Other tests are sometimes employed to detect specific types of insulation deterioration. Their use should be based on the need for the information they provide.

With many maintenance tests, the trends measured over a period of years are normally more important than absolute measured values determined at a specific inspection period. A sudden change in the values for a given machine should be investigated and the cause determined. In windings, large insulation areas are involved, and discrete areas of weakness may or may not significantly affect the overall measured values for the entire winding.

Inspections and tests of windings are usually made at convenient intervals in the range of 1 to 5 years. Ordinarily, intervals of 2 to 3 years (depending upon machine availability) between times of inspection and test are considered good practice.

8.1 Stator Winding

8.1.1 *Insulation Resistance.*

IEEE Std 43-1974 , Recommended Practice Testing Insulation Resistance of Rotating Machinery, outlines recommended practice for measuring insulation resistance.

8.1.2 *Dielectric Absorption Test.*

IEEE Std 43-1974 and IEEE Std 95-1962 , Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage, outline recommended practices for obtaining dielectric absorption data.

8.1.3 *Overvoltage Test.*

Overvoltage tests are used to obtain assurance concerning the minimum strength of the insulation. Such tests are made on all or parts of the ground insulation. Many users of large rotating machines apply overvoltage tests periodically, generally at the beginning of the overhaul of related equipment. This allows for the detection and possible repair of insulation weaknesses during the scheduled outage.

An overvoltage test should be applied to each phase separately with the remaining phases not under test being grounded. In this way, the insulation between phases (or lines) is also tested. This is only practical, however, where both ends of each phase are brought out to separate terminals, as is usually the case in generators. Some motors may have three or four leads brought out which precludes test between phases.

Overvoltage tests may be performed either with alternating or direct voltage. The level of overvoltage which should be applied will depend to a large extent on the type and age of the machine involved, the degree of exposure to overvoltages, and the level of serviceability required from the machine in question. It should, however, be sufficiently searching to discern any weakness or incipient weakness in the insulation structure which might lead to service failure. It should be recognized that if the windings are clean and dry, overvoltage tests may not detect defects which are in the end turns or in leads remote from the stator core.

The values of test voltages usually are selected in the range of 125 to 150% of the rated line-to-line voltage and are normally held for 1 min:

1) Refer to IEEE Std 4-1968 , Techniques for Dielectric Tests (ANSI C68.1-1968), for power frequency testing (see Section 9).
2) Refer to IEEE Std 433-1974 , Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency, for 0.1 Hz testing and recommended voltage level ratio (see Section 9).
3) Refer to IEEE 95-1977 for direct voltage testing and recommended voltage level ratio (see Section 9).

8.1.4 *Turn-To-Turn Insulation Test.*

In cases where the integrity of the insulation between adjacent turns in a coil is subject of concern, tests should be made to establish that a desired level of insulation strength is present. Test equipment, employed in the application of turn insulation tests, is usually of the type where a capacitor is alternately charged and then discharged into the coil under test (or into an inducing coil which has been placed in the stator bore, over the coil under test).

Since the insulation between turns of stator coils varies greatly in types of insulating materials, types of construction, and spacing, test values are usually determined after consultation with the coil or machine manufacturer. Any test value selected to verify the adequacy of interturn insulation should be based on the design, physical spacing and electrical strength of the insulating system. Refer to IEEE Project 522, Guide for Testing Turn-to-Turn Insulation on Form Wound Coils for Rotating Machines, for turn-to-turn testing (see Section 9).

8.1.5 *Partial-Discharge Tests*

8.1.5.1 *Slot-Discharge Test.*

The slot discharge test is made for the single purpose of checking the adequacy of the electrical contact between conducting-coil surfaces and the iron of stator slots. Loss of this electrical contact results in a relatively high energy discharge between the conducting-coil surface and the core. The energy is that resulting from a substantial portion of the coil-side capacitance. Since greatly accelerated deterioration of the major ground insulation is produced by slot discharge, early detection and correction of this condition is important.

Slot-discharge analyzers utilize detection circuits resonant in the frequency range where energy from surface discharging is high (approximately 2500 Hz), while blocking 60 Hz voltage by means of a high-pass filter.

Tests are made with the winding energized at approximately the operating stress to ground. Detection is accomplished by connecting the slot-discharge analyzer to the machine terminals, one phase at a time. When a discharge exists, high-frequency reflections are readily observable on a cathode-ray oscilloscope connected to the slot-discharge analyzer output. Location of specific coils suffering slot discharge is accomplished by a probe test. The probe test utilizes the slot-discharge analyzer in conjunction with a probe which successively contacts the conducting surfaces of individual stator coils.

If the rotor is removed to provide access to the stator-bore surface, an alternate test may be made to provide a partial check of the adequacy of coil surface grounding in the slot portion of the stator. With slot wedges removed, contact-resistance measurements between exposed top-coil surfaces and the iron of the slot may be taken with a low-voltage ohmmeter, used with a suitable probe. If slot wedges are not removed, it is often possible to obtain these resistance measurements, through core vents, from the coil side to the iron of the core. Resistance measurements should be made at several locations along the slot length of every stator coil. Since bottom-coil sides are relatively less accessible, evaluations are usually based on values measured on top-coil sides. Values of coil surface contact resistance, when in accordance with manufacturer's recommendations, verify adequate coil surface grounding and the absence of slot discharge.

8.1.5.2 *Corona-Probe Test.*

The corona-probe test is intended to be an indicator and locator of unusual ionization about the insulation structure. This test is sensitive to end-winding surface corona, as well as internal-cavity ionization in the insulation structure. Compared to slot discharge, the discharge energies involved in surface corona or internal-cavity ionization may be of a much lower order of magnitude. The energy in the discharge varies as the square of the voltage across the gap and directly as the effective capacitance at the point of breakdown.

Partial Discharge (Corona) has several undesirable effects, such as chemical action, production of heat, and ionic bombardment. The deteriorating effects of corona are dependent on its intensity and repetition rate as well as the design of the insulation system involved.

Inorganic insulation components such as mica and glass are not affected seriously by corona. Charring or decomposition of organic materials will occur in the vicinity of continued corona activity. However, surface effects may be limited by insulating finish treatments incorporating pigmentation to resist attack from the weak acid deposits formed by surface corona in the presence of oxygen and moisture.

Corona-probe-test equipment consists of three basic units:

1) Equipment capable of energizing the stator winding at its normal operating line-to-neutral voltage at rated frequency.
2) An antenna or corona probe. For end-winding corona measurement, the antenna usually about 1 in long, surrounded by an insulation housing, and mounted on the end of a long insulating handle.
   For internal-cavity-discharge (corona) measurements, these utilize a multiturn coil wound on a ferrite rod approximately 2 in long by 0.25 in diameter and mounted on the end of an insulating handle. Measurements are made by placing the ferrite rod over the teeth enclosing the coil being tested.

3) An amplifier and indicator (for connection to the antenna) or a peak-pulse meter (for connection to the ferrite corona probe).

The amplifier is one of the usual type for audio frequencies and must reject 60 Hz and radio frequency signals. The indicator may be earphones, an output meter, or a cathode-ray oscilloscope.

The peak-pulse meter is a broadband instrument calibrated in units of picocoulombs of apparent charge. Measurements may be obtained from the meter itself or by connecting the meter output to an oscilloscope or chart recorder.

The use of the corona-probe test and the evaluation of test data obtained is in relatively early stages of development and study. The ability of the test to distinguish varying intensities of external corona activity and internal cavity corona has been established. However, the evaluation of data, to permit discrimination between harmful and acceptable levels, has not yet reached the stage where industry standards are established.

8.1.6 *Winding Resistance.*

A reduction in winding resistance may indicate shorting of conductors. An increase in winding resistance may indicate poor connection.

Resistance of the stator winding is usually measured with a low-resistance (Kelvin) bridge or by the drop-in-potential method. Refer to IEEE Std 118-1949 , Master Test Code for Resistance Measurement (see Section 9). The measurement is normally made for each phase separately. The stator winding should be at room temperature when the cold resistance measurement is made, and the temperature of the winding carefully determined. Refer to IEEE Std 119-1974, Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus (see Section 9).

The resistance-temperature characteristic of copper in the range of temperatures usually encountered is a straight line which, if extrapolated, intersects the zero resistance axis at –234.5° C. Based on this characteristic, the temperature corresponding to any resistance of a copper winding may be determined from the formula:

$$t_2 = \frac{R_2}{R_1}(234.5 + t_1) - 234.5$$

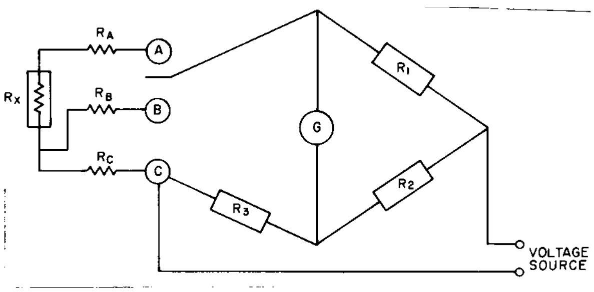
where R_1 and R_2 are winding resistance in ohms measured at temperatures of t_1 and t_2°C, respectively.

8.1.7 *Resistance Temperature Detectors.*

RTDs (Resistance temperature detectors) are resistance coils so constructed that the temperature may be measured by change in resistance.

Measurements are usually made in order to verify that RTDs are properly connected and that they are free of undesired ground contacts or open circuits. Measurements consist of comparisons of readings from each RTD with all others, and should be made at room temperature. Refer to IEEE Std 118-1949 and IEEE Std 119-1974 (see Section 9).

For the measurements, a resistance bridge is normally used. A special RTD meter for directly reading temperatures of detectors can also be used. Referring to Fig. 1, all three leads of a given RTD must be of equal length and wire size so that the three lead resistances all have the same value. By subtracting the resistance measured between terminals *B* and *C* from the resistance measured between terminals *A* and *C* (or *A* and *B*), the resistance of the temperature sensing element alone can be accurately determined. The temperature element is usually made of copper wire and is appropriately sized so that its resistance at 25°C is 10Ω. From the measured change in resistance, the temperature of the element may be calculated. After proper meter corrections are applied, temperature readings of each RTD and the thermometer readings should agree to within plus or minus 3°C.



R_x = RTD element
R_A, R_B, R_C = Lead resistances
A, B, C = RTD terminals
R_1, R_2, R_3 = Known resistances

Figure 1—RTD and Wheatstone Bridge Circuit

8.1.8 *Insulation-Resistance Test of Embedded Temperature Detectors.*

Stator winding embedded temperature detectors (resistance or thermocouple types) are connected by cable to a terminal board on the frame of the unit. Often one lead of each of the detectors is connected to a common ground strip at the terminal board. If a detector located in the slot portion should become grounded, circulating currents could occur between that ground and the terminal board ground. To guard against this possibility, insulation resistance measurement should be made on the detectors at convenient intervals. Tests are usually made on all detectors simultaneously at 500 V dc after the terminal board common has been isolated from ground. (Recording equipment, connected externally to the terminal board, should be isolated from the test potential.)

8.1.9 *Insulation Resistance Test of Insulated Stator- Through-Bolts.*

Insulation resistance to ground of Stator-Through-Bolts should be measured at a voltage level recommended by the manufacturer.

8.1.10 *Test of Interlaminar Insulation of Stator Core.*

A test, often referred to as a loop test or a ring test, has been found to be an effective and relatively easy method of testing interlaminar resistance of stator core. Prior to conducting this test it is recommended that the manufacturer be consulted.

In cases where significant damage is visually evident, the interlaminar insulation must be reestablished before the application of the test. Otherwise, additional overheating and burning damage may occur during the test.

8.1.10.1 *Safety Considerations.*

Considerable hazard may exist in connection with this test. All test personnel involved should be familar with the safety precautions which should be observed. The following is a list of some of the major safety items related to this test:

1) Shielded cable should never be used for the magnetizing coil as applied voltage will also be induced into the cable shield.
2) Do not go near the magnetizing coil or the stator core when the test setup is energized.
3) All electrical connections should be checked before a trial application of power is made.
4) Appropriate fire protection should be made available during the test.
5) Liquid cooling system, if present, should be drained and remain empty.
6) Machine terminals should be opened and safely covered and flagged.
7) Stator RTDs and their recorder should remain in service during tests.
8) Adequate phone and other communication systems should be established among various points for proper test control.
9) If thermocouples are used for temperature measurements, a considerable personnel hazard may exist since up to full search coil voltage can be induced in the thermocouple lead. Also, care should be exercised to avoid short circuiting laminations with the thermocouple lead.
10) On large machines, for example, steam-turbine generators, cables should be secured against motion during energizing.
11) Care must be taken that no metallic objects are in contact with the air-gap side of the core laminations. Also extraneous metallic structural objects, metal ladders, crane cables, etc, which might form a conducting circuit around the core, should not be left in the machine during test.

8.1.10.2 *Test Procedure.*

A summary of helpful notes and precautions concerning the performance of this test are given in Appendix A.

8.1.11 *Insulation Dissipation-Factor or Power-Factor Tests.*

IEEE Std 286-1975 , Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machinery Stator Coil Insulation, details the recommended practice for the power factor tip-up test.

Dissipation-factor or power-factor tests provide useful information for evaluating the insulation structure of high-voltage machine windings. The value and significance of the test is greatly dependent on the size of the test sample. Dissipation-factor or power-factor values measured on a complete assembly are averages of those values which would have been obtained on individual components of that assembly. Thus, weaknesses or deterioration in one component may be masked by the average dissipation factor or power factor measured on an entire assembly.

8.2 Rotor Winding

8.2.1 *Insulation Resistance.*

IEEE Std 43-1974 outlines a recommended practice for measuring insulation resistance.

8.2.2 *Dielectric Absorption Test.*

IEEE Std 43-1974 outlines a recommended practice for measuring dielectric absorption.

For this test the potential is usually 500 V dc.

8.2.3 *Winding Resistance.*

A reduction in winding resistance may indicate shorting of conductors. An increase in winding resistance may indicate poor connection.

When using the voltage-drop method, changes in winding temperature and resistance should be limited by using a value of direct current not exceeding one-third the rated value.

The rotor winding should be at room temperature before the cold resistance measurement is made, and the temperature of the winding carefully determined.

For synchronous machines, it is necessary that field resistance and the corresponding temperatures be accurately measured since the temperature rise of the field winding during operation is commonly determined from the change in resistance.

In measuring the rotor resistance by the voltage-drop method, it is essential that voltage contacts for the voltmeter be placed directly on the collector rings or exposed leads of the rotor winding.

8.2.4 *Winding Impedance.*

The presence of short-circuited turns in the windings of cylindrical rotors of turbine-generators or individual field coils of salient-pole generators or motors may be detected by impedance measurements. These measurements are usually obtained by applying 110 V at power frequency across the collector rings and measuring the input current and voltage at standstill. At constant input conditions, voltages are measured across the field coils of individual poles. With the field coils connected in series, similar coils should have a comparable voltage drop. A running impedance test may be performed by measuring voltage and current at the collector rings while the rotor speed is increased. This method determines the speed at which an intermittent short circuit occurs. (If a rotor has brushless excitation, the manufacturer's instructions should be reviewed carefully before making impedance tests.)

Under test conditions, the effect of a short-circuited turn in a field coil can be compared to the effect of a shorted secondary on the impedance of a transformer. Field coils with shorted turns will have a significantly lower impedance (and lower voltage drop) than the remaining coils, with no short circuits, in the series circuit. When a coil with short-circuited turns has been discovered, the test may be expanded to measure the voltage drops across individual coil turns. The ease of applying this exploratory test is dependent on the construction of the coil and the available access to individual turns.

The overall ohmic value of winding impedance obtained from the impedance test is useful if an initial reading, with no short-circuited turns, is available for comparison. When ohmic values are used for comparison purposes, test results should have been obtained at approximately the same voltage for the two tests being compared.

Rotor windings of synchronous motors often suffer progressive damage from the high currents induced in the shorted turns during each start up. However, generator rotors have been known to operate satisfactorily for many years with a few short circuits between successive turns in one or more coils. Therefore, re-insulation of generator rotor short-circuited turns is often unnecessary.

In operation, the first signs of short-circuited rotor turns may be increased rotor vibration or increases in excitation requirements.

The effects of short-circuited turns on rotor vibration may be due to electromagnetic or thermal influences. Electromagnetic effects would inherently be more pronounced on rotors with four or more poles. Removal of excitation will often indicate whether the effects are electromagnetic. thermal, or both. If short-circuited turns cause thermal unbalance, the vibration will vary with temperature and hence will lag any increase in excitation by the length of time required for heating to occur. If variations from the cold to the hot condition are not too great, weight adjustments can sometimes be made to keep the vibration amplitude entirely within a satisfactory range for all temperatures. Otherwise, either thermal balancing or reinsulation of the short-circuited turns is necessary.

If the primary effect of short-circuited rotor turns is an increase in excitation requirements, reinsulating would be dependent on the ability to supply sufficient field excitation, under normal reactive load conditions, without exceeding exciter or rotor recommended operating temperature limits.

Experience on generators has shown that short-circuited rotor turns are not usually progressive in nature and are more apt to reduce the temperature in their respective coils than increase them. However, due to increased excitation current requirements, the average rotor temperature is increased even though a voltage-drop type of temperature indicator may show the reverse.

Changes in rotor excitation requirements may be detected by comparison of a recent no-load saturation curve with the original curve. If the rotor has a temperature recorder, the chart should be examined for indications of a sudden drop in rotor resistance at the time vibration appeared.

8.2.5 *Winding Flux Distribution.*

In addition to the impedance measurements referred to in Section 8.2.4 of this guide, several other tests are available by means of which short circuits between turns of cylindrical-pole rotors can often be detected and located.

Location of the slots containing short-circuited turns or coils may be possible in solid rotors without retaining ring removal, by measuring the leakage flux across the top of the slot wedge with an alternating voltage applied to the collector rings, and comparing the readings for the various slots. With nonmagnetic wedges, a single short-circuited turn out of 20 to 30 turns will reduce by nearly 50% the alternating voltage induced in an exploring coil held above the slot wedge. Slots with magnetic wedges should be compared with one another, as their leakage flux is quite low. An oscilloscope is often useful to measure the exploring-coil voltage, which will be quite low, if a 110 V ac supply is used across the collector rings. Other means are also used, such as an ac potentiometer or a vectormeter. In some cases, a detector coil may be built into the stator, in the main stator body, embedded in a stator slot-wedge or inserted into the gap.

9. References

9.1 IEEE Standards

IEEE Std 4-1968, Techniques for Dielectric Tests (ANSI C68.1-1968).

IEEE Std 43-1974, Recommended Practice for Testing Insulation Resistance of Rotating Machinery.

IEEE Std 51-1955, Guiding Principles for Dielectric Tests.

IEEE Std 62-1958, Guide for Making Dielectric Measurements in the Field.

IEEE Std IEEE Std 67-1972. Guide for Operation and Maintenance of Turbine-Generators (ANSI C50.30-1972).,

IEEE Std 95-1976, Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage.

IEEE Std 100-1972, Dictionary of Electrical & Electronics Terms (ANSI C42.100-1972).

IEEE Std 115-1965, Test Procedure for Synchronous Machines.

IEEE Std 118-1949, Master Test Code for Resistance Measurement.

IEEE Std 119-1974, Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus.

IEEE Std 286-1975, Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machiney Stator Coil Insulation.

IEEE Std 432-1976, Guide for Insulation Maintenance for Rotating Electrical Machinery (5 HP to less than 10 000 HP).

IEEE. Std 433-1974, Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency.

IEEE Std 454-1973, Recommended Practice for the Detection and Measurement of Partial Discharges (Corona) During Dielectric Tests.

IEEE Project 522, Guide for Testing Turn-To-Turn Insulation on Form Wound Coils for Rotating Machinery.

9.2 ASTM[1] Standard

ASTM Std D3382-75, Standard Methods of Test for Measurement of Energy and Integrated Charge Transfer Due to Partial Discharges (Corona) Using Bridge Techniques.

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Annex A Test of Laminar Insulation in Stator Cores

(Informative)

[This appendix is not a part of IEEE Std 56.1977. Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10 000 kVA and Larger).]

Included in this appendix are some helpful considerations to aide in the testing of laminar insulation in stator cores.

A.1 Design of Magnetizing Coil

In order to test the stator core adequately, it is necessary to magnetize the core at approximately its normal operating peak.

The turns of the magnetizing coil should encircle the stator through the main bore (after rotor is removed) and around the outer frame. A preferable return route, if available, is near the outside diameter of the core, within the frame. On large-diameter machines (such as waterwheel generators), the magnetizing coil should be distributed around the periphery of the stator to ensure uniform flux distribution around the entire core. A clearance of 3 in to 12 in should be maintained between the magnetizing-coil conductor and solid metal (that is, metal floor, frame, etc).

A.2 Search Coil

A single turn of AWG 12 to 18 wire, insulated adequately for the volts per turn applied, should be placed around the core, preferably diametrically opposite from the magnetizing coil. The actual core flux density can be measured by placing the search coil so that it encircles only the core and does not include the frame members. On most machines this is not possible, but the error in measured flux density is acceptable.

A voltmeter connected to the search coil will read approximately the volts per-turn value calculated in Section A3.

A.3 Calculations

The following calculations are performed in designing the test. Volts-per-turn value for the magnetizing coil as well as the search coil is given by:

$$\mathrm{VPT} = 4.44 f \, \phi \, 10^{-8} \tag{1}$$

$$\phi = B \frac{(D_1 - D_2)}{2} L_{\mathrm{eff}} \tag{2}$$

where

VPT = volts (rms) per turn
f = frequency in hertz
ϕ = peak core flux in lines
B = peak core-flux density in lines per square inch (from manufacturer)
D_1 = outside diameter of core in inches
D_2 = diameter to bottom of stator slots in inches
L_{eff} = effective length of core in inches

The effective length of core should be obtained from the manufacturer. If that is not possible, the value can be calculated as follows:

$$L_{\mathrm{eff}} = (L - N_v b_v) F_{\mathrm{s}} \tag{3}$$

where

L = gross length in inches
N_{v} = number of ventilation ducts
b_{v} = width of ventilation duct in inches
F_{s} = core stacking factor (from manufacturer

From the known supply of voltage and the volts-per-turn value from Eq (1), the number of turns for the magnetizing coil can be determined by direct division. The result should be surrounded to the next higher integer. This number of turns should be used in the first trial test.

In order to determine the size of the cable necessary for the magnetizing coil, data on ampere-turns per inch of mean back iron periphery corresponding to the core-flux densities will be required. These data should be obtained from the manufacturer.

The magnetizing-coil current requirement is given by:

$$I_{\mathrm{t}} = \frac{\mathrm{ATI}}{N_{\mathrm{t}}}\left(\frac{D_1 + D_2}{2}\right)\pi \tag{4}$$

where

I_{t} = magnetizing coil current in amperes
ATI = ampere-turns per inch (from manufacturer)
N_{t} = number of turns
π = 3.14
$D_1 + D_2$ = (see Eq 2)

Using the results from Eq (4), the approximate minimum conductor area can be calculated.

A.4 Temperature Measurements

The magnetizing coil should be located remote from the areas suspected as damaged in order to facilitate temperature measurement. Thin shavings of paraffin, thermometers affixed with a suitable putty, thermocouples, portable pyrometers, or infrared cameras can be used to detect hot spots. These should be detectable in 15 to 30 s if the low interlaminar resistance is located at the bore surface. If the low interlaminar resistance is radially outward from the tooth surface or in core areas below the bottom of stator slots, 10 to 20 min of excitation may elapse before the heat becomes evident at the tooth bore surfaces. A final heat run of 1 to 3 h should be made after all repairs are completed.