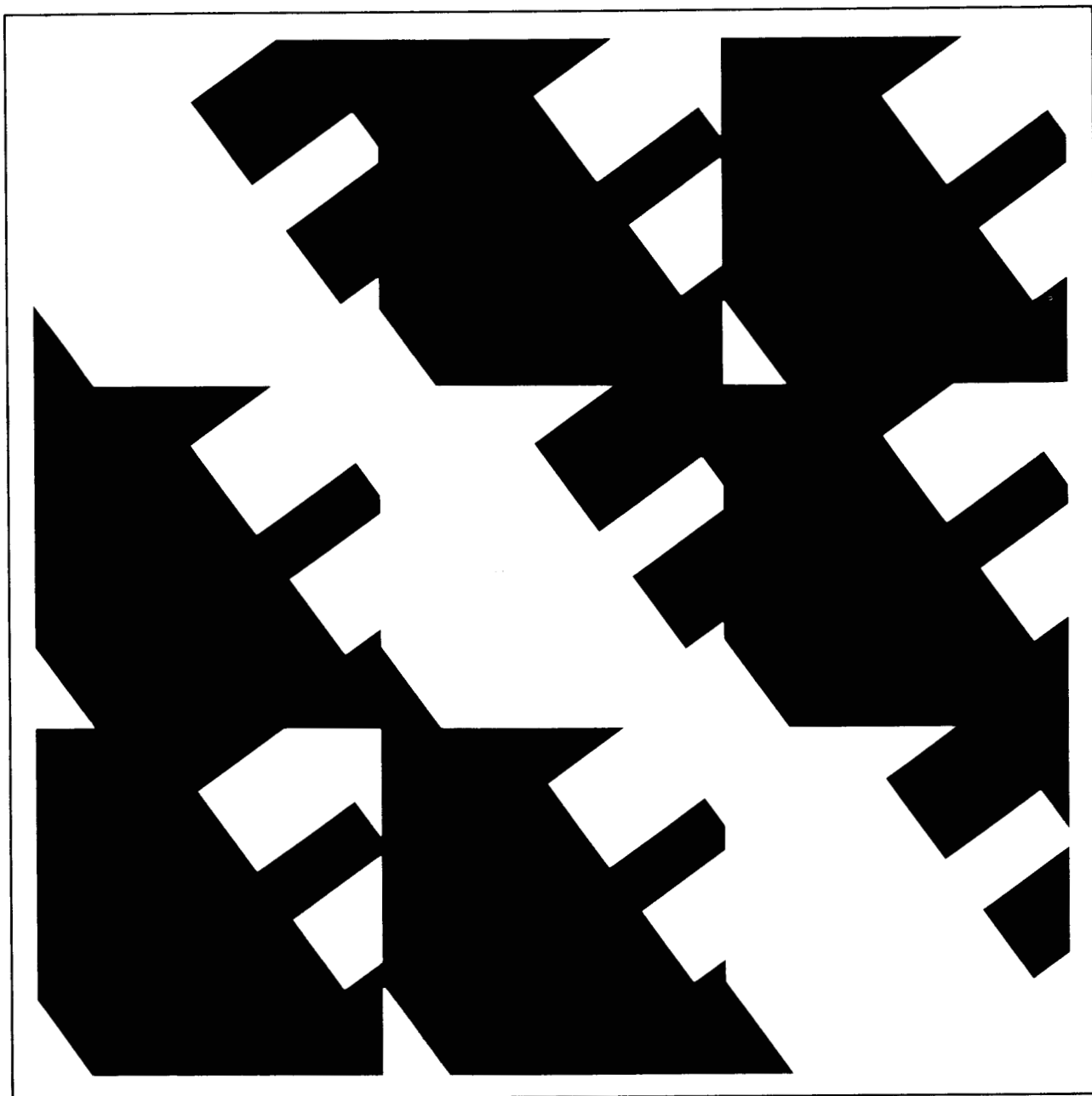


IEEE Guide: Test Procedures for Synchronous Machines

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IEEE Guide: Test Procedures for Synchronous Machines

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**Rotating Machinery Committee
of the
IEEE Power Engineering Society**

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Foreword

(This Foreword is not a part of IEEE Std 115-1983, IEEE Guide: Test Procedures for Synchronous Machines.)

IEEE Std 115-1983 is the first major revision of this standard since 1965. Work on a separate standard for testing of synchronous machines was originally initiated within IEEE in 1929, and a preliminary report was issued in 1931. The first approved standard (originally designated AIEE No 503) was published in 1945. Work on a revision was initiated in 1953, but the task was a large one requiring a complete restructuring of the original standard and the substitution of references to other standards, rather than inclusion of material that had originated elsewhere. The revision was approved and published as IEEE Std 115-1965. A review of that standard was initiated by the Rotating Machinery Committee in 1977, and in 1979 that Committee requested authorization from the IEEE Standards Board to initiate a new revision. A working group was established to update the standard in the same year.

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IEEE Guide: Test Procedures for Synchronous Machines

1. Introduction

1.1 Scope. This guide contains instructions for conducting the more generally applicable and accepted tests to determine the performance characteristics of synchronous machines. Although the tests described are applicable in general to synchronous generators, synchronous motors (larger than fractional horsepower), synchronous condensers, and synchronous frequency changers, the descriptions make reference primarily to synchronous generators and synchronous motors. The tests described may be applied to motors and generators, as needed, and no attempt is made to partition this guide into sections applying to motors and sections applying to generators. It is not intended that this guide shall cover all possible tests, or tests of a research nature, but only those more general methods which may be used to obtain performance data. The schedule of factory and field tests which may be required on new equipment is normally specified by applicable standards or by contract specifications. This guide should not be interpreted as requiring the making of any specific test in a given transaction or implying a guarantee to meet specific performance indices or operating conditions.

CAUTION: *Many of the tests described in this guide subject the machine to thermal or mechanical stresses, or both, beyond normal operating limits. To minimize the risk of damage to the machine, it is recommended that all tests be performed either under the manufacturer's supervision or in accordance with the manufacturer's recommendations.*

The tests covered by this guide are given in Sections 3 through 8. Alternative methods of making many of the tests covered in this guide are described and are suitable for different sizes and types of machines and different conditions. In some cases the preferred method is indicated. The manufacturer's choice

of method for factory or field tests on new equipment will govern, in absence of prior agreement or contract specification.

The term *specified conditions* for tests as used in this guide will be considered as rated conditions unless otherwise agreed upon.

This guide should provide sufficient instructions for performing normally required tests. Throughout this guide cross references from one section to another have been used frequently to call attention to pertinent related material. When reference is made to a section having a specific heading, it is intended that the reference include not only the specific section but any immediately following sections without headings that apply to the same general subject. When reference is made to a section without a heading, it is intended that the reference be limited to the numbered section only.

It is anticipated that the development of improved practices and new equipment such as electronic and automatic devices will result in new or improved methods of carrying out the intent of this standard. New or modified methods may be used as substitutes when their results have been shown to be reliable and consistent with those obtained by methods given in this guide.

1.2 Instrumentation. The tests described in this guide usually require considerable care to obtain the desired accuracy. It is important that instruments of proper type and range be used.

Information relating to the proper use of instrument transformers and instruments for obtaining the measurements described herein is contained in IEEE Std 120-1955 [19].¹ Consequently, the measurement circuits shown in

¹The numbers in brackets correspond to those of the references listed in Section 2 of this standard.

the figures of this guide are often only schematic and IEEE Std 120-1955 [19] should be referred to for accurately detailed circuits. However, for some special tests and for purposes of improved clarity, more detailed figures of meter connections have been included.

Calibrated high-accuracy instrumentation and accessory equipment should be used. When suitable automatic data acquisition systems or high-speed recorders are available they may be used. Where appropriate, special methods which may be required to obtain accurate data have been indicated.

WARNING: *Because of the dangerous currents, voltages, and forces encountered, adequate safety precautions should be taken for all tests. No attempt is made here to list or review the manifold general safety precautions which are well established throughout the industry. However, this guide recommends special safety precautions applicable to the particular tests described. All tests should be performed by knowledgeable and experienced personnel.*

2. References

- [1] ANSI C50.10-1977, American National Standard General Requirements for Synchronous Machines²
- [2] ANSI C50.13-1977, American National Standard Requirements for Cylindrical-Rotor Synchronous Generators
- [3] ANSI C50.14-1977, American National Standard Requirements for Combustion Gas Turbine Driven Cylindrical Rotor Synchronous Generators
- [4] ANSI/IEEE Std 4-1978, IEEE Standard Techniques for High-Voltage Testing
- [5] ANSI/IEEE Std 43-1974 (R1979), IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery
- [6] ANSI/IEEE Std 67-1972 (R1980), IEEE Guide for Operation and Maintenance of Turbine Generators
- [7] ANSI/IEEE Std 86-1975, IEEE Standard Definitions of Basic Per-Unit Quantities for Alternating-Current Rotating Machines
- [8] ANSI/IEEE Std 100-1977, IEEE Standard Dictionary of Electrical and Electronics Terms
- [9] ANSI/IEEE Std 112-1978, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators
- [10] ANSI/IEEE Std 433-1974 (R1979), IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency
- [11] ANSI/IEEE Std 492-1974 (R1981), IEEE Guide for Operation and Maintenance of Hydro-Generators
- [12] ANSI/NEMA MG1-1978, Motors and Generators
- [13] ASME PTC 18-1949, Hydraulic Prime Movers³
- [14] IEEE Std 1-1969, IEEE General Principles for Temperature Limits in the Rating of Electric Equipment
- [15] IEEE Std 62-1978, IEEE Guide for Field Testing Power Apparatus Insulation
- [16] IEEE Std 95-1977, IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage
- [17] IEEE Std 118-1978, IEEE Standard Test Code for Resistance Measurement
- [18] IEEE Std 119-1974, IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus
- [19] IEEE Std 120-1955 (R1972), Master Test Code for Electrical Measurements in Power Circuits
- [20] NEMA MG5.2-1972 (R1977), Installation of Vertical Hydraulic-Turbine-Driven Generators and Reversible Generator/Motors for Pumped Storage Installations⁴
- [21] DUESTERHOEFT, W. C. The Negative-Sequence Reactance of an Ideal Synchronous

² ANSI documents are available from the Sales Department of American National Standards Institute, 1430 Broadway, New York, NY 10018.

³ ASME standards are available from the Sales Department of American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017.

⁴ NEMA standards are available from the Sales Department of National Electrical Manufacturers Association, 2101 L Street, NW, Washington, DC 20037.

Machine. *AIEE Transactions*, vol 68, part 1, 1947, pp 510-514. (Discussion by W. A. Lewis, pp 513, 514.)

3. Miscellaneous Tests

3.1 Insulation Resistance. The recommended methods for testing insulation resistance are given in ANSI/IEEE Std 43-1974 [5]. Polarization index and the effects of temperature, moisture, and duration of application of test voltage are covered in ANSI/IEEE Std 43-1974 [5].

Too low a value of insulation resistance may indicate the presence of moisture in or on the insulation. In this case, the machine should be dried out before dielectric tests are made or before the machine is placed in operation. See ANSI/IEEE Std 43-1974 [5] and NEMA MG5.2-1972 [20] for methods of dry-out. (While NEMA MG5.2-1972 [20] is written specifically for vertical hydraulic-turbine-driven generators, the procedure is applicable to other types of machines.) Any questions regarding the proper methods to be used for drying out a machine should be referred to the manufacturer.

3.2 High-Potential (Dielectric) Tests

3.2.1 General. The high-potential test is usually but not necessarily applied after all other tests have been completed. The magnitude, frequency, wave shape, and duration of the test voltage are given in ANSI C50.10-1977 [1] and ANSI/NEMA MG1-1978 [12].

WARNING: *Due to the high voltage used, which could cause serious personal injury or death, high-potential tests should be conducted only by experienced personnel, and adequate safety precautions should be taken to avoid such injury to personnel or damage to property. For the procedures recommended, refer to ANSI/IEEE Std 4-1978 [4] and IEEE Std 62-1978 [15].*

The test voltage should be applied to each electric circuit (including each phase of polyphase windings if they are not internally connected) with all other electric circuits and metal parts grounded. The leads of each winding or phase should be connected together, whether the winding is to be tested or grounded.

3.2.2 Preparation. During testing of the field

windings of large machines the brushes normally should be lifted and isolated electrically from the collector rings so that no excessive voltage stress will be imposed on the field winding if some part of the brush rigging or the leads fails. The brush rigging and station leads should be tested separately from the field. If it is desired to test the brush rigging of a machine at the same time the field is being tested, the exciter leads should be disconnected unless it is intended that the exciter be tested simultaneously. In any case, the permanent instrumentation leads should be disconnected. They may be tested separately if desired.

During testing of the field windings of brushless machines, the dc excitation leads should be completely disconnected from the exciter unless it is intended that the exciter and associated components be tested simultaneously. In either case, the brushless circuit components (diodes, thyristors, etc) should be short circuited (not grounded) during the test.

Additional methods, procedures, and precautions are given in ANSI C50.10-1977 [1] and ANSI/NEMA MG1-1978, parts 3, 21, and 22 [12].

3.2.3 Method 1. Alternating-Voltage Testing at Power Frequency. An alternating-voltage of power frequency is applied to the winding being tested. Two standard methods of measuring alternating voltage are recognized: the transformer-voltmeter and the sphere gap. These methods are fundamentally different in kind and each can readily be checked against the other.

The transformer-voltmeter method is based upon the use of potential transformers designed for instrument use and having accurately determined voltage ratios.

The sphere-gap method is based on an extensive calibration of the breakdown of air as a dielectric between spheres of specified sizes and spacings. Every precaution should be taken against the occurrence of overvoltage oscillations due to sphere-gap discharges. The sphere gap is frequently used only for overvoltage protection.

During application, the test voltage should be increased smoothly and promptly, held for the test period (normally one minute) and then promptly and smoothly reduced to zero.

3.2.4 Method 2. Direct-Voltage Testing of Stator Windings. A direct-voltage equal to 1.7 times the rms value of the specified power fre-

quency test voltage (effective value) is applied to the winding being tested. For the method of test see ANSI/IEEE Std 4-1978 [4] and IEEE Std 95-1977 [16].

The resistor-ammeter method is the standard method for direct-voltage measurements.

WARNING: *Following a direct-voltage high-potential test, the tested winding should be thoroughly grounded. The insulation rating of the winding and the test level of the voltage applied determine the period of time required to dissipate the charge. In many cases, the ground must be maintained for several hours to dissipate the charge to avoid hazard to personnel.*

3.2.5 Method 3. Very-Low-Frequency Testing of Stator Windings. A very-low-frequency (VLF) voltage (frequency being in the range of 0.1 Hz) with crest equal to 1.63 times the rms value of the specified power-frequency test voltage (effective value) is applied to the winding being tested. VLF testing is advantageous on large machines with high winding capacitance where it may result in reduced size and rating of the test equipment required. For the method of test see ANSI/IEEE Std 433-1974 [10].

3.3 Resistance Measurements

3.3.1 General. To obtain direct-current resistance measurements of armature and field windings, the procedures given in IEEE Std 118-1978 [17] should be used. The following sections give special considerations pertaining to the measurement of winding resistance.

Where generator field leads are inaccessible, such as when brushless exciters are used, it may not be possible to measure the field resistance unless provision is available through special instrumentation and procedures. The manufacturer should be consulted.

3.3.2 Correction to Specified Temperature. When the resistance, R_t , of a winding has been determined by test at a winding temperature t_t , the resistance may be corrected to a specified temperature t_s by the following equation:

$$R_s = R_t \left(\frac{t_s + k}{t_t + k} \right) \text{ ohms} \quad (\text{Eq 1})$$

where

R_s = winding resistance, corrected to specified temperature, t_s

t_s = specified temperature, Celsius
 R_t = test value of winding resistance
 t_t = temperature of winding when resistance was measured, Celsius
 k = characteristic constant for the winding material, see 6.4.4

3.3.3 Reference Field Resistance. The resistance is commonly measured at standstill in order to obtain a reference value (R_b) from which to determine field temperature during running tests by the method of Section 6.4.4. For this purpose, the rotor is allowed to be exposed to an essentially constant ambient temperature for a time sufficiently long enough for the entire rotor to reach the ambient temperature. It is important that the method of measurement does not alter the temperature of the winding. When a double bridge is used, the current through the winding is not sufficient enough to produce a change in temperature.

When the field resistance is to be measured by drop of potential, a relatively low value of current should be used so that the resulting I^2R loss will not cause a significant change in temperature during the time of application. The application of current should be no longer than necessary for the electric transient due to field inductance to die out and the meters to come to rest.

If the field resistance is measured by drop of potential, the current should be applied through clamping rings or other equivalent devices to avoid damage to the active surface of the collector. The field temperature can be measured by thermometers or thermocouples.

3.3.4 Reference Field Resistance from a Running Test. Although it is preferable to obtain the reference value of field resistance at standstill, because both the resistance and temperature can be determined more accurately, it is often advantageous to obtain or verify the reference value by a test made at or near normal speed using the drop-of-potential method. For conductor-cooled rotors, winding temperature may change too rapidly to make this practicable. The making or relieving of turn-to-turn short circuits in the field winding may cause the measured resistance of the field circuit to differ substantially from the standstill value, thus providing a possible incidental check for short-circuited turns (see 3.4).

Immediately after the machine has been brought up to speed, starting with the rotor at a known uniform temperature, direct current is

applied to the field in as small a value as will permit accurate current and voltage measurements. As soon as the current has become constant, the voltage drop across the collector rings should be measured. Since the voltage drop of the normal brushes may be a substantial fraction of the impressed voltage in this test, it is essential that the brush drop be eliminated from the voltage measurement, or minimized by special methods of voltage measurement or special test procedures (see 3.3.6).

3.3.5 Field Resistance for Running Temperature Tests. To determine the field temperature under specified or desired load conditions, the field resistance should be measured by the drop-of-potential method after the machine has been operated at the required field current and as near as practicable to the required loading conditions long enough for a uniform temperature to have been reached. The temperature of the field winding is then determined in accordance with 6.4.4. The resistance obtained from this test should be called R_f in Eq 36.

Because including brush voltage drop in the measured field voltage may introduce a substantial error in the temperature determination, it is highly desirable to eliminate or minimize its effect in this test (see 3.3.6).

When measuring the resistance of the field with the machine loaded, the voltage regulator should be disconnected and a number of armature voltage, power, and current readings should be taken simultaneously with field current and voltage readings to ensure that the resistance is measured under constant conditions.

3.3.6 Effect of Brush-Voltage Drop. To determine the field resistance of a running machine accurately, it is necessary to obtain the voltage drop across the field winding without including the voltage drop of the brushes supplying the field current. This is especially important when the field current is very small, as when determining the reference resistance value (see 3.3.4). For this purpose it is desirable to measure the voltage drop directly across the collector rings, using special brushes that are in contact with the collector rings only during voltage measurement. For this purpose, it is possible to use:

- (1) Special copper or bronze leaf brushes bearing directly on the collector rings
- (2) Insulated brushes that have not developed a glazed surface

(3) Insulated special carbon or graphite brushes compounded with highly conducting materials to reduce their resistance

Unless a very small voltage drop occurs across these measurement brushes, a significant error may be introduced.

When these special methods of voltage measurement are not available, the voltage measurement necessarily includes the voltage drop across the brushes. In such cases, efforts to reduce its effect should be made. Since the voltage drop across the brushes remains reasonably constant with varying current, the effective brush resistance is reduced by increasing the current density. This may be accomplished by reducing the number or cross section of brushes used during the test, particularly for low field currents. When information is available regarding the expected voltage drop across the brushes, more accurate results can be obtained by subtracting the brush drop from the measured voltage before calculating the resistance, but the results thus obtained should be used with caution.

On machines whose collectors have high peripheral speed, care must be exercised to avoid damaging the surface condition of the collector by voltage-measuring devices.

3.4 Tests for Short-Circuited Field Turns

3.4.1 General. The object of these tests is to detect field coils that have short-circuited turns, an incorrect number of turns, or incorrect conductor size. Not all short-circuited field turns are apparent at standstill, and a test at speed may be required.

3.4.2 Method 1. Voltage Drop. Direct-Current. This method can be used to detect short-circuited turns only when connections between coils are accessible. The test is made, with the rotor at standstill, by passing a constant direct current through the entire field winding. The drop in voltage of each coil or pair of coils is measured by means of a voltmeter. If these readings vary more than $\pm 2\%$ from the average, it is an indication that there may be short-circuited turns in the coil, or that part of the winding is wound with the wrong number of turns or size of conductor.

3.4.3 Method 2. Voltage Drop. Alternating-Current. A more sensitive test for short-circuited turns is made by passing constant-amplitude alternating current through the entire field winding. If there is access to connections

between coils, with the rotor at standstill, the voltage across each coil or pair of coils should be measured. The voltage across a coil having a short-circuited turn will be substantially less than that across a sound coil. The voltage across a sound coil adjacent to the coil with a short-circuited turn will be somewhat less than that across other sound coils because of the reduced flux in the short-circuited coil. Comparison of the measured voltages will readily locate any coils that are defective.

If the connections between coils are not accessible, the current and voltage drop (across the entire winding) should be measured. The impedance of a one-circuit winding in which one coil has a short-circuited turn will be reduced to approximately $(m-1)/m$ times the value across a sound winding, where m is the number of coils in the winding. This test is useful for detecting a machine which has a short-circuited turn only when running. If the speed is varied while the alternating current is applied, a discontinuity in the current or voltage readings should indicate the occurrence or removal of a short circuit.

NOTE: The sensitivity of this method of test is much lower for cylindrical rotors in which the field winding lies in slots, especially for solid-steel rotors. The sensitivity varies, depending on which coil has a short-circuited turn. Factory trials in which temporary short circuits are applied can be made to serve as the basis for future analysis when short-circuited turns are suspected. For cylindrical-rotor machines, Method 3, 4, or 5 may be preferred.

3.4.4 Method 3. Direct-Current Resistance. In this method, a comparison is made between the field resistance and a value previously obtained by test or calculation.

After the rotor has been exposed to an ambient temperature for a period sufficient enough for the entire rotor winding to be at ambient temperature, the field resistance is measured by double bridge and the temperature of the rotor is measured by several thermometers or thermocouples located at suitable points. The resistance is then corrected to a temperature at which the resistance has previously been determined by a similar test (or by calculation in the case of a new machine). If the corrected value of the newly obtained resistance is significantly lower than the reference value, short-circuited turns may be present.

3.4.5 Method 4. Exciting Coil for Cylindrical Rotors. This method uses a testing device having a U-shaped core capable of bridging one

coil slot of a cylindrical rotor, and having an exciting coil wound on the core. The test is made by placing the device successively across each field coil slot and passing alternating current (normally at power frequency) through the exciting coil. The voltage across the field winding or the impedance of the exciting coil should be determined for each slot. When the device spans a coil side with a short-circuited turn, the voltage of the field winding or the impedance of the coil will be lower than for a slot containing a sound coil.

3.4.6 Method 5. Rotor Waveform Detection for Cylindrical Rotors. This method utilizes a transducer or coil pick-up to determine the rotor magnetic field waveform. The magnetic pick-up should be mounted from the stator, in the air gap in close proximity to the rotor, according to the manufacturer's recommendations, and connected to an oscilloscope or other suitable recording device. With the rotor rotating at speed and the field winding excited, the occurrence of short-circuited turns can often be detected as discontinuity or dissymmetry in the recorded trace (see ANSI/IEEE Std 67-1972 [6]).

3.5 Polarity Test for Field Poles. The polarity of the field poles may be checked by means of a small permanent magnet mounted so that it may turn and reverse its direction freely. The field winding should be energized by 5% to 10% of rated current. The magnet indicates proper polarity by reversing direction as it is passed from pole to pole. The magnet should be checked to ensure that its magnetism has not been lost or its polarity reversed by the field flux.

3.6 Shaft Current and Bearing Insulation

3.6.1 General. Irregularities in the magnetic circuit may cause a small amount of flux to link the shaft, with the result that an electromotive force is generated between the shaft ends. This electromotive force may cause a current to flow through the shaft, bearings, bearing supports, and machine framework, and back to the other end of the shaft, unless the circuit is interrupted by insulation. (While other causes may produce a shaft voltage not involving a difference in potential from one end of the shaft to the other, special tests are not provided for the resulting effects because each of these sources requires specially adapted

methods of test, essentially of a research nature.)

For Methods 1 through 4, the machine should be run at rated speed and excited at rated armature voltage open circuit, unless other operating conditions are specified.

3.6.2 Method 1. Across End Shafts. The presence of shaft voltage may be determined by measuring the voltage from end to end of the shaft with a high-impedance voltmeter.

3.6.3 Method 2. Across Bearing Oil Film, Uninsulated Bearings. This method requires that the insulating properties of the bearing oil film be adequate to withstand the shaft voltage without breaking down. The presence of shaft voltage or current may be determined by running the machine at rated speed and voltage, and connecting a low-resistance conductor from the shaft to the frame of the machine at one bearing, and a low-range alternating-current voltmeter (or a high-range alternating-current ammeter) with low-resistance leads from the shaft to the frame at another bearing. Deflection of the meter indicates the presence of a voltage that may produce shaft currents. If the meter does not deflect, there is either insufficient voltage present or the bearing oil film is not acting as an adequate insulator.

3.6.4 Method 3. Across Bearing Insulation. Many machines have one or more bearings insulated to eliminate shaft currents. In the following sections, it is assumed that insulation is located between the bearing and the frame of the machine. To determine the presence of a voltage that will produce shaft currents in such a machine, a low-resistance conductor is connected from the shaft to the uninsulated bearing in order to short-circuit the oil film, and a low-range alternating-current voltmeter (or a high-range alternating-current ammeter) is connected between the shaft and the frame successively at each insulated bearing. Deflection of the meter indicates the presence of a voltage that will produce shaft currents if the bearing insulation is not present.

3.6.5 Method 4. Bearing Insulation. The insulation can be tested by connecting a low-range alternating-current voltmeter (or a high-range alternating-current ammeter) across the insulation. A low-resistance conductor may be applied from the shaft to each bearing to short-circuit the oil film. Deflection of the meter, in this case, is evidence that the insulation is at least partially effective. If there is no deflection

of the meter, either the insulation is defective or there is no shaft voltage present.

3.6.6 Method 5. Bearing Insulation. A layer of heavy paper is placed around the shaft to insulate the journals of the uninsulated bearings. The coupling of the driving or driven units should be disengaged if it is not insulated. Then, from a 110 V–125 V source, with either a filament lamp suitable for the circuit voltage or a voltmeter of approximately 150 V full scale with a resistance in the range of 100 Ω /V–300 Ω /V placed in a series with the voltage source, two leads should be run, one to the insulated bearing and the other to the frame (across the insulation). If the lamp filament does not show color (or if the reading of the voltmeter does not exceed 60 V) the insulation may be considered satisfactory.

A 500 V megger may also be used. This is much more sensitive than the above method and may tend to reject insulation which is adequate to prevent the small shaft voltage from causing injurious current.

3.6.7 Method 6. Double Insulation. On some machines, bearings are provided with two layers of insulation with a metallic separator between them. The test of Method 5 is applied between the metallic separator and the frame of the machine. This test should be carried out on each of the various multiple paths between the shaft and the frame where insulated bearings are used (for example, thermometer tubes, control pipes for a hydraulic turbine, hydrogen seals, and insulated couplings). This test may be made with the machine stationary or running. The test should be supplemented by careful visual inspection to assure that there are no possible parallel paths which are not provided with insulation.

3.7 Phase Sequence

3.7.1 General. The phase-sequence test is made to check the agreement of the machine with the terminal markings and phase rotation that have been specified, or with the requirements of ANSI/NEMA MG1-1978 [12]. The results are used when connecting line leads to the armature terminals to obtain correct phasing of a generator to the bus, or the correct direction of rotation for motors. The phase sequence on three-phase machines can be reversed by interchanging the line connections to any two armature terminals. The phase sequence on two-phase machines can be re-

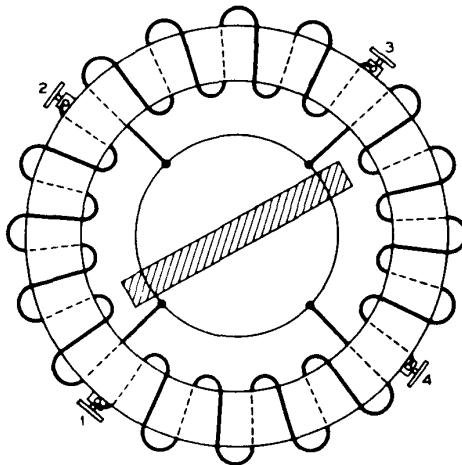


Fig 1
Phase-Sequence Meter

versed by interchanging the two leads of either phase.

3.7.2 Method 1. Phase-Sequence Indicators. Phase sequence is determined by running the machine as a generator in the direction of rotation for which it was designed and by connecting to the terminals a phase-sequence indicator or an induction motor, whose direction of rotation is known when a given phase sequence is applied to its terminals.

3.7.2.1 Figure 1 is a diagram of one type of phase-sequence indicator which consists of windings placed on a laminated iron core, with a steel bar mounted in the center. The terminals of the machine under test, whether three-phase or two-phase, should be connected to the corresponding terminals of the indicator. The indicator shown in Fig 1 will operate clockwise if the phase sequence is 1, 2, 3 and counter-clockwise if the phase sequence is 1, 3, 2.

3.7.2.2 A type of phase-sequence indicator without moving parts is also available for three-phase machines and is shown schematically in Fig 2. The indicator makes use of a small capacitor and two neon lamps connected in Y across the three-phase circuit to be tested. For phase sequence 1, 2, 3 the lamp connected to terminal 1 will glow. For phase sequence 1, 3, 2 the lamp connected to terminal 3 will glow.

To check the indicator, the switch shown in Fig 2 should be closed. If operating correctly, both lamps will glow with equal intensity.

3.7.2.3 When it is necessary to connect a phase-sequence indicator to the machine terminals through potential transformers, extreme care is required because the reversal of polarity of any transformer winding will alter the phase relations between the voltages applied to the indicator. If a Y-Y connection is used, selected terminals of the high-voltage windings of the potential transformers should be connected to form the primary neutral. Corresponding terminals of the low-voltage windings should be connected to form the secondary neutral.

If a delta-delta (Δ - Δ) or open-delta connection is to be used, similar care is required to assure proper phasing of the secondary.

For any of the above cases, it is important to retain the identification of the proper phase sequence in the secondary network.

3.7.3 Method 2. Indication of Differential Voltage. A convenient check of the phase sequence of a synchronous generator compared to the system to which it is to be connected can be obtained as follows:

Four potential transformers should be connected as shown in Fig 3 for three-phase machines. Great care is necessary to maintain the correct polarity of the transformer connections. The asterisks show the corresponding terminals of the primary and secondary windings. This connection effectively places indicating lamps across open disconnecting switches between the generator and the system. The generator should be brought up to speed and excitation applied corresponding to normal voltage. When it is near synchronous speed, lamps connected to the potential transformer secondaries will brighten or dim simultaneously if the generator has the same phase sequence as the system, whereas they will brighten or dim one after the other if the phase sequences are opposite.

3.7.4 Method 3. Comparison with System Voltage. This method provides an absolute check of the phase sequence of a synchronous generator compared with the system to which it is to be connected. It is necessary that the generator be separated from the system by a circuit breaker, and means should be provided for disconnecting the generator from the circuit breaker. A phase-sequence indicator should be connected to the generator side of the circuit breaker through suitable potential transformers. With the generator disconnected, the circuit breaker should be closed and the in-

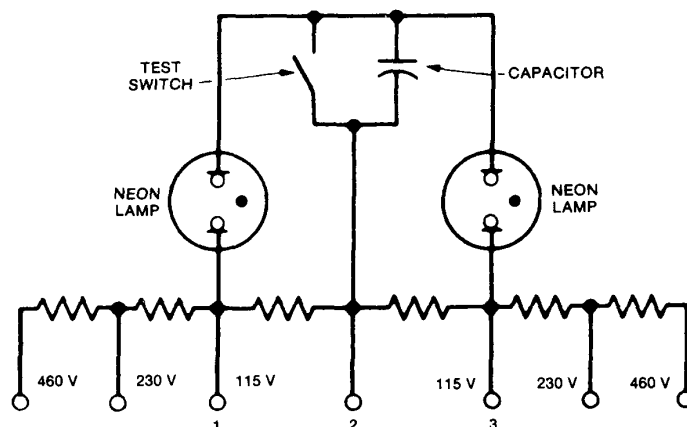


Fig 2
Neon-Lamp Phase-Sequence Indicator

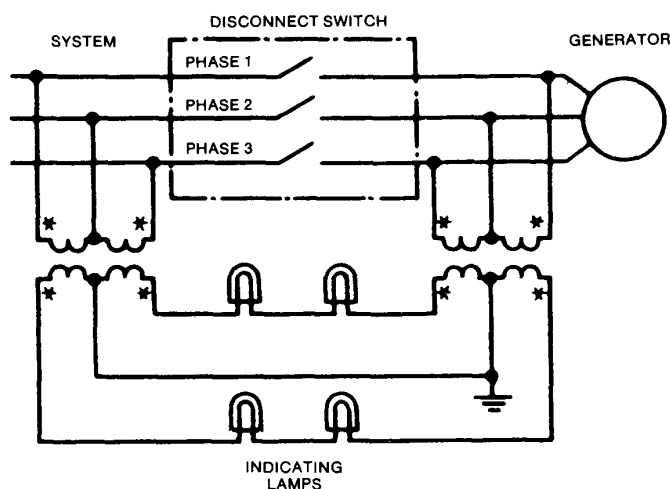


Fig 3
Connection Diagram for Comparing the Phase-
Sequence of a Generator with that of a
System by Indicating the Voltage Across an
Open Disconnect Switch

dication of the phase-sequence indicator noted. With the generator connected to the circuit breaker, but with the latter open, the indication of the phase-sequence indicator should be noted when the generator is operating at normal speed and is excited to produce normal voltage. If the two indications of the phase sequence are the same, the generator is known to have the same phase sequence as the system.

3.7.5 Method 4. Direction of Rotation—for Motors. In the case of a motor, the phase sequence can be checked by starting it from its normal source of power and observing its direction of rotation. If damage can result from improper rotation, the motor should be disconnected from the apparatus which would be damaged. In some cases, apparatus such as a nonreverse ratchet cannot be disconnected. In

this case, a sufficiently low voltage should be used so as not to damage the apparatus, or another procedure such as Method 1 or an adaptation of Method 2 or 3 should be used.

3.8 Telephone-Influence Factor

3.8.1 Telephone-influence factor (TIF) for the synchronous machine alone is normally measured when its rectified excitation has been replaced by a ripple-free supply and power transformers have been removed from the line. It is obtained as the quotient of a weighted root-mean-square value of the fundamental and harmonics of a voltage wave, and the root-mean-square value of the wave. This can be done analytically from data taken by harmonic analysis in conjunction with the weighting factors using the following equations:

$$\text{TIF} = \frac{E_{\text{TIF}}}{E_{\text{rms}}} \quad (\text{Eq 2})$$

where

$$E_{\text{TIF}} = \sqrt{\sum (T_n E_n)^2} \quad (\text{Eq 3})$$

E_{TIF} = weighted rms value of the voltage wave, using the weighting factors T_n

T_n = the TIF weighting factor for the n th harmonic

E_n = rms value of the n th harmonic component of voltage (including the fundamental component of voltage) in the same units as E_{TIF}

E_{rms} = rms value of the voltage wave, in the same units as E_{TIF}

NOTE: The weighting factor, T_n , used above, is equal to the single frequency telephone influence factor, TIF_f , corresponding to the n th harmonic frequency.

3.8.2 For the weighting factors to be used in calculating TIF, see ANSI C50.13-1977 [2] or ANSI/NEMA MG1-1978 [12].

3.8.3 If a potential transformer is connected between the machine and the instrument, it should be established that the harmonic content of the machine voltage is not affected by the presence of the transformer. To perform such a check, a resistance voltage divider (having approximately 300 Ω /V and designed to produce the desired voltage for a harmonic analyzer) should be placed across the terminals of the machine with the potential transformer disconnected, and the harmonic content of the machine voltage should be obtained. The potential transformer should then be placed across the machine terminals and the harmonic

analysis repeated, using the voltage divider. A second check can be made by making a harmonic analysis using the secondary of the potential transformer. If the three analyses of machine voltage harmonic content agree, the transformer can be considered satisfactory for use on other similar machines.

3.9 Balanced Telephone-Influence Factor

3.9.1 General. For the definition of balanced telephone-influence factor, see ANSI/IEEE Std 100-1977 [8].

3.9.2 Method 1. Line-to-Line Voltage. For a three-phase Y-connected machine, Eq 2 can be used, based on line-to-line voltage. The value of E_{TIF} for a Y-connected machine can be measured by means of a TIF meter, or can be obtained from a harmonic analysis of the line-to-line voltage using Eq 3. Readings are taken with the machine operating at rated voltage and speed, without load.

3.9.3 Method 2. Phase Voltage. The balanced telephone-influence factor of a three-phase Y-connected machine can be obtained using Eqs 2 and 3 based on a harmonic analysis of line-to-neutral voltage, but omitting the third harmonic and multiples thereof from the computation of E_{TIF} . Readings are taken with the machine operating at rated voltage and speed, without load.

3.10 Residual-Component Telephone-Influence Factor

3.10.1 General. For the definition of residual-component telephone-influence factor, see ANSI/IEEE Std 100-1977 [8].

3.10.2 Method 1. Machines Which can be Connected in Delta. The residual-component telephone-influence factor of a three-phase machine can be obtained by connecting the machine in delta with one corner open and with the machine operating at normal speed and no load, with excitation corresponding to rated open-circuit voltage. A TIF meter or harmonic analyzer is placed across the open corner of the delta. Equation 4 should be used to evaluate residual TIF from this method.

$$\text{Residual TIF} = \frac{E_{\text{TIF}}}{3 E_{\text{rms}}} \quad (\text{Eq 4})$$

where

E_{TIF} = weighted root-mean-square voltage taken across the open corner of the delta. It can be obtained from the

reading of a TIF meter or is calculated from harmonic analyzer data using Eq 3.

E_{rms} = voltage across one phase of the delta, in the same units as E_{TIF} . This can be taken as the average of the voltages of the three phases.

For other nomenclature, see Eq 2.

Caution should be used in making the open-delta test on high-voltage machines. The voltage to be measured is a very small fraction of the voltage of one side of the delta. Hence a low-ratio potential transformer (from 1:1 to 10:1) might be used even on high-voltage machines. However, should one side of the delta accidentally become completely or partially short-circuited during the test, the voltage across the TIF meter or harmonic analyzer would jump to many times (from 10 to 100 times) the instrument voltage before the accidental short circuit. This new voltage would equal approximately the voltage which existed between the two points which were short-circuited divided by the ratio of the potential transformer. For a 1:1 transformer, this could equal full normal line-to-neutral voltage of the machine.

To eliminate the hazard associated with such an accidental short circuit, it is necessary on high-voltage machines to isolate the instrument and circuits from all personnel, or to use protective gaps and fuses to ground the instrument and isolate it from the machine in case of over-voltage. The duration of excitation during the test should be kept to a minimum.

3.10.3 Method 2. Machines Which Cannot be Connected in Delta. In those cases where the machine cannot be conveniently connected in delta, the residual-component TIF may be obtained by connecting three identical potential transformers in Y to the terminals of the machine and connecting the secondaries in Δ with one corner open. The neutral of the potential transformer primaries should be connected to the neutral of the machine. The measurements then may be taken in the potential transformer secondary in the same manner as when taken directly on the machine as in Method 1. When this method is used, it should be recognized that with low values of TIF, the accuracy may be affected by the exaggerated effect of slight variations among the transformers.

3.10.4 Method 3. Line-to-Neutral Test. In the

case of a three-phase machine where the phase voltages are balanced (the usual case), the residual-component telephone-influence factor can be computed using Eqs 2 and 3 from a harmonic analysis of the line-to-neutral voltage, considering only the third harmonic and multiples thereof. Readings are taken with the machine operating at rated voltage and speed, without load.

3.11 Line-to-Neutral Telephone-Influence Factor

3.11.1 General. The line-to-neutral telephone-influence factor of a three-phase machine is calculated from Eq 2 based on the line-to-neutral no-load voltage of the machine (considering all harmonics). This has significance only for a Y-connected machine, and is of value primarily for checking (see 3.11.3).

3.11.2 Method of Test. The line-to-neutral TIF can be measured with one potential transformer connected from line-to-neutral across one phase of the machine when operating at rated voltage and speed, without load. The weighted root-mean-square value, E_{TIF} , of the voltage across the secondary of the transformer is obtained by TIF meter or by harmonic analysis using Eq 3. The TIF is obtained from Eq 2.

3.11.3 Check of Balanced, Residual, and Line-to-Neutral TIF. A useful check of the values of balanced, residual, and line-to-neutral telephone-influence factors is obtained from the following relationship:

$$\text{line-to-neutral TIF} = \sqrt{(\text{balanced TIF})^2 + (\text{residual TIF})^2} \quad (\text{Eq 5})$$

3.12 Wave Form

3.12.1 General. For the definition of deviation factor, see ANSI/IEEE Std 100-1977 [8].

3.12.2 The wave form of the test voltage is recorded by an oscillograph adjusted to produce a wide deflection, and operated at high speed so that the time interval of one-half cycle may be subdivided into a series of equal intervals. To permit adequate analysis, the maximum amplitude of the wave from zero should be at least 1.25 inches and the distance for one-half cycle at least 1.5 inches. Figure 4 shows the trace of an exaggerated wave to be analyzed, in rectangular coordinates. Also, the equivalent sine wave has been plotted on the same figure, so located that the maximum deviation of the wave to be analyzed from the

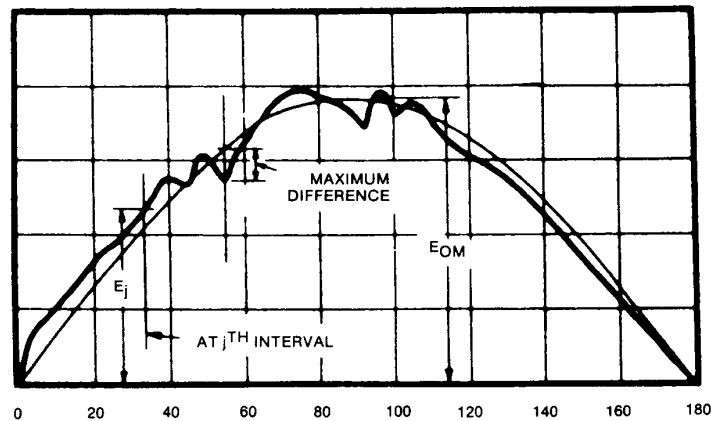


Fig 4
Plot of Wave for Deviation Factor

sine wave is a minimum. The amplitude of the equivalent sine wave may be determined by the method described in 3.12.3. Plots of the wave in polar coordinates may also be used.

3.12.3 To obtain the amplitude of the equivalent sine wave, the time interval of one-half cycle of the wave to be analyzed is divided into J (at least 18) equal intervals, beginning at a point where the trace of the wave crosses the axis of abscissas, and a vertical line is erected at the end of each interval, crossing the trace. If the value of the instantaneous voltage, E_j , is measured at each of the J points of intersection with the wave trace, the zero-to-peak amplitude of the equivalent sine wave, E_{OM} , is given by Eq 6.

$$E_{OM} = \sqrt{\frac{2}{J} \sum_{j=1}^J E_j^2} \quad (\text{Eq 6})$$

where

E_j = instantaneous value of voltage wave at j th point

In certain machines even harmonics of voltage may be produced, resulting in alternate half cycles differing from the negative of the intervening ones. For such an unsymmetrical wave, a complete cycle should be analyzed.

As an alternate method, the root-mean-square value of the equivalent sine wave, E_O , may be measured by an accurate dynamometer or thermocouple type alternating-current in-

strument which has been calibrated against the same reference standard as the oscillograph. Since differences in calibration cause a magnified relative error in the deviation factor, a voltmeter reading should not be relied upon unless the calibrations of the oscillograph and the voltmeter have been carefully intercompared. The crest value of the equivalent sine wave, E_{OM} , is the meter reading E_O multiplied by $\sqrt{2}$.

3.12.4 To adjust the equivalent sine wave so that the deviation between the wave being analyzed and the equivalent sine wave is a minimum, it is convenient to plot the equivalent sine wave on a transparent overlay to the same scales as the oscillogram, and slide the overlay over the oscillogram, with the axes of the abscissa coincident, until a location is found where the absolute value of the vertical deviation between the two waves is a minimum. This location will usually occur when the zero values of voltage occur at nearly the same point in time, and often when the maximum positive deviation is the same or nearly the same as the maximum negative deviation during the half cycle (see Fig 4).

3.12.5 The maximum value of the deviation between the two waves, when located as described in 3.12.4, may be designated by ΔE . Then the deviation factor F_{DEV} is given by Eq 7.

$$F_{DEV} = \frac{\Delta E}{E_{OM}} \quad (\text{Eq 7})$$

3.12.6 The distortion factor, F_{Di} , of a wave is obtained by dividing the root-mean-square harmonic content (the square root of the sum of the squares of the root-mean-square amplitudes of all frequency components except the fundamental), by the root-mean-square value of the wave including the fundamental, according to Eq 8.

$$F_{Di} = \frac{\sqrt{\sum E_n^2}}{E_{rms}} \quad (\text{Eq 8})$$

where

$\sum E_n^2$ = sum of the squares of all components of the voltage except the fundamental

E_{rms} = root-mean-square value of the voltage

3.12.7 The root-mean-square value of the harmonic content of the wave can be obtained by a filter which blocks out only the fundamental, in conjunction with a dynamometer type alternating-current voltmeter calibrated with the circuit. A harmonic analyzer can also be used to measure E_n .

3.12.8 When a special instrument is not available, the root-mean-square amplitude of the harmonic components of the wave can be determined by a Fourier analysis of the instantaneous values obtained in 3.12.3, according to one of several methods available in handbooks and other general references. It should be noted that the number of intervals into which the half cycle is to be divided is related to the order of the highest harmonic to be determined. In most cases the amplitude of the harmonic decreases as the order of the harmonic increases, so that determination of the amplitudes of the first few harmonics is all that is needed to obtain a satisfactory value of the distortion factor. However, if the trace of the wave indicates by the presence of high-frequency ripples that harmonics of a relatively high frequency have significant amplitude, the number of intervals used should be sufficient to provide a determination of the amplitudes of these harmonics. When the root-mean-square amplitudes, E_n , of the several significant harmonics have been determined, the distortion factor may then be calculated by Eq 8.

3.12.9 The root-mean-square value of the wave is obtained using a dynamometer or thermocouple type alternating-current instrument of suitable accuracy. (Other types of instru-

ments are likely to give incorrect readings because they do not respond to the root-mean-square value of distorted waves.)

3.13 Overspeed Tests

3.13.1 Overspeed tests are made only when specified. They are generally specified for synchronous generators connected to turbines or other mechanical equipment that may be overspeeded on loss of load or other causes. The manufacturer should be consulted prior to conducting any overspeed test.

3.13.2 Before making an overspeed test the machine should be carefully inspected, making sure that all holding-down bolts and rotating parts are tight and in good condition. The rotor should be in as good mechanical balance as possible before starting the test. Every precaution should be made to protect life and property in case of any mishap. The speed should be read with an electric tachometer or other accurate remote speed-indicating device. The tachometer should be calibrated with the leads used in the test and the reading checked at normal speed before starting the test.

3.13.3 When making the test, the machine should be operated at rated speed for a sufficiently long period for vibration readings to be made and stabilized, and to ascertain that the machine is running satisfactorily. The machine should then be accelerated with reasonable promptness to the specified overspeed. For tests at speeds greater than 115% of rated speed, it is desirable to pause briefly at various speeds during acceleration to check such operating conditions as vibration, runout of the rotor shaft, and behavior of the oil in the bearings. Vibration readings should also be made at rated speed following the test for comparison and reference.

3.13.4 Normally, the overspeed test is made with the machine unexcited. If the machine is excited, care should be exercised to reduce excitation during the test so that the voltage does not exceed 105% of rated voltage.

3.13.5 Following operation at the specified speed for the specified time, the machine should be brought promptly and smoothly back to or below rated speed.

If the overspeed has been applied for any prolonged period, the bearings will be at substantially higher than normal temperatures and the viscosity of the oil much lower than normal. Therefore either the machine should be returned to normal speed or below until the bear-

ing temperatures return to normal, or it should be shut down quickly and not restarted until the bearing temperatures cool down to normal conditions.

The machine should be carefully inspected after the test.

3.14 Line-Charging Capacity

3.14.1 General. The line-charging capacity of a synchronous machine is its reactive power in kilovoltamperes when operating synchronously at zero power factor, rated voltage, and with the field current reduced to zero. (This quantity has no inherent relationship to the thermal capability of the machine, therefore note the caution in 3.14.5.)

3.14.2 Method 1. As Motor. The machine is operated as a synchronous motor at no load, preferably uncoupled, and at rated voltage and frequency, with excitation reduced to zero. Because machine losses are supplied from the driving units, the line-charging capacity is approximately the reactive power input in kilovoltamperes. If the machine is coupled to a condensing steam turbine, it should be uncoupled to prevent overheating of the turbine.

3.14.3 Method 2. As Generator. The machine under test is driven at normal speed and is connected to a load consisting of idle-running over-excited synchronous machines, or to a bus which may be considered as an infinite-capacity voltage source, with rated voltage on the generator at rated frequency, and with its excitation reduced to zero. The line-charging capacity is approximately the reactive power input in kilovoltamperes.

3.14.4 Method 3. As Generator. The machine is driven at normal speed and is connected to sections of transmission line, using sufficient sections to give rated voltage when generator excitation is reduced approximately to zero. The line-charging capacity is the reactive power input in kilovoltamperes. Because a transmission line requires at least a small synchronous source of excitation, it is not possible to make the test at zero excitation. Therefore, a series of tests with successively smaller values of excitation can be used as a basis for extrapolating the reactive power to zero excitation.

3.14.5 Caution. Note that a limit for reduction of field current of cylindrical-rotor machines at rated voltage may be set by the manufacturer to avoid local heating in the armature. If such a limit exists, the data may be taken at several greater values of field current (at rated

voltage and zero power factor) and extrapolated to obtain a value of reactive power at zero excitation (see ANSI/IEEE Std 67-1972 [6]).

If armature current in excess of rated current is expected, the data may be taken at several values of reduced current (and voltage) and extrapolated to obtain a value of reactive power at rated voltage.

4. Saturation Curves, Segregated Losses, and Efficiency

4.1 General

4.1.1 Efficiency. The true efficiency of a machine is the ratio of output power to input power under specified conditions. On small machines, these can be measured directly. On larger equipment where the mechanical power cannot be measured accurately, a conventional efficiency is used, based on segregated losses (see 4.6.1).

The losses to be used in determining the conventional efficiency of a synchronous machine and their method of evaluation are prescribed in the applicable ANSI C50 Standards Series and ANSI/NEMA MG1-1978 [12]. Test procedures for determining the following individual losses are given in the subsequent sections:

- (1) Friction and windage loss
- (2) Core loss (on an open circuit)
- (3) Stray-load loss (on a short circuit)

Armature I^2R loss is determined using the armature current at the specified load and the direct-current armature resistance corrected to a specified temperature (see 3.3.1 and 3.3.2). Field I^2R loss is determined from field resistance corrected to a specified temperature (see 3.3) and field current (see 5.1).

4.1.2 Methods of Loss Measurement. There are four methods available to measure the losses of a synchronous machine:

- (1) Separate-drive method (see 4.2)
- (2) Electric-input method (see 4.3)
- (3) Retardation method (see 4.4)
- (4) Cooler method (see 4.5)

It is convenient to obtain data for the open-circuit and short-circuit saturation curves during the tests for determination of losses, if one of the first three methods is used.

Each of the first three methods of loss determination requires the machine to be operated for two series of runs to simulate load condi-

tions, one with the armature terminals open-circuited and another with them short-circuited. For the cooler method, the machine may be operated either with load or with simulated load conditions as for the first three methods.

If the armature terminals are open-circuited, the total loss includes friction and windage of all mechanically connected apparatus and the open-circuit core loss corresponding to the armature voltage and frequency. If the armature terminals are short-circuited, the total loss includes friction and windage of all mechanically connected apparatus and the armature copper loss and stray-load loss corresponding to the armature current and frequency.

4.1.3 Elimination of Exciter Input. If a direct-connected or belted exciter is used for excitation during the loss tests, its power input should be deducted from the total input when determining friction and windage loss, core loss, and stray-load loss.

4.1.4 Effect of Temperature and Pressure. The bearing temperature should be held as constant as possible during the test because it affects the viscosity of the oil and therefore the friction loss. Therefore, the machine should be run at rated speed until the bearing temperatures or friction and windage losses become constant before starting the loss measurements.

Ambient temperature, barometric pressure, and humidity affect air density and therefore the windage loss. For machines in which this loss is of major significance, correction for changes in air density may be needed to correlate tests made under different conditions.

These effects should be considered in establishing conditions of tests for losses for those machines where temperature can be adjusted.

4.1.5 Coupled Machines. The preferred condition for testing for friction and windage loss is with the machine uncoupled from other apparatus. It is frequently necessary to test a machine coupled to other apparatus for which the friction and windage loss cannot be determined experimentally. The bearings may not be designed to permit running it uncoupled, or circumstances may make it inadvisable to uncouple for test and to recouple and realign after test. In these cases, it is necessary to allocate the total measured friction and windage loss to the various machines. Such a procedure would frequently be required for a hydraulic-turbine-driven generator (see ANSI/IEEE Std 492-1974

[11]). Motor-generator sets and frequency-changer sets are examples of equipment where this allocation may not be necessary, since the efficiencies are usually guaranteed on an overall basis.

When the tested friction and windage loss should be allocated to the various machines it should be done in proportion to the best available estimates of the expected values for each.

The thrust bearing of a vertical unit is usually included with the generator (or motor). However, only the thrust bearing loss due to the weight of the generator rotor is considered a generator loss. When the machine is tested coupled to other apparatus, there is an additional thrust bearing loss due to the weight of the connected apparatus. An estimate of this additional loss may be obtained from the generator manufacturer. This loss (as well as other losses of the connected apparatus) should be considered in the allocation described above.

ASME PTC 18-1949 [13], gives formulas for calculating the windage of a hydraulic turbine runner. Since these formulas have been found to give inaccurate results in many cases, they should be used with care. Test data on similar runners should be used as a basis for the estimated friction and windage loss when available.

4.1.6 Steam Turbine Overheating. Occasionally, steam-turbine-driven generators are tested for losses without steam on the turbine blades. During such tests, precautions should be taken to avoid severe overheating of parts of the turbine. Because of the many factors involved and the differences between machines, the turbine manufacturer should be consulted before making the test.

4.1.7 Unwatering Hydraulic Turbines. A hydraulic-turbine-driven generator must be tested with its turbine completely unwatered and the runner seal cooling water shut off if accurate values of generator losses are to be obtained (see ASME PTC 18-1949 [13]).

Unwatering the turbine should be done in accordance with instructions from the turbine manufacturer. Impulse turbines generally can be unwatered while motoring at normal speed. Francis and propeller turbines usually must be unwatered at standstill, but there are exceptions. Their scroll cases should be empty to eliminate the effect of even minor leakage through the wicket gates. Unless there is a butterfly valve ahead of the scroll case, this requires draining the penstock, which is a time-

consuming operation. If the runner is set above tailwater, proper venting through the turbine air valve will allow the water to drain out of the draft tube. When the runner is not sufficiently high enough above tailwater, the tailwater in the draft tube can be depressed by compressed air or by pumping. The water in the turbine seals produces appreciable loss. For this reason, it is preferable to run loss tests without the seal water. The turbine manufacturer's approval should be obtained to do this since some types of seals cannot be operated without water. It should be recognized that inaccurate test values may result if tests are run with seal water flowing.

4.1.8 Electric Starting. When it is not feasible to bring the machine to speed by mechanical means, it is necessary to start it electrically.

Occasionally, the generator (or motor) is suitable for starting from a rated-frequency full-voltage power source. If the power source is adequate, this is the simplest method of starting.

If the inrush current or the heating of the amortisseur winding is excessive with full-voltage starting, it is occasionally feasible to use reduced-voltage starting. This requires a power supply whose voltage can be reduced to a suitable value. For large machines, it is usually necessary that a second machine of suitable size be available, to be connected only to the machine being tested, for variable-voltage operation.

Most generators do not have amortisseur windings capable of starting the machine at full frequency and accelerating it to full speed. In such cases, it is necessary that another machine of suitable size and capable of operation at variable speed be available for synchronous starting of the machine to be tested.

For synchronous starting, the armatures of the driving and driven machines are connected together electrically while the machines are at rest. Under certain conditions, synchronous starting can be initiated in accordance with the manufacturer's recommendation while both machines are being driven by their turning gears. Separate sources of excitation for both machines should be available, however, a single source of excitation feeding both fields in series may be used. The exciter of a third synchronous machine is sometimes used. Approximately normal no-load full-voltage field current is applied to the driving machine and approxi-

mately 80% of normal no-load full-voltage field current is applied to the driven machine. The prime mover of the driving machine is then started slowly and the two electrically connected machines are brought up to the desired speed. Unless the bearings of the driving machine are equipped for the supply of high-pressure oil at starting, the sudden reduction of friction torque after breakaway may cause such rapid acceleration that the driven machine will oscillate and will fail to accelerate. A restart immediately after shutdown before the oil film has been squeezed out of the bearing may prove successful. Where the design of the bearing permits, jacking of the rotor prior to the starting operation may reduce the breakaway torque by introducing a fresh oil film.

Reduced-frequency starting can sometimes be used on successive test runs as a means of saving the time required to slow the driving machine completely to rest. With the driving machine running at a frequency recommended by the manufacturer of the machine to be tested, sufficient excitation is applied to the driving machine to produce the recommended volts per Hertz at the terminals of the machine under test. The field of the machine under test is short-circuited through a starting resistor. When the driven machine approaches synchronism with the driving machine, approximately 80% of normal no-load full-voltage excitation is applied to the driven machine and normal no-load full-voltage excitation is applied to the driving machine to pull them into synchronism and to bring them up to the desired speed.

4.2 Separate-Drive Method for Saturation Curves and Losses

4.2.1 Driving Motor. The machine under test is usually driven by a motor, directly or through a belt or gear. The motor should be a shunt direct-current motor (preferably the commutating-pole type), an induction motor, a synchronous motor, or the direct-connected exciter (if it is large enough). Preferably, the capacity of the driving motor should be such that it will operate at not less than 15% to 20% of its rating when supplying friction and windage losses of the driven machine; and not more than 125% of its rating when supplying friction, windage, and rated-voltage core loss; or friction, windage, rated-current stator I^2R , and stray-load loss. This permits the motor to operate on the flat part of its efficiency curve and often it may not be necessary to correct

for change in efficiency. The no-load losses of the driving motor should be known and where extreme accuracy is required, a curve of losses against input should be available.

4.2.1.1 The driving motor should be capable of operating the driven machine at its rated speed. When using an induction-motor drive, a source of adjustable frequency is necessary to provide for variations in slip with change of losses of the machine being tested. A synchronous motor has a decided advantage where all tests are to be made at rated speed; however, the synchronous motor either should have variable-frequency power for starting or it should have sufficient starting torque and thermal capacity to start and accelerate the machine under test. It simplifies the determination of driving-motor losses if the line voltage of a synchronous or induction driving motor is held constant throughout the run. The field of a shunt motor may be excited from a separate source so that the field current may be held constant to simplify the determination of its losses.

4.2.1.2 When a machine that does not require a belt in service is belt-driven for test, the tension of the belt should be kept as low as possible so that the increased bearing friction is not detrimental to the bearings and will not increase the friction loss appreciably. The belt should be of minimum width and weight to carry the load without slipping. Its losses should be known for the test conditions.

When a gear drive is used, the losses of the gear should be known under the test conditions.

4.2.1.3 The driving-motor method will give erroneous results if the machines are either accelerating or decelerating. Hence, readings should be taken only when the speed is constant at the correct value as measured by a reliable tachometer or a stroboscope.

4.2.1.4 The usual procedure for the test is to drive the machine at its rated speed until the bearings reach constant temperature and the friction loss becomes constant; this can be determined by observing when the input to the driving motor becomes constant. The input to the driving motor minus the losses of the driving motor (and belt or gear, if any) equals the input to or the losses of the tested machine (see 4.1.3).

4.2.2 Dynamometer as Driver. It may be desirable to use a dynamometer as a driving

motor, in which case only readings of torque and speed are required to determine the power input to the machine being tested. The power input in kilowatts to the machine under test is obtained from the following equation:

$$\text{power in kilowatts} = \frac{n \cdot T}{k} \quad (\text{Eq 9})$$

where

- n = rotational speed, r/min
- T = torque
- k = 9549 if T is in N·m
- = 7043 if T is in lb·ft

For correction of dynamometer and coupling windage and bearing loss see ANSI/IEEE Std 112-1978 [9].

4.2.3 Mechanical Driver. The machine can be driven by its prime mover or other mechanical apparatus such as a turbine or engine. Since it is usually not feasible to obtain an accurate measurement of power input to the machine being tested, this method can seldom be used to obtain losses but is satisfactory for determining the saturation curves if the speed can be controlled accurately and held constant at the desired value.

4.2.4 Open-Circuit Saturation Curve. The open-circuit saturation curve is obtained by driving the machine being tested at rated speed, open-circuited, and recording its armature terminal voltage and field current. Normally at least 12 sets of these readings should be distributed approximately as follows:

- (1) 4 below 60% of rated voltage (1 at zero excitation)
- (2) 2 between 60% and 90% of rated voltage
- (3) 4 between 90% and 110% of rated voltage, including one reading at approximately rated voltage
- (4) 2 above 110% of rated voltage, including one point at approximately 120% of the rated no-load field current (or at the maximum value recommended by the manufacturer).

NOTE: For cylindrical-rotor machines it is recommended that the manufacturer be consulted to determine the maximum voltage, or excitation, which should be used in making the open-circuit saturation curve, recognizing the ability of the machine to operate for the required time at each test point.

Testing should not be made with a transformer on the line unless the transformer manufacturer has approved operation at the intended overvoltages.

At rated voltage, readings should be taken of the terminal voltage (line-to-line) of all three