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IEEE Recommended Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation

Sponsor

Electric Machinery Committee
of the
IEEE Power Engineering Society

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Abstract: The power factor tip-up testing of stator coils and bars for use in large electric is covered in this recommended practice.

Keywords: cell capacitance, electric generators, power factor, stator bar, stator winding, tan delta

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Introduction

(This introduction is not part of IEEE Std 286-2000, IEEE Recommended Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation.)

This power factor tip-up test for stator coils has been used by electric machinery manufacturers and users since the original standard was issued in 1968. The original versions discussed minimally the theory of measurements. In this updated version, additional theory of the measurement and additional procedures are given for individual stator coils and bars and completely assembled windings.

This recommended practice was prepared by the Materials Subcommittee of the Electric Machinery Committee, which had the following membership:

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Contents

IEEE Recommend Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation

1. Overview

1.1 Scope

This recommended practice applies to stator coils or bars (half coils) of electric machinery operating at any voltage level. It usually applies to machines with a voltage rating of 6 kV and higher. Individual stator coils outside a core (uninstalled), individual stator coils installed in a core, and completely wound stators are covered in this recommended practice.

The tests apply to all coil insulation systems: pre-impregnated coils, post impregnated coils (global impregnation), and fully-loaded (resin-rich) taped coils. This recommended practice is not applicable to non-impregnated individual coils.

The coil insulation under test is the major groundwall insulation that is external to the conductor structure. Only that part of the strand and turn insulation that is dielectrically in series with the groundwall insulation enters into the measurements. When testing individual coils and utilizing guard electrodes, only that part of the groundwall insulation under the low voltage electrode (outer electrode) enters into the measurement.

1.2 Purpose

The purpose of this recommended practice is to describe the power factor and the power factor tip-up of the coil insulation and to specify test procedures for their measurements.

2. References

The following publications shall be used in conjunction with this standard. When the following standards are superseded by an approved revision, the revision shall apply.

ASTM D150-98, Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation.[1]

ASTM D1868-93 (1998), Standard Test Method for Detection and Measurement of Partial Discharge (Corona) Pulses in Evaluation of Insulation Systems.

IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition.

IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing (ANSI).[2]

IEEE Std 43-2000, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery.

IEEE Std 62-1995, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Part 1: Oil-Filled Power Transformers, Regulators, and Reactors.

IEC/TR 60894 (1987-03), Guide for Test Procedure for the Measurement of Loss Tangent of Coils and Bars for Machine Windings.[3]

3. Definitions

For the purposes of this recommended practice, the following terms and definitions apply. IEEE 100[4] should be referenced for terms not defined in this clause.

The electrical equivalent circuit for an insulation system with a dielectric loss can be represented by either a parallel or a series arrangement of passive components. Both representations are given in Figure 1 and Figure 2. The insulation is represented by a lossless capacitor, and a resistor represents the dielectric loss.

To maintain consistency throughout this standard, the terms *power factor* and *power factor tip-up* are used. This is done with the understanding these terms may be used interchangeably with the terms *dissipation factor* and *delta tangent delta*, respectively. The specific definitions for these terms are given later in this section.

Comparison of the power factor and dissipation factor for phase angles and complementary loss angles is given in Table 1.

As is shown in this table, the two measurements are very nearly the same for a specimen with a power factor or dissipation factor of 0.1000 or less. The following equations show how power factor and dissipation factor can be converted into one another:

$$PF = \frac{DF}{\sqrt{1 + DF^2}}$$

$$DF = \frac{PF}{\sqrt{1 - PF^2}}$$

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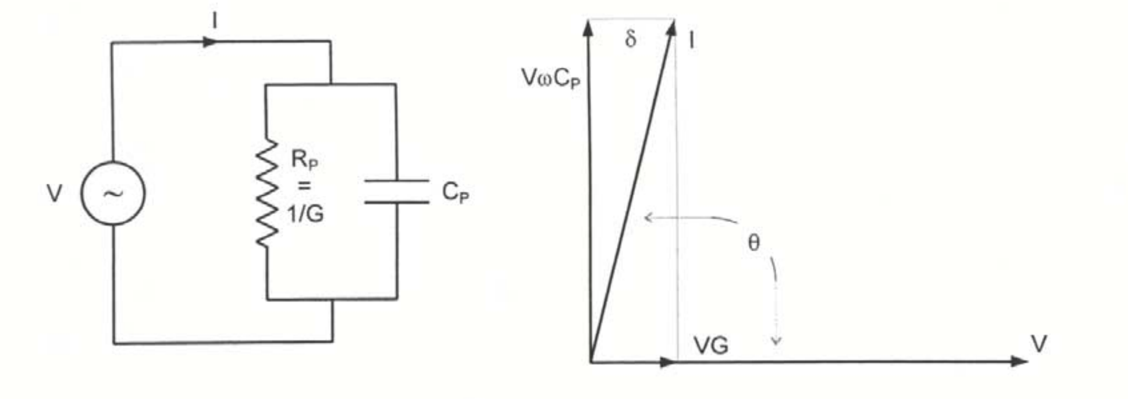
[1] ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).

[2] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

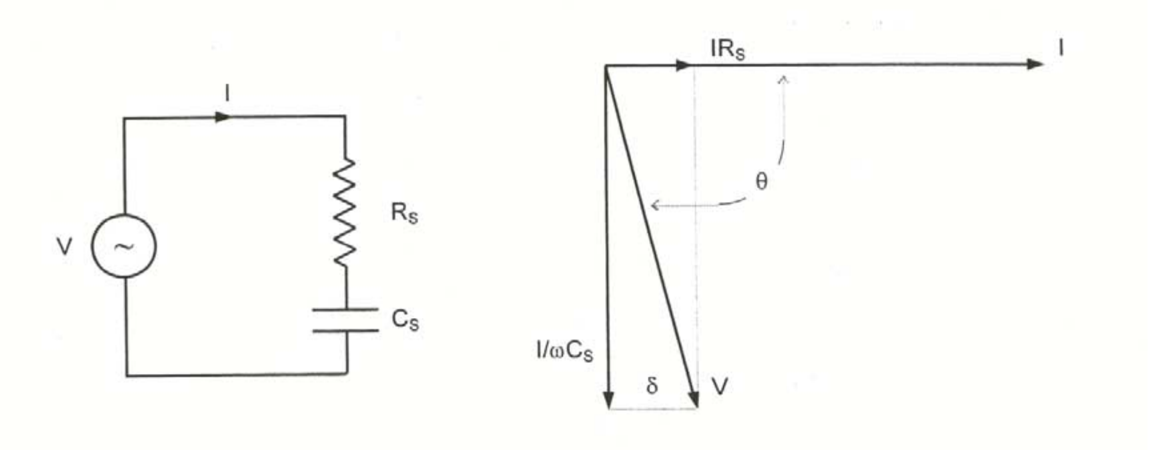
[3] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[4] Information on references can be found in Clause 2.



C_P	is parallel capacitance
G	is equivalent ac conductance
R_P	is equivalent ac parallel resistor
X_P	is parallel reactance
ω	is $2\pi f$ (for a sinusoidal wave)
θ	is phase angle
δ	loss angle

Figure 1—Parallel circuit and vector diagram



C_S	is parallel capacitance
R_S	is equivalent ac conductance
X_S	is equivalent ac parallel resistor
ω	is $2\pi f$ (for a sinusoidal wave)
θ	is phase angle
δ	loss angle

Figure 2—Series circuit and vector diagram

Table 1—Comparison of power factor and dissipation factor

Power factor, $\cos\theta$	Phase angle, θ, degree	Complementary loss angle, δ, degree	Dissipation factor, $\tan\delta$	Difference
0.000000	90.000000	0.000000	0.000000	0 part in 10^6
0.005000	89.713520	0.286480	0.005000	$< \pm 1$ part in 10^6
0.010000	89.427033	0.572967	0.010000	$< \pm 1$ part in 10^6
0.020000	88.854008	1.145992	0.020004	± 4 parts in 10^6
0.050000	87.134016	2.865984	0.050063	± 63 parts in 10^6
0.100000	84.260830	5.739170	0.100504	± 504 parts in 10^6
1.000000	0.000000	90.000000	infinity	

3.1 capacitance: That property of a system of conductors and dielectrics that permits the storage of electrically separated charges when potential differences exist between the conductors.

Capacitance, C, is the ratio of a quantity, q, of electrical charge stored in a capacitor to the potential difference, V.

$$C = \frac{q}{V}$$

The SI unit of capacitance is the farad, which is equal to one coulomb per volt.

3.2 complex relative permittivity, complex relative capacitivity (ε_r*): If a dielectric medium is lossy, the relative permittivity under sinusoidal excitation can be represented by a complex number:

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' = \frac{Y}{j\omega C_0}$$

where

Y is admittance of a given configuration of electrodes with the dielectric material
ωC_0 is admittance with the electrodes in vacuum

In general, the complex relative permittivity will depend upon the frequency of excitation.

3.3 corona: Visual luminous discharge caused by ionization of the air surrounding a conductor with or without insulation caused by a voltage gradient exceeding a certain critical value.

3.4 delta tan delta (Δ tan δ): Increment in the dielectric dissipation factor, tan δ, of the insulation measured at two designated voltages (see Figure 3).

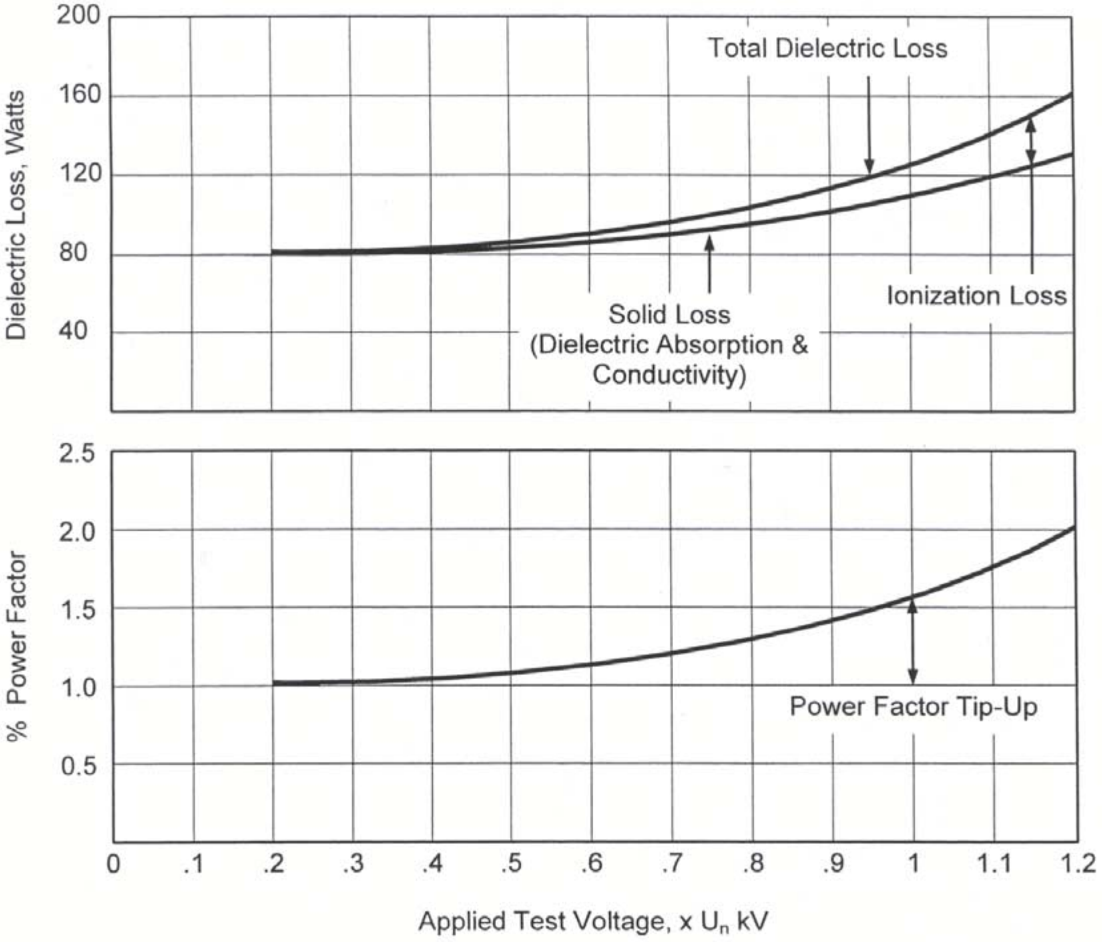


Figure 3—Power factor x U_n kV

3.5 dielectric dissipation factor (tan δ) (DF): Tangent of the dielectric loss angle, δ, or the cotangent of the dielectric phase angle, θ (see Figure 1 and Figure 2).

$$DF = \tan\delta = \cot\theta = \frac{X_p}{R_p} = \frac{G}{\omega C_p} = \frac{1}{\omega R_p C_p} = \frac{I_l}{I_c}$$

where

C_p	is parallel capacitance
G	is equivalent a-c conductance
R_p	is equivalent a-c parallel resistor
X_p	is parallel reactance
C_s	is series capacitance
R_s	is equivalent a-c series resistor
X_s	is series reactance
I_l	is loss current
I_c	is capacitive current
ω	is $2\pi f$ (for a sinusoidal wave)
θ	is dielectric phase angle
δ	is dielectric loss angle

The dissipation factor of a dielectric is the same for the series and parallel representations by the relationship:

$$DF = \frac{1}{\omega R_p C_p} = \omega R_s C_s$$

The components in the series and parallel representations of a dielectric (see Figure 1 and Figure 2) are related by the relationships:

$$C_p = \frac{C_s}{1 + DF^2}$$

$$R_p = \left(\frac{1 + DF^2}{DF^2}\right) R_s$$

Also, the dissipation factor is the ratio of the dielectric loss index to the relative dielectric constant.

$$DF = \frac{\varepsilon_r''}{\varepsilon_r'}$$

ε_r''	is dielectric loss index
ε_r'	is real relative permittivity

3.6 dielectric loss angle (δ): Angle whose tangent is the dissipation factor or arctan $\varepsilon_r''/\varepsilon_r'$. It is also the complement of the phase angle (or $\delta = 90° - \theta$).

3.7 dielectric loss index (ε_r''): Magnitude of the imaginary part of the complex relative permittivity.

3.8 dielectric phase angle (θ)**:** Angular difference in the phase between the sinusoidal alternating voltage applied to a dielectric and the component of the resulting current having the same period as the voltage. Also, the angle whose cotangent is the dissipation factor, arccot $\varepsilon_r''/\varepsilon_r'$.

3.9 dielectric power factor (PF): Ratio of the power dissipated in the insulation, in watts, to the product of the effective sinusoidal voltage and current, in volt-amperes. Also, the cosine of the dielectric phase angle, θ, or the sine of the dielectric loss angle, δ (see Figure 1 and Figure 2).

$$PF = \frac{W}{VI} = \cos\theta = \sin\delta$$

3.10 discharge extinction voltage (ionization or corona extinction voltage) (DEV): Voltage at which discharge pulses that have observed in an insulation system, using a discharge detector of specified sensitivity, cease to be detectable as the voltage applied to the system is decreased.

3.11 discharge inception voltage (ionization or corona inception voltage) (DIV): Voltage at which discharge pulses in an insulation system become observable with a discharge detector of specified sensitivity, as the voltage applied to the system is increased.

3.12 groundwall insulation: Main high-voltage electrical insulation that separates the copper conductors from the grounded stator core in motor and generator stator windings.

3.13 guard electrode: One or more electrically conducting elements, arranged and connected in an electric instrument or measuring circuit so as to divert unwanted conduction or displacement currents from, or confine wanted currents to, the measurement device.

3.14 ionization: The process or the result of any process by which a neutral atom or molecule acquires either a positive or negative charge.

3.15 partial discharge (PD): Electrical discharge that only partially bridges the insulation between conductors. A type of localized discharge resulting from transient gaseous ionization in an insulation system when the voltage stress exceeds a critical value. Reference ASTM D1868-93.

3.16 permittivity, capacitivity (ε)**:** Physical quantity defined by the equation,

$$D = \varepsilon E$$

where

E is the electric field strength
D is the electric flux density

Note that for a parallel plate capacitor the capacitance is given by

$$C = \varepsilon\frac{A}{d}$$

where

A is area of the plate
d is separation

Note that the dimensions of the electrode must be much larger than d.

3.17 permittivity of vacuum, electric constant (ε_0): In SI the permittivity of vacuum is equal to 8.8542 *pF*/m. This number is a result of choices made in setting up the equations of electromagnetism, and in that sense it is not a property of vacuum. Therefore, the preferred term is *electric constant*. In some cgs systems, which were formerly used in electrical engineering, the electric constant is set equal to unity.

3.18 power factor tip-up: Difference in the dielectric power factor of the insulation measured at two designated voltages (see Figure 3).

3.19 real relative permittivity (ε_r'): Real part of the complex relative permittivity. That property, which determines the electric charge stored per unit volume for unit potential gradient. The numerical value normally is given relative to a vacuum.

3.20 relative permittivity, relative capacitivity (ε_r): The relative permittivity, a number, is the quotient of the permittivity divided by the electric constant,

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

Because capacitance is proportional to permittivity, the ratio of the capacitance, C_x, of a given configuration of electrodes with a certain material as a dielectric to the capacitance, C_0, of that same configuration of electrodes in vacuum, is given by

$$\frac{C_x}{C_0} = \varepsilon_r$$

Dielectric constant is a synonym for relative permittivity; however, its use is discouraged by many authorities.

3.21 semiconductive slot coating: The partially conductive paint or tape layer in intimate contact with the groundwall insulation in the slot portion of the stator core. This coating ensures that there is little voltage between the surface of the coil or bar and the grounded stator core.

3.22 stress control coating: The paint or tape on the outside of the groundwall insulation that extends several centimeters beyond the semiconductive slot coating in high-voltage stator coils and bars. The stress control coating often contains silicon carbide particles that tend to linearize the electric field distribution along the coil or bar endturn. The stress control coating overlaps the semiconductive slot coating to provide electrical contact between them.

4. Theory of measurements

The power factor versus voltage characteristics of coil insulation is the net result of several phenomena occurring in the insulation structure. Ionization of gaseous inclusions (voids) in the insulation structure causes an increase in power factor with voltage increase as the critical voltage gradient is exceeded. Void ionization is a form of partial discharge or corona. The energy dissipated by the partial discharge is represented by a resistor in series (or parallel) with the coil capacitance. A typical coil with a small void content will exhibit a measurable level of power factor tip-up with the resistance having a finite value. A coil with high dielectric loss exhibits a large value of series resistance, caused by the higher level of partial discharge (PD), and exhibits a much higher level of power factor tip-up. Dielectric absorption and conductive losses in the insulation structure will also cause an increase in power factor with voltage (see Figure 3).

The energy associated with a single PD event is minute [B1]. The cumulative effect of many PD events can degrade the insulation. For this reason, it is important to quantify the level of PD activity in the insulation system.

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

For example, pronounced dielectric losses would be expected to occur due to space charge accumulation at interfaces of contiguous tapes, having different conductivities because of different degrees of contamination.

It is difficult to analyze the effect of space charges upon the tan δ value as a function of voltage without the introduction of a number of disposable constants. However, tan δ's dependence on partial discharges is easily accounted for in terms of partial discharge rate and pulse magnitude as a function of voltage.

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

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

where

P' is the power loss within the solid dielectric portion of the bar
ΔP_j is the power loss due to the j^{th} discharge

If tan δ′ is taken to represent the dissipation factor value of the dielectric loss contribution and whose change with voltage is assumed to be negligible, then Equation (1) may be rewritten as

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

where

ω is the radial frequency term
C is the capacitance of the bar specimen measured at an applied voltage V
tan δ is the total dissipation factor value in the presence of both the dielectric and partial discharge losses

Here C' represents the capacitance of the specimen bar under the occurrence of only the dielectric losses, while C'' denotes the specimen capacitance in the presence of discharges at the applied voltage V. The voltage $V_j(t)$ is the instantaneous value of the applied voltage at which the j^{th} discharge pulse of amplitude ΔV_{cj} takes place with a repetition rate of n_j pulses per second. The tan δ of the bar insulation in terms of Equation (2) becomes thus

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

Hence, on the assumption that tan δ, which is determined by the dielectric losses, remains unchanged with voltage, the overall tan δ value of the bar insulation will vary with the second term on the right hand side of Equation (3), which represents the discharge power loss contribution to the dissipation factor.

As long as an increasingly larger number of voids begin to undergo discharge with rising applied voltage, the value of tan δ will continue to increase. Once all voids become ionized and are discharging, the tan δ value, after attaining a maximum, will commence decreasing with voltage. This behavior is manifested when the power loss due to all the partial discharges is increasing at a lower rate than the square of the applied voltage term, V^2, in the denominator of the second term of the right hand side of Equation (3). Consequently, a negative tip-up value of tan δ (if it is caused by partial discharge losses) occurs when all the existing voids become ionized and begin discharging at some lower voltage, and a further rise in applied voltage does not result in any additional discharging voids.

5. Applications

- The power factor versus voltage test is useful in the laboratory evaluation of insulating material or processes applied to coil insulation. Two or more voltage levels can be used for this evaluation.
- The power factor tip-up test is used as a quality control test on newly manufactured coils. Power factor measurements are usually made on each coil or a sampling of a production run, and the data is analyzed on a statistical basis.

  Usually the power factor versus voltage is plotted for a specified voltage range, and the power factor tip-up is calculated between two designated voltage levels. Specified ranges of power factor tip-up values are permitted, depending on the coil design and many other factors.
- Individual coils in a stator slot can also be power factor tested, with the purpose of determining the power factor tip-up of the coils after installation or a period of service as a maintenance test.
- A completely wound stator winding can be power factor tested only as a post-impregnated winding. This is useful as a maintenance tool over the life of the machine.

  The test method and the test equipment differ from that when testing individual coils. A change in power factor tip-up over a period of time can be an indication of change in the condition of the coil insulation, semiconductive slot coating, stress control coating, end windings, or slot support systems.

6. Interpretation

The normal procedure is to measure power factor of the coil, or coils, over a specific voltage range. Except in special cases, the power factor measurements are taken at room temperature.

The range of voltage is usually determined by specification or by the personnel responsible for the test. The power factor is then plotted with respect to the test voltage levels.

Once the power factor data is plotted, interpretation of the data is then done. Figure 3 shows an example of a typical plot of power factor versus voltage. “U_n” is used to denote the line-to-line voltage of the coil or machine and has units of kV rms.

a) The initial value of power factor is used to determine the cure state of the insulation system. If insulation cure is adequate, the initial value is usually consistent with the particular insulation system being measured. The increase in power factor with an increase in applied voltage is the normal phenomenon that indicates increased partial discharge of the voids. Many factors affect the degree of increase in the power factor. Some of these factors are delamination, imperfect impregnation, incomplete cure, inadequate bonding, wrinkling, and contaminants. The condition of the coils surface treatment and voltage grading system also influences the degree of increase in power factor.

b) Differences in power factor tip-up between individual coils of the same fabrication are usually due to variations in the extent of incidental void formation in the insulation structure. As shown in Figure 3, coils that have a greater power factor tip-up are considered to have a larger total void content.

c) As indicated in Figure 3, the power factor tip-up can be calculated between any two voltage levels. The actual voltage levels selected for the test are determined by agreement between the manufacturer and user. There are usually three values associated with the power factor curve. U_n is defined to be the coil line-to-line voltage and is commonly the voltage rating of the coil.

   The three values to consider are:

   1) The initial value of power factor at the first test voltage level; e.g., at 0.2 U_n (20%).
   2) The value of the power factor tip-up calculated between two different voltage levels; e.g., between 0.8 U_n (80%) and 0.2 U_n (20%).
   3) The value of the power factor tip-up calculated between each successive voltage value; e.g., between 0.2 U_n (20%) and 0.1 U_n (10%), and 0.3 U_n (30%) and 0.2 U_n (20%), etc.

d) A change in the power factor tip-up of the coil insulation during its service life may be the result of deterioration processes. A combination of electrical, thermal, mechanical, and environmental factors can affect the insulation system.

e) Power factor test results on separate coils before installation may not be comparable to that measured for the installed winding.

f) Reduced frequency (e.g. 0.1 Hz) power factor testing is used to facilitate field-testing in some cases. When performing tests in this manner, it should be recognized that the data obtained will not be comparable to data taken at the rated frequency. This may make interpretation of the data difficult.

g) Power factor and power factor tip-up cannot be regarded as an absolute indication of the condition of the coil insulation. The power factor data should be used in conjunction with the results of other evaluation methods.

7. Test parameters

The following parameters affect the power factor test results when the coil is tested separately in or out of the slot, singly or in groups.

a) The length of the coil or the length of the test electrode on the coil influences the sensitivity of the power factor test for locating small areas having abnormally high power factor tip-up. The power factor tip-up of coil insulation may be considered as the average tip-up of the coil length or electrode length. The sensitivity of the test decreases with an increase in coil length. When testing coils outside the slot, electrode size can be changed to measure a particular location along the length of the coil.

b) An ideal test unit for an installed winding is one coil, or half coil. To expedite testing, coils can be tested in groups of two or three, with a resulting loss in the sensitivity of the test. To compensate for reduced sensitivity it is recommended to establish an acceptance limit, which permits less deviation than a single coil power factor tip-up limit. If this limit is exceeded, the group is then broken down into individual coils and tested separately. It is important to recognize that only results from coils or groups of coils tested under similar conditions should be compared.

c) When a power factor test is made on the insulation of a complete phase or of an entire winding, a coil having an abnormally high tip-up can have no appreciable effect on the test results.

d) Power factor tests on coils installed in their normal position may be affected by the following factors:

    1) Corona losses that can occur at the test connections.

    2) Losses caused by ionization at the interface between the coil surface and the grounded slot surface.

    3) Losses in some grading systems which may be applied to the coil or bar arms external to the ground insulation and losses in grading system which may be applied to the coil or bar internally on the conductor surfaces will affect the voltage dependence of the power factor of the insulated coil or bar (See Clause 8). The impedance of some grading systems changes with current density causing a dependence of power factor tip-up on applied test voltage.

e) Power factor test results on coils outside a slot are affected by the electrodes used to simulate the coil slot. To compare results between individual coils, or groups of coils, identical electrode systems shall be used.

f) If the coils have a semiconductive coating, the coating is used as the outer electrode provided plates, wrapped foil, or spiraled wires are applied along the entire electrode length. These methods are used to effectively lower the resistance of the semiconductive coating to eliminate its effect on the power factor measurement.

    When using the spiral wire method, 0.8 mm (20 AWG) bare copper wire is wrapped in a spiral fashion, with a maximum spacing between wraps of 5 to 8 cm. The wire should be wrapped tight around the coil to make as much contact to the outer surface of the semiconductive coating as possible. When using the foil wrap or metal plates, great care should be taken to minimize the voids between the metal electrode and semiconductive coating on the coil. Foil electrodes and clamped plates are recommended.

g) If the coils do not have a semiconductive coating, temporary conductive electrodes must be applied without voids between the electrode and coil surface. Foil electrodes or foil electrodes with clamped plates are recommended in this application.

h) The end effect will have an excessive influence on the power factor measurement. The use of guard electrodes is recommended to prevent erroneous power factor readings in all cases. Guard electrodes are treated in Clause 8.

i) The power factor versus voltage characteristic is affected somewhat by the temperature of the coil insulation. It is recommended that tests be made at room temperature (25 °C). The temperature of the coil insulation should be recorded.

j) The power factor versus voltage characteristic curve is affected by the test method. If the coil under test has been subject to a dielectric (hi-pot) test on the groundwall insulation, prior to being subjected to the power factor test, the level of tip-up will be affected. It is recommended on new separate coils, to power factor test the coils prior to being subjected to the dielectric test.

k) When power factor testing a coil, a conditioning voltage usually equal to or slightly higher than the coil voltage rating, i.e., 1.2 U_n, may be applied to the coil for a time period from 20 sec to 4 min, depending on the requirements. The application of a conditioning voltage will help to stabilize the coil temperature due to dielectric heating of the insulation. The use of the conditioning voltage will affect the power factor tip-up test results.

    Conditioning can be replaced by performing an additional power factor reading at the initial voltage, e.g. 0.2 U_n, after the highest voltage measurement. If comparing test results on a set of coils, it is recommended to test all the coils using the same voltage conditioning procedure.

8. Coil or bar screening and stress control coating

The slot (or cell) portions of stator coils or bars may be provided with a conductive (semiconductive) material on the outer surface. This provides an equipotential surface when it is installed in the stator core and is intended to prevent the formation of slot discharge activity. High-voltage coils and bars are also provided with a layer of high-resistance material on the overhang portions. This high-resistance material is non-linear with voltage and its purpose is to grade (control) the voltage distribution on the coil where it exits the stator core. In all cases, the semiconductive slot coating extends beyond the stator core. There is an overlap of the stress control coating and the semiconducting slot coating.

Measuring power factor of the slot portion may be affected by a contribution from the resistive graded region of each overhang section. The dielectric losses in the stress control portions of the overhang, together with the losses dissipated in the resistive grading material, will be measured in addition to the dielectric losses in the ground insulation.

8.1 Guarding techniques

Various techniques are available to minimize the measuring errors caused by the electrically graded portions of the overhang. The move-effective guarding techniques are described in 8.1.1 through 8.1.4.

8.1.1 Guard electrode on surface of stress control coating

This procedure requires a guard electrode to be wrapped circumferentially around the surface of the stress control coating. This arrangement is shown in Figure 4(a) and Figure 4(b). The recommended material for the guard electrodes is foil with conductive adhesive. However, any material demonstrated to be effective for the guard electrodes may be used. The guard electrode is installed a short distance beyond the actual end of the semiconductive slot coating, for example at a distance of 3.0 mm (0.125 inches), including both ends of the coil. Locating the actual end of the semiconductive slot coating can be difficult if it is overlapped with the stress control coating. This procedure is normally used on production coils since it is known at that time where the exact overlap of these two coatings is located. There is merit in determining the optimum electrode location, which duplicates the results obtained in 8.1.2.

8.1.2 Interruption of semiconductive slot coating

By introducing a temporary gap in the semiconductive slot coating at each end of the slot portion and using the remainder of the slot portions together with the stress control portions as guard electrodes, only the dielectric losses in the slot portion are measured. A technique for establishing a gap in the semiconductive coating should be used which eliminates the risk of damaging the coil insulation. This procedure gives the correct power factor and power factor tip-up. Its use is only practical in the case where the semiconductive coating is paint. Any attempt to cut semiconductive tape in order to create a temporary interruption may result in the unwrapping of the tape from the coil. Although this method gives the most satisfactory results, it is time consuming to perform because the gap in the paint must be eliminated on completion of the measurements. This is accomplished by repainting the gap with semiconductive paint. Repainting the gap will require adequate cure time before addition testing of the coil. This arrangement is shown in Figure 5(a) and Figure 5(b). It must be noted that the gap width will have some influence on the measured power factor value(s).

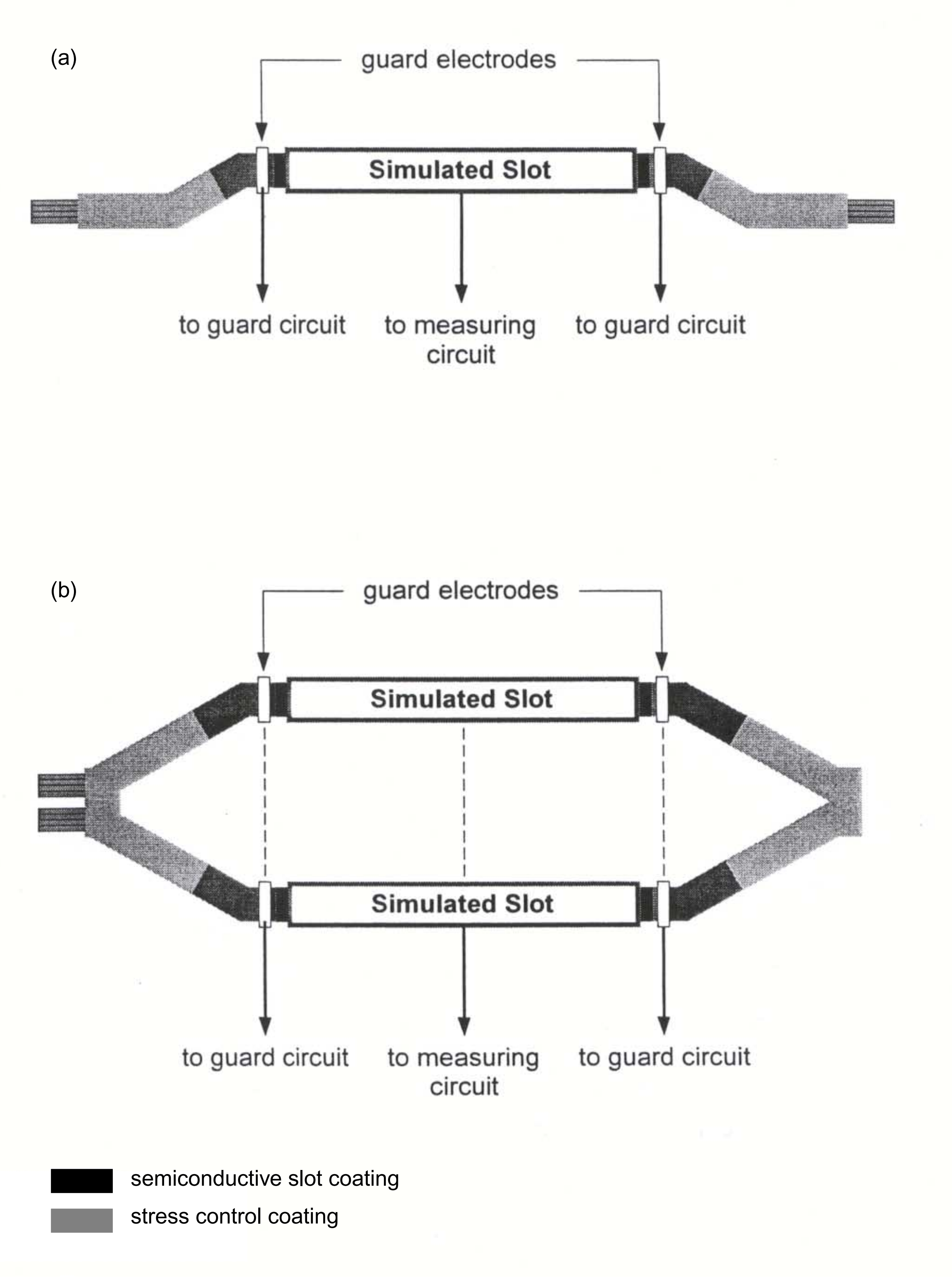


Figure 4—Guard electrode on surface of stress control coating

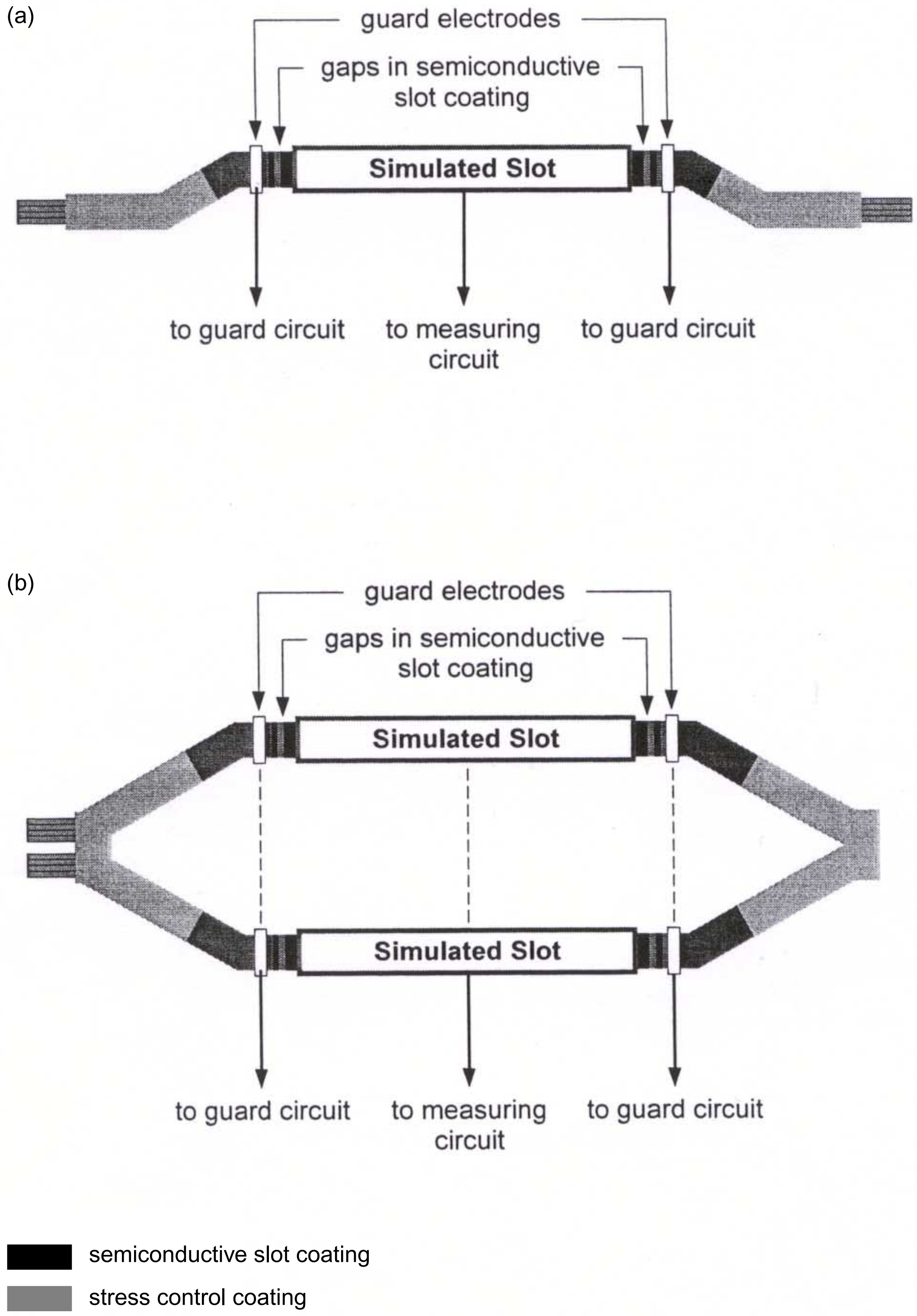


Figure 5—Guard electrode on surface of stress control coating

8.1.3 Foil-wrap method

In this procedure, the stress control coating is wrapped in metal foil. The foil is electrically connected to the dummy slots (used during measurements) on the slot portions. It is important to apply the foil tightly and minimize voids and air pockets that can affect the measured test results. The dummy slots are extended, in effect, to the outer ends of the stress control coating. Guard electrodes are installed on the overhangs beyond the stress control portions. Since a longer portion of the coil is under test, the power factors and power factor tip-ups will be of a different value than obtained when the end turn region is not included in the measurement. Also, the dielectric losses of the stress control coatings are included in the measurements. The arrangement is shown in Figure 6.

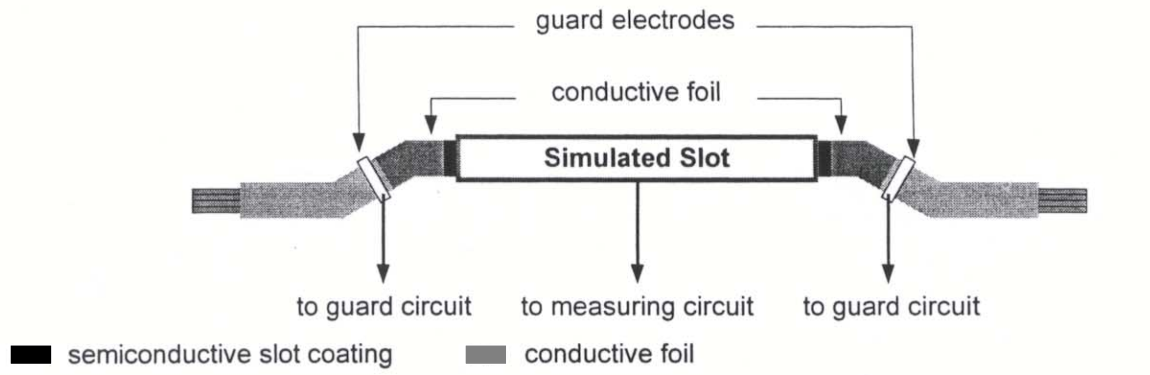


Figure 6—Foil wrap

8.1.4 Driven-guard method

In this procedure, the guard electrodes are wrapped around the outer ends of the semiconductive coating on the slot portions. The contact resistance between the guard electrodes and the coil surface is very low in this region and, consequently, the guard electrodes successfully intercept all current flowing from the stress control portions of the coils. Measuring errors potentially occur due to currents flowing between the ends of the dummy slots and the guard electrodes. The voltage follower circuit has high input impedance, low output impedance, unity voltage gain, and zero phase shift. This technique gives essentially the same results obtained in Clause 8.1.2, but it eliminates the need for the interruptions in the semiconductive coating and can be used with either tape or paint coatings. The arrangement is given in Figure 7.

CAUTION

If the semiconductive coating is below 1000 ohms/sq., the driven guard method may not work well.

9. Testing of individual coils

For individual coils or bars, the typical test setup is shown in Figure 8.

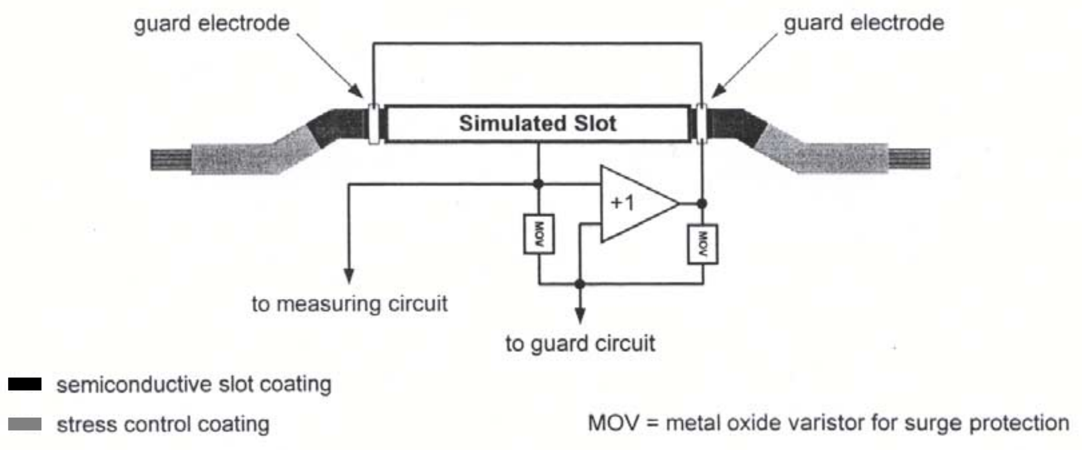


Figure 7—Driven guard

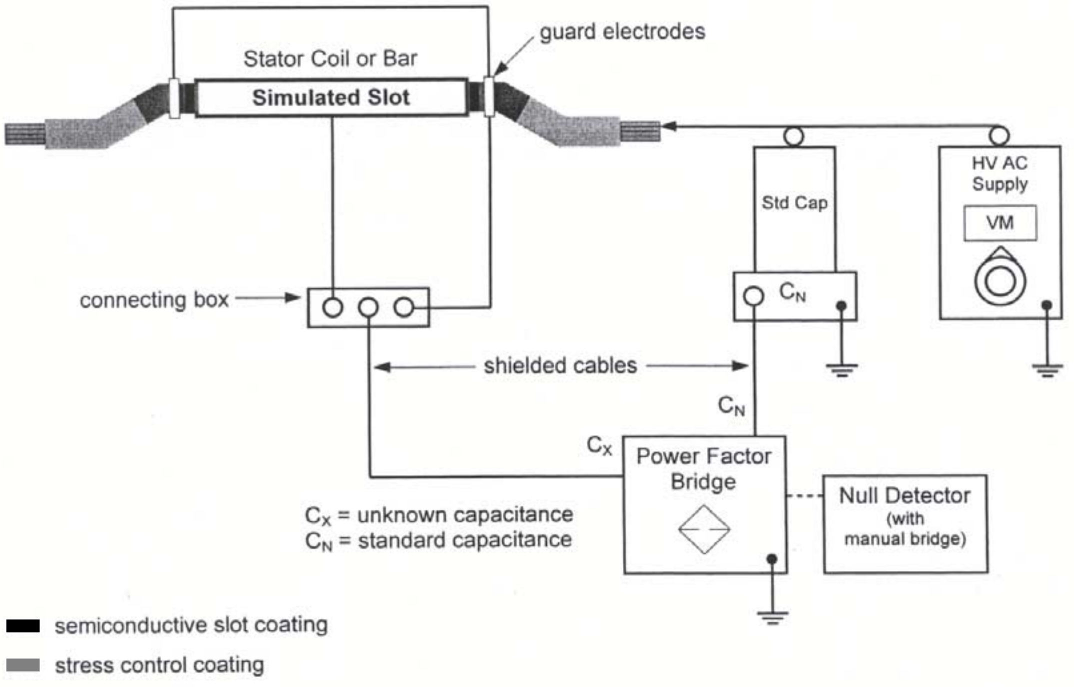


Figure 8—Typical test setup for measuring power factor of individual bars and coils

9.1 Required equipment

9.1.1 Test voltage supply

A voltage supply at power frequency is required. The kVA rating should be adequate for the size of coil being tested.

The sinewave shape of the power frequency voltage should conform to good industrial practice as defined in IEEE Std 4-1995.

9.1.2 Test voltage measurement

AC voltage measuring system with an accuracy of 3.0%, to ensure the effective value (rms) of the test waveform, shall be used, in accordance with IEEE Std 4-1995.

9.1.3 Power factor bridge

Either a manual or automatic capacitance bridge or power factor test set shall be used. The bridge shall provide the power factor value and the cell capacitance of the coil or bar under test. The equipment should be capable of measuring power factor with an error not exceeding ~ 0.002 (0.2%) power factor or ~ 10% of the measured value, whichever is greater.

9.1.4 Shielding

The measuring equipment, including the connecting leads to the test specimen, should be suitably shielded so the measurement is confined to the insulation of the test specimen.

9.1.5 Standard capacitor

A high-voltage capacitor of the correct value is used as a reference standard in the bridge circuit. The value of the capacitance is typically 100 pF or 1000 pF. The voltage rating of the capacitor shall be higher than the highest test voltage level. The tolerance of the capacitor shall be at least –5.0% with less than 5 pC of partial discharge at rated capacitive voltage according to ASTM D1868-93. The power factor value of the standard capacitor should be equal to or less than 0.001%.

9.2 Test procedure for individual coils

Power factor and power factor tip-up testing are used as a quality assurance tool in determining the consistency of the stator bar manufacturing process.

Each manufacturer has its own test performance protocol and various sampling levels may be selected. The differences in protocol include sample size, conditioning, application of voltage, number of voltages used in the measurement, temperature, and calculation of power factor tip-up.

The power factor versus voltage characteristic should be measured over a wide range. A frequently used voltage range is from 0.2 U_n to 1.2 U_n of rated coil line-to-line voltage (U_n), in steps of 0.2 U_n or greater. The lowest test should be substantially lower than the operating phase-to-ground voltage rating of the coil or machine in the coil is to be used. The higher test voltage may be selected to be equal to or somewhat in excess of the operating phase-to-ground voltage.

9.2.1 Sample size

The number of coils tested from a coil (bar) production run can vary from all coils from a set to one or two coils from a set. The important criterion is to select a sample size that ensures the determination of whether the production process is under control. It is important to select enough samples to ensure that a statistically significant sampling has been made.

9.2.2 Coil preparation

All coil strands must be electrically connected. It is best to use 0.8 mm (20 AWG) bare copper wire and wrap each individual bare coil strand. It is good practice to electrically connect all strands at each coil end.

A ground electrode should run the length of the specimen to be tested. Guard electrodes should be correctly placed on the test specimen. No sharp conductive regions should appear on the outer coil surface. The high-voltage connections shall be discharge free. Any abnormal external partial discharge will result in a high coil power factor tip-up and will mask the actual power factor tip-up of the insulation system. It is recommended to perform power factor testing prior to any high potential test.

9.2.3 Conditioning

Power factor and power factor tip-up are affected during the first application of a test voltage. Most manufacturers perform some form of conditioning test prior to making the power factor measurement to stabilize the coil and the partial discharges and dielectric loss. It is common to use a conditioning voltage up to 1.2 U_n. It is important that all coils, in a particular set, are subject to the same conditioning, if a conditioning method is used.

9.2.4 Application of voltage

When measuring power factor at different voltage levels, either an increasing voltage or a decreasing voltage can be used. It is recommended that measurements be made with increasing voltage, because it usually results in a more accurate measure of power factor tip-up. Decreasing voltage may result in a high power factor at the lower test voltages, which will result in a lower value of power factor tip-up. This is because for a given void, the discharge extinction voltage is lower than the void s inception voltage. Whichever method is selected to be used, it should be followed on each of the coils from the selected set. If a conditioning voltage is being used, the applied voltage shall be lowered to zero and then raised to the lowest voltage measurement to assure all PD is extinguished prior to taking the baseline measurement at the initial voltage value. This applies to tests using either an increasing voltage technique or a decreasing voltage technique.

9.2.5 Number of measurements

The number of voltage steps taken for each power factor test can vary. Power factor varies with applied test voltage. It is necessary to measure power factor at a minimum of two voltage levels. The lowest voltage is usually selected to be below the coil s discharge inception voltage but high enough to cause dielectric loss measurements. The second voltage level is selected to be well above the discharge inception voltage and should be close to the actual service voltage of the coil. Power factor can also be measured at each 0.2 U_n (or greater) increments in test voltage, which provides sufficient data points for a plot of power factor versus applied test voltage.

9.2.6 Cell capacitance

The cell capacitance value is used to check that correct impregnation of the coil has resulted after manufacturing.

The measured cell capacitance should agree within 10% of the calculated cell capacitance which is calculated from the equation

$$C = \varepsilon A/d.$$

9.2.7 Temperature of specimen

Normally, power factor and power factor tip-up, measured on new production coils, are done at room temperature (25 °C). However, both power factor and power factor tip-up can be measured at elevated temperature. Only a very small sample of a set of coils would be measured and the data is used to determine degree of coil cure. This high temperature power factor tip-up test is not normally done on production coils. The power factor versus temperature curve is one measure of the degree of cure or intrinsic characteristic of the insulation system. The glass transition temperature can be approximated using this data. Usually this test is performed at one elevated temperature that is usually the temperature class of the insulation system.

9.2.8 Voltage examples

Following are examples of voltages used to measure the coil power factor. The letter U_n is used to denote the line-to-line voltage of the coil or machine and has units of kV rms.

Measure power factor at two voltage levels which are 25% and 100% of the operating phase-to-ground voltage of the machine.

Measure power factor at two voltage levels, such as 2 kV rms and the phase-to-ground operating voltage of the machine.

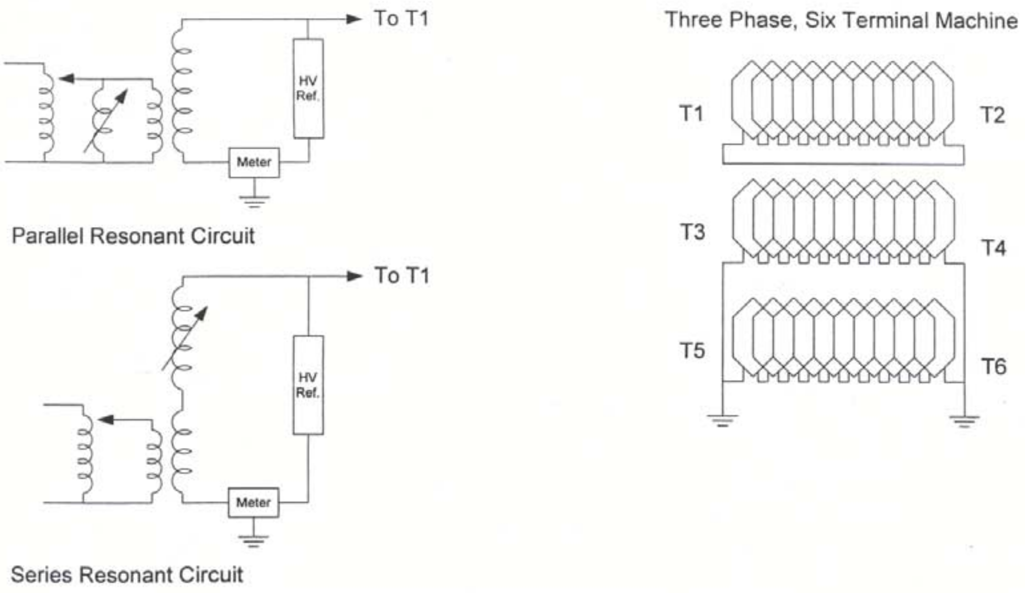
Measure power factor at 0.2 U_n, 0.4 U_n, 0.6 U_n, 0.8 U_n, 1.0 U_n, and 1.2 U_n, where U_n is the coil line-to-line voltage. For example, for a 13.8 kV coil, the power factor and cell capacitance would be measured at voltage levels of 2.8 kV (0.2 U_n), 5.5 kV (0.4 U_n), 8.3 kV (0.6 U_n), 11.0 kV (0.8 U_n), 13.8 kV (1.0 U_n), and 16.6 kV (1.2 U_n).

For all these techniques, the cell capacitance is also measured and recorded along with the power factor. Also, if desired, a conditioning voltage can be used for a selected dwell time. Usually, the highest test voltage level is selected. A conditioning time from 20 s to 4.0 min is usually used. Immediately after the conditioning time, the power factor and cell capacitance is recorded. The test voltage is then set to the lowest selected voltage and the power factor and cell capacitance is recorded. The successive voltages are then set and the resulting power factor and cell capacitance are recorded.

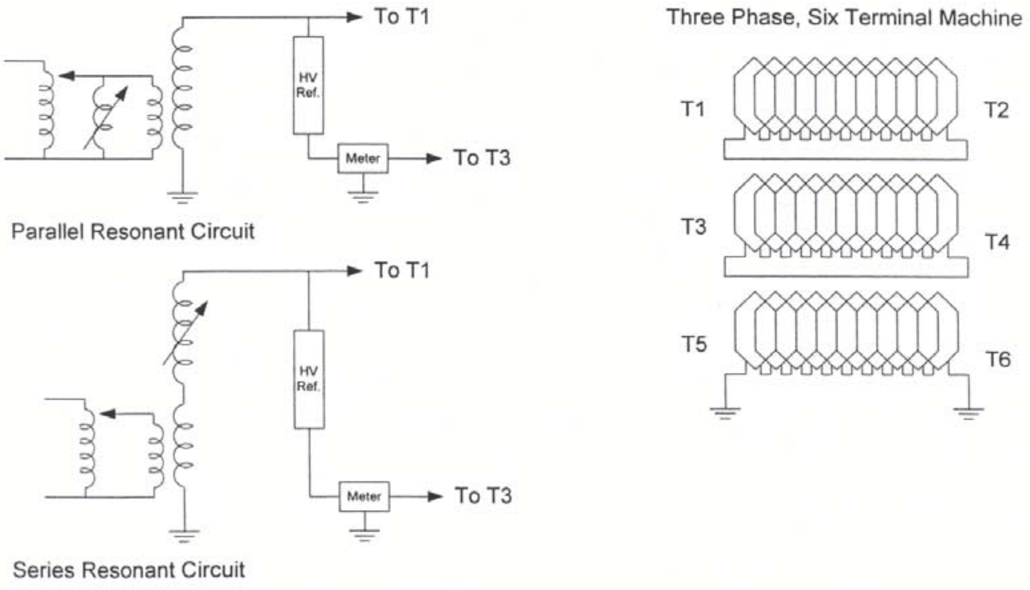
The calculation of power factor tip-up is recommended to be calculated between any two voltage levels. The power factor tip-up value, in percent or per unit, is calculated by subtracting the value of power factor measured at the selected lower test voltage from that measured at the selected higher test voltage. The power factor tip-up value is expressed in percent or per unit.

10. Testing complete windings

In many utility and industrial applications, the ground connections of motors and generators cannot readily be removed. Hence, the power factor must be measured with the test object solidly grounded. Some types of power factor bridges are not designed to perform measurements on grounded specimens. In these cases, correct power factor measurement requires that the bridge and the power supply operate ungrounded. Only higher-trained and experienced personnel should attempt a measurement with this configuration because of the danger inherent in operating ungrounded apparatus. The typical test setup is shown in Figure 9.



Measure Winding to Ground Insulation of T1 - T4 Winding.



Measure Winding to Winding Insulation between T1 - T4 and T2 - T5 Phase-Windings.

Figure 9—Typical circuit arrangements for measuring power factor of assembled stator windings

10.1 Required equipment

10.1.1 Test voltage supply

A voltage supply at power frequency is required. The kVA rating shall be adequate for the size of the specimen being tested and may include a series-resonant or parallel-resonant circuit.

The waveform of the power frequency voltage shall conform to good industrial practice, in accordance with IEEE Std 4-1995.

10.1.2 Test voltage measurement

AC voltage measuring system with an accuracy of 3.0%, to ensure the effective (rms) value of the test waveform shall be used, in accordance with IEEE Std 4-1995.

10.1.3 Power factor bridge

Either a manual or automatic capacitance bridge or power factor instrument shall be used. The bridge or instrument shall provide the specimen capacitance and power factor (tangent delta) being tested.

The bridge or instrument shall be capable of measuring capacitance with an error not exceeding 2.0% and measuring power factor with an error not exceeding 0.001 (0.1%) power factor or 5.0% of the measured value, whichever is greater.

10.1.4 Shielding

The measuring equipment, including the connecting leads to the test specimen, should be properly shielded so the measurement is confined to the insulation of the test specimen.

10.1.5 Calibration

The calibration of the measuring equipment shall be traceable to a National Agency (e.g., in the U.S., the National Institute of Standards and Technology).

A high-voltage standard capacitor (low loss typically less than 1×10^{-5}; Tan δ) can be used for calibration. This type of low-loss capacitor is usually a gas capacitor. Other low-loss capacitors are made with low-loss polypropylene. The solid dielectric capacitors are usually larger than 100 pF. Unlike gas capacitors, solid dielectric capacitors are more rugged for transport. The capacitance of a solid dielectric capacitor typically ranges between 100 to 1000 pF, with a nominal tolerance of –5.0%. The capacitor choice also is a function of the selected instrument used for making the power factor measurements. The capacitor voltage rating must be selected to be about 20% higher than the highest expected test voltage. The capacitor shall be discharge free (less than 5 pC) at rated voltage of the capacitor, in accordance with ASTM D1868-93.

10.2 Test voltage

The power factor (and capacitance) voltage characteristic shall be measured. The lowest test voltage shall be substantially lower than the operating phase-to-ground voltage, $U_n/\sqrt{3}$, of the winding and is normally 1.0 or 2.0 kV rms. The highest test voltage may be selected to be equal to or to be higher than the operating phase-to-ground voltage, $U_n/\sqrt{3}$, of the winding.

CAUTION

Caution shall be taken to not over-voltage the winding when performing the power factor test.

The following are examples of voltages selected to measure the winding capacitance and power factor:

a) Measure power factor at 25% and 100% of the operating phase-to-ground voltage, $U_n/\sqrt{3}$, of the winding.

b) For 13.8 kV windings, measure power factor at 2.0 kV rms and 8.0 kV rms.

c) Measure power factor at 2.0 kV rms and the operating phase-to-ground voltage, $U_n/\sqrt{3}$, of the winding.

d) Measure power factor in 2.0 kV rms increments from 2.0 kV rms to the operating phase-to-ground voltage, $U_n/\sqrt{3}$, of the winding (and perhaps higher).

10.3 Power factor tip-up

The power factor tip-up shall be calculated by subtracting the measured power factor at 2.0 kV rms from that measured at the operating phase-to-ground voltage, $U_n/\sqrt{3}$, of the winding.

10.4 Test procedure

Three procedures are recommended: two for conventionally-cooled windings and one for water-cooled windings.

10.4.1 Testing conventionally-cooled windings

The procedures for a three-phase winding/six-terminal machine and a three-phase winding/12-terminal machine are given in Figure 10, Figure 11, and Figure 12.

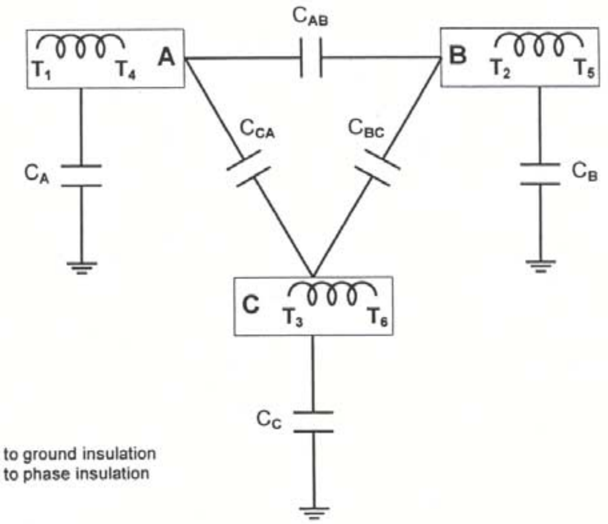
Completely isolate the terminals of each phase-winding. For example, the line and neutral terminals are disconnected from the system and ground circuit, respectively, and the phase-windings are separated at their neutral end.

Connect together the line and neutral terminals of the phase-winding being energized to ensure a constant voltage is applied across that entire phase-winding.

CAUTION

Special leads may be required to connect the line to neutral terminals because of the distance between them. This connection is required to ensure the voltage at both ends of the winding is the same magnitude.

To maximize the sensitivity of the test and its capability to detect localized conditions, test each phase-winding independently to ground at several voltages. If the measuring equipment has an ungrounded (grounded-guard) meter circuit, also test each phase-winding to an adjacent phase-winding at several voltages. The common tests and test connections are given in Figure 10, Figure 11, and Figure 12.



C_A, C_B, C_C = phase to ground insulation
C_{AB}, C_{BC}, C_{CA} = phase to phase insulation

Test	Energize	Ground	Ungrounded Meter Circuit	Measure
1	T1 – T4	T2, T3		C_A (+ C_{AB} + C_{AC})
2	T1 – T4	T3	T2	C_{AB}
3	T2 – T5	T3, T1		C_B (+ C_{BC} + C_{BA})
4	T2 – T5	T1	T3	C_{BC}
5	T3 – T6	T1, T2		C_C (+ C_{CA} + C_{CB})
6	T3 – T6	T2	T1	C_{CA}

Figure 10—Dielectric circuit and test procedure for the assembled winding of a three-phase/six-terminal machine with the three phase-windings separated

10.4.2 Testing water-cooled windings

The following procedure requires that the deionized water is circulating in the winding during these tests. The water conductivity should not be greater than 0.25 microsiemens per centimeter (0.25 micromhos per centimeter). The procedure is given in Figure 13.

Completely isolate the terminals of each phase-winding. For example, the line and neutral terminals are disconnected from the system and ground circuit, respectively, and the phase-windings are separated at their neutral end.

When practicable, connect together the line and neutral terminals of the phase-winding being energized to ensure a constant voltage is applied across that entire phase-winding.

To maximize the sensitivity of the test and its capability to detect localized conditions, test each phase-winding independently to ground at several voltages. If the measuring equipment has an ungrounded (grounded-guard) meter circuit, also test each phase-winding to an adjacent phase-winding at several voltages. The common tests and test connections are given in Figure 13.

It is necessary to correct the power factor measured for the ground insulation tests for the losses added by the columns of deionized water and insulating hoses. These losses are measured by performing a dc insulation resistance test on each phase-winding. The corrected power factor approximates the power factor of the winding insulation.

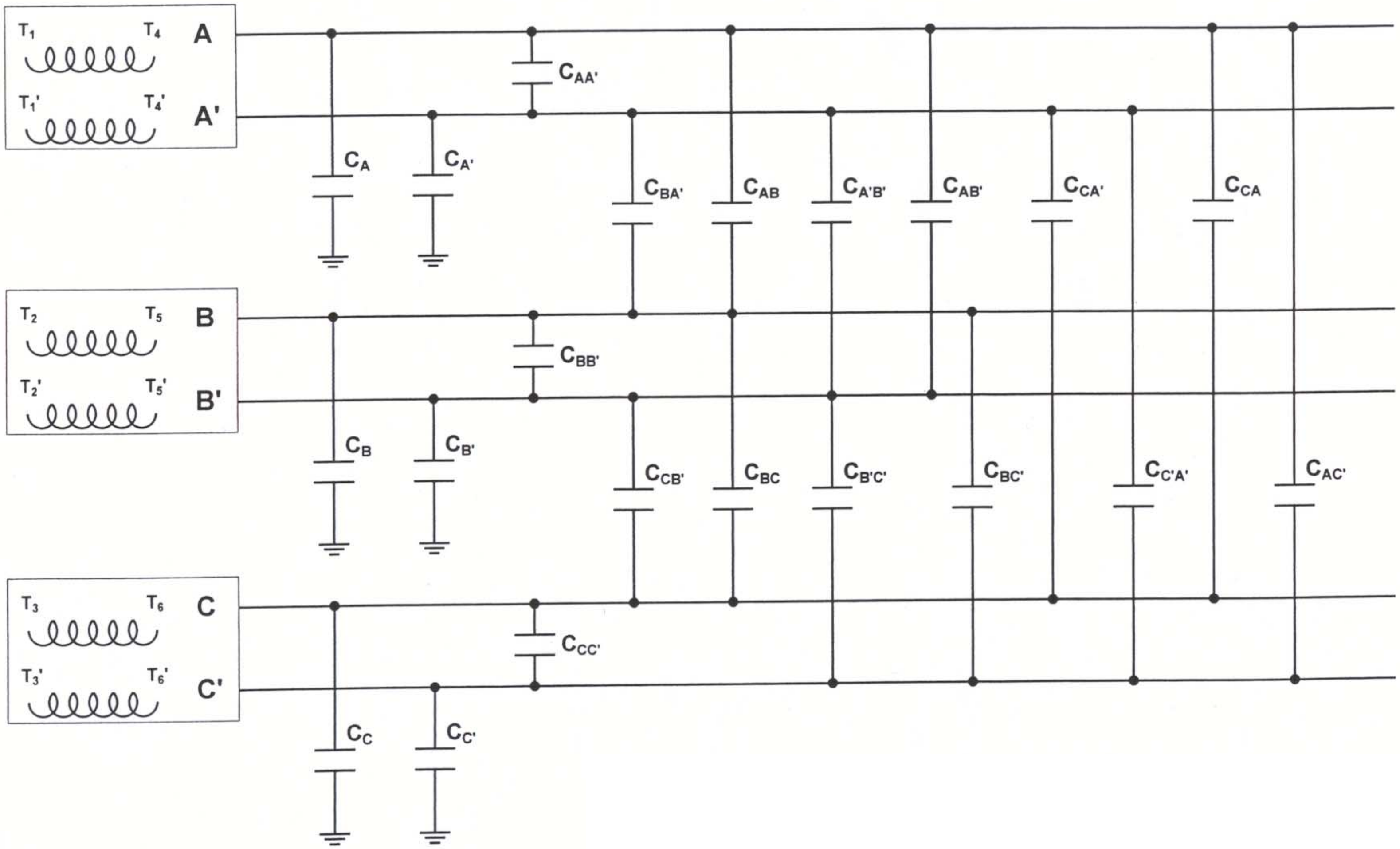


Figure 11—Dielectric circuit for the assembled winding of a three-phase/double-winding/12-terminal machine with six phase-windings separated

Test	Energize	Ground	Ungrounded Meter Circuit	Measure
1	T1 – T4	T2,T3, T1',T2',T3'	-	C_A (+ C_{AB} + C_{AC} + $C_{AA'}$ + $C_{AB'}$ + $C_{AC'}$)
2	T1 – T4	T3, T1',T2',T3'	T2	C_{AB}
3	T1 – T4	T2,T3, T2',T3'	T1'	$C_{AA'}$
4	T1 – T4	T2,T3, T3',T1'	T2'	$C_{AB'}$
5	T1 – T4	T2,T3, T1',T2'	T3'	$C_{AC'}$
6	T2 – T5	T3,T1, T1',T2',T3'	-	C_B (+ C_{BC} + C_{BA} + $C_{BA'}$ + $C_{BB'}$ + $C_{BC'}$)
7	T2 – T5	T1, T1',T2',T3'	T3	C_{BC}
8	T2 – T5	T3,T1, T3',T1'	T2'	$C_{BB'}$
9	T2 – T5	T3,T1, T1',T2'	T3'	$C_{BC'}$
10	T2 – T5	T3,T1, T2',T3'	T1'	$C_{BA'}$
11	T3 – T6	T1,T2, T1',T2',T3'	-	C_C (+ C_{CA} + C_{CB} + $C_{CA'}$ + $C_{CB'}$ + $C_{CC'}$)
12	T3 – T6	T2, T1',T2',T3'	T1	C_{CA}
13	T3 – T6	T1,T2, T1',T3'	T3'	$C_{CC'}$
14	T3 – T6	T1,T2, T2',T3'	T1'	$C_{CA'}$
15	T3 – T6	T1,T2, T3',T1'	T2'	$C_{CB'}$
16	T1' – T4'	T1,T2,T3, T2',T3'	-	$C_{A'}$ (+ $C_{A'A}$ + $C_{A'B}$ + $C_{A'C}$ + $C_{A'B'}$ + $C_{A'C'}$)
17	T1' – T4'	T1,T2,T3, T3'	T2'	$C_{A'B'}$
18	T2' – T5'	T1,T2,T3, T3',T1'	-	$C_{B'}$ (+ $C_{B'A}$ + $C_{B'B}$ + $C_{B'C}$ + $C_{B'C'}$ + $C_{B'A'}$)
19	T2' – T5'	T1,T2,T3, T1'	T3'	$C_{B'C'}$
20	T3' – T6'	T1,T2,T3, T1',T2'	-	$C_{C'}$ (+ $C_{C'A}$ + $C_{C'B}$ + $C_{C'C}$ + $C_{C'A'}$ +
21	T3' – T6'	T1,T2,T3, T2'	T1'	$C_{C'A'}$

Figure 12—Test procedure for the assembled winding of a three-phase/ double-winding/12-terminal machine with six phase-windings separated

10.4.3 Loss calculations

The following is an example of two procedures to calculate the losses.

The capacitance and power factor of each phase-winding are measured at several voltages. The dc insulation resistance of each phase-winding is commonly measured at 2.5 kV, 5 kV, or 10 kV dc.

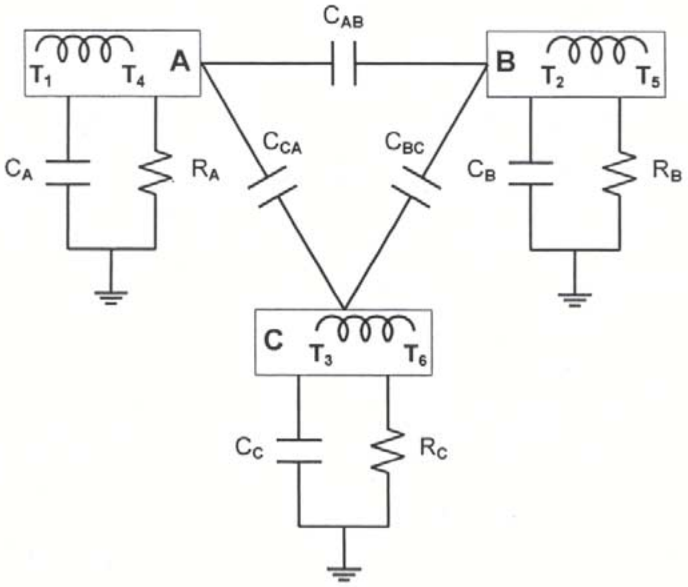
For each phase-winding:

Calculate the correction factor for each ac test voltage using the measured dc insulation resistance and the respective capacitance.

Correction Factor = 1/RωC

Subtract this correction factor from the power factor measured at each ac test voltage.

Measured Power Factor–Correction Factor = Corrected Power Factor



C_A, C_B, C_C = phase to ground insulation
C_{AB}, C_{BC}, C_{CA} = phase to phase insulation
R_A, R_B, R_C = losses in the stator winding cooling water system, i.e., the columns of deionized water and insulating hoses

Test	Energize	Ground	Ungrounded Meter Circuit	Measure
1	T1 – T4	T2, T3		C_A (+ C_{AB} + C_{AC} + R_A)
2	T1 – T4	T3	T2	C_{AB}
3	T2 – T5	T3, T1		C_B (+ C_{BC} + C_{BA} + R_B)
4	T2 – T5	T1	T3	C_{BC}
5	T3 – T6	T1, T2		C_C (+ C_{CA} + C_{CB} + R_C)
6	T3 – T6	T2	T1	C_{CA}

Supplemental dc Insulation Resistance Test

Test	**Energize**	**Ground**	**Measure**
1	T1 – T4	T2, T3	R_A
2	T2 – T5	T3, T1	R_B
3	T3 – T6	T1, T2	R_C

Figure 13—Dielectric circuit and test procedure for the assembled winding of a three-phase/six-terminal machine with water-cooled stator winding, with the three phase-windings separated and the cooling water circulating

The following is an example of the procedure and calculations if the test equipment also measures the dielectric loss:

The capacitance and power factor of each phase-winding are measured at several voltages. The total ac dielectric loss dissipated in the stator ground insulation, including the cooling water system, is also measured. For example, for an 18.0 kV machine, tests are performed at 2 kV, 4 kV, 6 kV, 8 kV, and 10.5 kV (rated rms voltage, phase-to-ground), and perhaps higher voltages. The dc insulation resistance of each phase-winding is commonly measured at 2.5 kV, 5 kV, or 10 kV dc.

For each phase-winding:

Calculate the dc power losses, normalized to each ac test voltage, by using the measured dc insulation resistance and the respective ac test voltage.

$$P_{L\mathrm{dc}} = V_{\mathrm{ac}}^2 / R_{\mathrm{dc}} = kV^2 / M\Omega \text{ (normalized to the ac test voltage)}$$

With voltage measured in kV and resistance in megohms, the power will be in watts.

Subtract this loss from the ac power loss measured at each ac test voltage to obtain the corrected power loss, P_{corr}:

$$P_{L\mathrm{ac}} - P_{L\mathrm{dc}} = P_{\mathrm{corr}}$$

Calculate a corrected power factor from the remaining loss (P_{corr}) at each test voltage.

Experience has indicated that when the conductivity of the water is less than 0.25 microsiemens per centimeter, the capacitance and ac conduction current of the cooling water system are negligible when compared to the capacitance and ac charging current of the winding. Also, the insulation resistance of and dissipated losses in the cooling water system are linear with test voltage. This procedure assumes the dc conduction current in the winding insulation is insignificant, so the measured dc resistance is substantially that of the cooling water system.

10.5 Analysis

An acceptable power factor offers assurance that the coil or the bar was properly fabricated with inherently low-loss materials and was properly processed. A low power factor tip-up reflects the quality of the construction and compactness (lack of gaseous inclusions or voids) of a coil or bar, the composition of the impregnating material and quality of the impregnating process, and the quality and condition of the semi-conductive surface treatment in the slot area. Differences in the tip-up measured for coils or bars of similar composition and fabrication are generally attributed to a variation in the incidental void content.

The power factor measured at a low voltage, e.g., 2 kV rms, is, for the most part, unaffected by partial discharge and is an indication of:

a) The inherent dielectric losses of the insulation and its general condition

b) The quality of the contact of the semi-conductive surface with the core

c) The moisture content and degree of cleanliness

d) The degree of curing of materials

The power factor tip-up is sensitive to:

a) The void content (gaseous inclusions) of the insulation

b) Any partial discharge damage to the insulation

c) The continuity of the semi-conducting surface

d) The quality of the impregnation process for resin-type systems

e) The delamation resulting from thermal stresses

The interwinding insulation tests are primarily a test of the end-winding insulation and generally are the first to display the effects of moisture contamination.

However, any power factor tip-up measured for these tests is likely to be affected by any stress control coating applied to the end-windings since it is not practicable to install guard electrodes.

The measured capacitance, power factor, and power factor tip-up should be comparable between the phase-windings for a machine. If the insulation remains in stable condition, periodic testing should yield similar results. The results measured for similar machines should also yield similar results.

The expected power factor and power factor tip-up vary with the type and age of the insulation system. The type of insulation system shall be identified, i.e., asphalt-mica, epoxy-mica, or polyester-mica. The power factor is also affected by the temperature of the insulation, and accordingly, periodic tests should be performed at similar temperatures. The power factor tip-up is also affected by the atmosphere during the test, e.g., air versus sealed with rated hydrogen pressure. If the machine is closed, the type of cooling gas, and its relative pressure and the temperature of the stator insulation during the test, shall be measured and reported. If the winding is exposed to the atmosphere, also record the ambient temperature and relative humidity. The conductivity, flow rate, and the inlet and outlet temperatures of the water shall be measured and recorded for water-cooled windings.

11. Bibliography

[B1] Bartnikas, R., and MacMahon, E. J., Engineering Dielectrics, Vol. 1, Corona Measurement and Interpretation, STP 699, ASTM, Philadelphia, 1979.

[B2] Povey, E. H., Power Factor Tests on Water-Cooled Generators, Minutes of the Fortieth International Annual Conference of Doble Clients, 1973, Sec. 7-601.