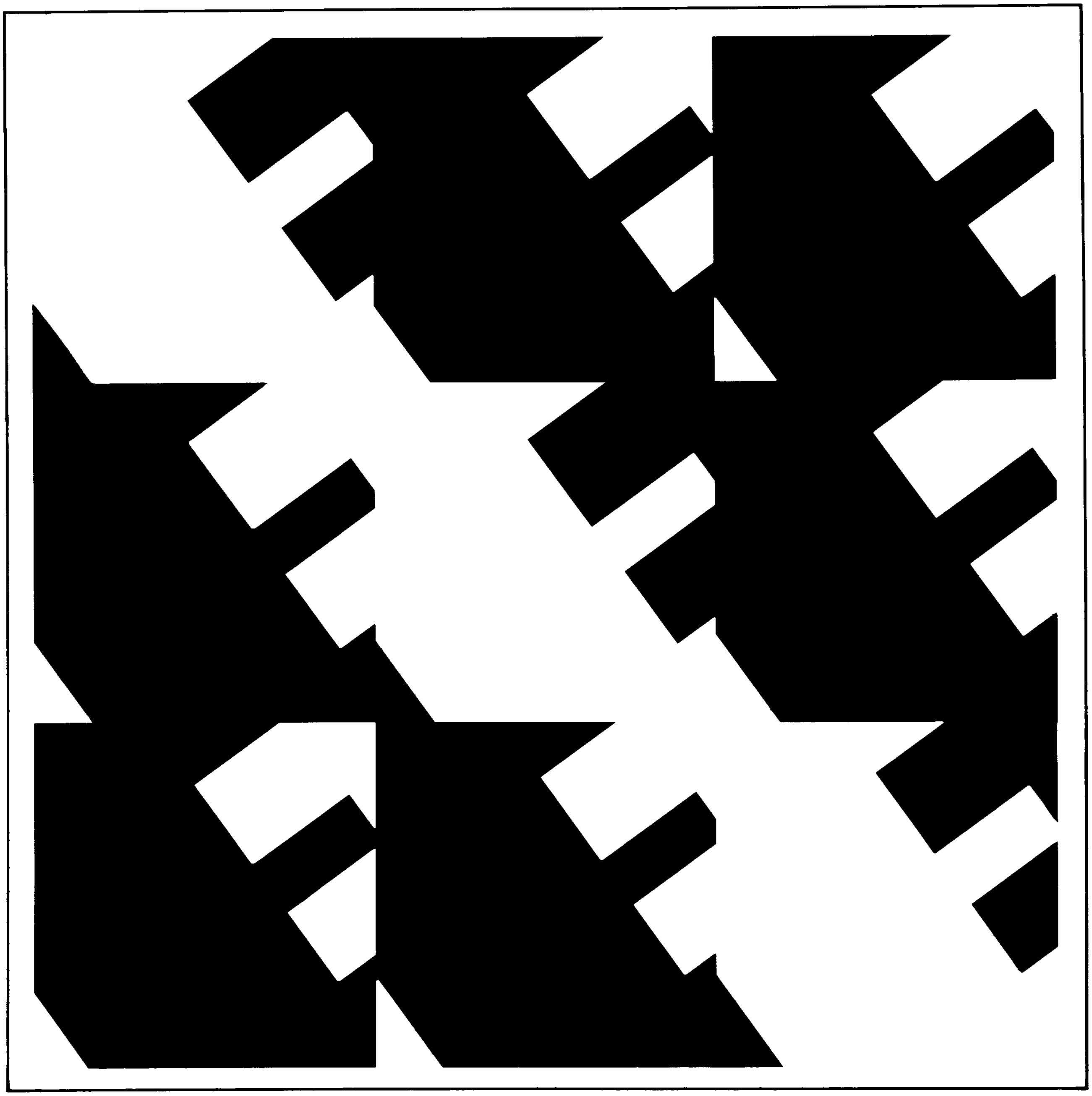
IEEE Std 62-1978
(Revision of IEEE Std 62-1958)

IEEE Guide for Field Testing Power Apparatus Insulation



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IEEE Guide for Field Testing Power Apparatus Insulation

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Foreword

(This Foreword is not a part of IEEE Std 62-1978, Guide for Field Testing Power Apparatus Insulation.)

Factory tests assure the initial quality and condition of power apparatus insulation. During shipment, installation, and service, the apparatus is subject to influences that may affect the insulation and shorten its useful life. As a result, apparatus insulation is tested in the field from time to time to determine its suitability for continued service and to detect deterioration which often can be checked or corrected by suitable maintenance procedures.

The variety of test methods and equipment used for the assessment of insulation quality necessitates the restriction of this guide to a general description of the more commonly used methods. An attempt has been made to supply sufficient information to identify those tests more applicable to a given situation and to provide references to a more detailed coverage.

This guide was first published in April 1958 as AIEE Std 62, Recommended Guide for Making Dielectric Measurements in the Field. This revision is the first since that time. Withstand tests have been given greater coverage and the material on measurement of insulation characteristics reflects experience gained in the intervening years.

This revision has been prepared by a Working Group under the sponsorship of the High Voltage Testing Techniques Subcommittee of the IEEE Power Systems Instrumentation and Measurements Committee. The assistance of A. F. Rohlfs, Chairman, and other members of the High Voltage Testing Techniques Subcommittee, is gratefully acknowledged.

At the time of approval of this standard the membership of the Working Group was as follows:

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Approved September 8, 1977

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IEEE Guide for Field Testing Power Apparatus Insulation

1. Scope

This guide discusses the significance of various types of tests commonly employed to evaluate the insulation of power apparatus in the field, where environmental conditions cannot readily be controlled; the equipment and techniques required for each type of test; problems peculiar to field testing, and methods of dealing with these problems; and the application of field tests to specific types of power apparatus.

2. Safety

2.1 Personnel

2.1.1 Hazards. Insulation tests in the field can present a hazard to personnel unless suitable precautions are taken. Apparatus or circuits to be made available to test personnel must be disconnected from the power system. Typical safety procedures call for a visual check of the disconnection or, when this is not possible, a check with a voltage indicator. Grounds are then applied. Personnel are usually instructed to treat all ungrounded apparatus as energized.

2.1.1 Ground Connection. Grounds may be removed to permit application of test voltage. When feasible, it is preferable to retain the ground connection during the tests and to provide between the ground and the apparatus under test a second disconnection of sufficient clearance for the test voltage (see 6.8.3.2).

2.1.3 Precautions. When the test voltage is over a few volts, precautions should be taken to prevent personnel from contacting the energized circuit. An observer may be stationed to warn approaching personnel and may be supplied with means to deenergize the circuit. The means may include a switch to shut off the power source and, particularly in case of a direct test voltage, provisions for grounding the circuit until all stored charges are dissipated.

2.1.4 Warning Signs and Barriers. The test area may be marked off with signs and easily visible tape. Warning signs should conform to the requirements of governing bodies such as the Occupational Safety and Health Administration (OSHA) in the United States.

2.2 Apparatus

2.2.1 Consequences of Failure. When the test voltage to be applied to apparatus insulation exceeds the normal operating value, there exists the possibility of failure under test. Before applying the test, consideration should be given to the time, material, and labor required for a possible repair. If failure could result in fire, fire-fighting equipment should be available.

2.2.2 Overvoltage. In the conduct of high-voltage tests the voltage may accidently exceed the desired maximum. A sphere gap, adjusted to spark over at a voltage slightly above the desired maximum, may be connected across the voltage source. By selecting the proper value of series resistor, the gap may be used to provide a warning signal, to inhibit further rise in the test voltage, or to activate an overcurrent circuit breaker in the power supply circuit.

2.2.3 Graded Insulation. When an alternating test voltage is applied to a short-circuited winding, or when a direct test voltage is used, the insulation of the entire winding is subject to this test voltage. When the insulation level of the winding is graded from one end to the other, the magnitude of the applied test voltage should correspond to the lowest insulation level.

3. Withstand Voltage Tests

3.1 Description

3.1.1 General. A withstand voltage test subjects an insulation for a restricted period of time to a voltage stress greater than that encountered under normal service conditions. The magnitude of the test voltage used in the field is generally based on the factory acceptance test voltage, reduced by a factor to allow for the effects of transportation, installation, and in-service degradation.

3.1.2 Type of Voltage. The voltage specified for a withstand test may be alternating at power frequency or some other frequency, may be direct (having a specified polarity in respect to ground), may be a pulse having a specified polarity and wave shape, or may be a pulse-generated transient.

3.1.3 Duration of Voltage Application. For alternating or direct test voltages, the duration of application is specified, commonly 1 min after the desired test value has been reached. Voltage applications are made at a prescribed rate or in scheduled increments.

3.1.4 Impulse Voltage. For an impulse, the voltage—time relation (wave shape) is specified. A standard lightning impulse wave is denoted by two figures: 1.2/50. The first figure is the virtual rise time in microseconds of the pulse; the second is the virtual time to half value in microseconds.

3.1.5 Pulse-Generated Voltage. For pulse-generated transients, the peak voltage and oscillation frequency are specified. If repetitive, the repetition rate is also specified.

3.2 Significance. The withstand voltage test is a demonstration that an insulation can withstand a specified overvoltage for a specified length of time and is essentially a go—no-go type of test. Successful completion of the test gives some assurance that no gross defect is present in the insulation structure. However, the ability of a withstand voltage test to expose incipient faults is less certain. For this reason the test is often supplemented by measurements of insulation characteristics, made during or at the completion of the withstand test.

3.3 Elementary Theory

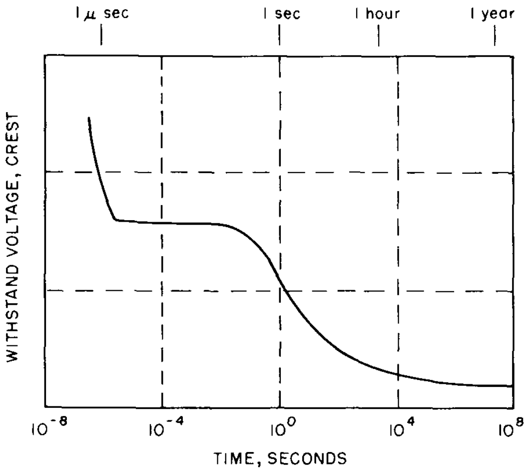
3.3.1 Intrinsic Dielectric Strength. As opposed to a conductor, in which electrons move with little restriction, an insulator is a material in which the electrons are tightly bound to atoms or molecules. When an insulator is subjected to a moderate potential gradient, some electrons may be pulled free from their bonds, but are recaptured in collision with a neighboring atom of molecule. When the gradient is strengthened beyond a critical value, called the intrinsic dielelectric strength of the material, collisions occur with sufficient impact to free more electrons than are captured, and disruptive breakdown follows.

3.3.2 Practical Dielectric Strength. Most insulating materials are not entirely homogeneous and so contain some regions having less than average dielectric strengths. Under test there will be a tendency for breakdown to occur in a path which includes regions of lower dielectric strength. The actual dielectric strength of an insulating material in practice is usually substantially lower than its intrinsic strength.

3.3.3 Time and Temperature Effects. Continued application of a voltage gradient below the value required to cause immediate breakdown will cause temperature rises in local weak regions. The temperature rise further reduces the dielectric strength of these regions, and consequently the overall dielectric strength of the material, and may result in eventual failure without further increase in the applied voltage. As an example of the time dependence in withstand testing, Fig 1 illustrates the general behavior of oil-impregnated pressboard in terms of withstand voltage versus time of voltage application.

Materials which are normally lossy under voltage stress are subject to destruction from

Fig 1
Effect of Time on Withstand Voltage



thermal runaway. Runaway occurs when the applied stress is high enough to generate more heat in the material than can be dissipated into the environment. The voltage at which termal runaway occurs is therefore not only a function of the material but also of the effectiveness of provisions for dissipating the generated heat.

3.4 Comparison of Tests

3.4.1 Power-Frequency Withstand Test. A power-frequency withstand test is generally considered to subject the insulation under test to a stress pattern most closely resembling that occurring in service. The disadvantages of the power-frequency test are possible damage to corona-sensitive insulation and the massive equipment necessary to energize high-capacitance specimens. The latter disadvantage may be partially alleviated by the use of resonant methods.

3.4.2 Direct-Voltage Withstand Test. The direct-voltage withstand method requires relatively light-weight equipment. Partial discharge damage is less than with power-frequency tests. There is the possibility, under certain conditions, of predicting and thus avoiding breakdown of weak insulation. The prediction procedure involves the application of the test voltage in steps in accordance with a predetermined schedule, with a measurement of current or resistance made at each step.

A disadvantage of the direct-voltage withstand test for a composite insulation system designed to operate under alternating-voltage stress is that the test may not produce a normal stress pattern in the insulation. With time of voltage application, the direct-voltage stress pattern tends to conform more to the resistive characteristics of a composite system then to the combined resistive and capacitive characteristics which determine the alternating-voltage stress pattern. This disadvantage is particularly apparent for systems where resistive-capacitive stress grading is employed, since with an applied direct voltage the stress will not be graded in the designed manner. Prolonged direct-voltage withstand tests are not recommended for oil-immersed equipment because contaminating particles in the oil tend to line up and form a breakdown path.

3.4.3 Very Low Frequency Withstand Tests. Withstand tests on high-capacitance specimens may be made using an alternating test voltage of very low frequency (for example, 0.1 Hz) to obtain the advantage of reduced weight and reduced partial discharge damage while providing an approximately normal stress pattern. The weight of very low frequency test equipment is less than the usual power-frequency test equipment and approximately the same as power-frequency equipment when resonant methods are employed.

3.4.4 High-Frequency Withstand Test. Withstand test voltages at higher than normal frequency are used for testing the insulation of windings on magnetic cores, as in transformers and reactors. The higher frequency permits an overvoltage to be applied across the winding without the problem of core saturation. This type of test applies overvoltage on turn-to-turn insulation as well as on the insulation between winding and ground.

3.4.5 Impulse Test. Impulse tests may be made on insulation systems subject to voltage surges in service. Such systems include turn-to-turn insulation of coils or windings. Impulse testing of apparatus insulation in the field is usually restricted to low-voltage apparatus because high-voltage impulse generators are not readily portable.

3.5 Environmental Influences. The voltage withstand capability of insulation structures designed for field service is affected to some extent by normal variations in the field environment. Low barometric pressure, surface dirt, and moisture are conditions which tend to lower surface flashover voltages and thus interfere with the conduct of a withstand test. In general, however, the reduction in test voltage levels allowed for field testing is usually sufficient to permit tests to be succesfully conducted.

3.6 Test Equipment. Commercial equipment is available for all types of withstand tests. Important specifications which must be considered include:

(1) Type of voltage output — impulse, direct, alternating (include frequency)

(2) Voltage range

(3) Voltage control facilities including rate-of-rise capability

(4) Power output — real and reactive power capability for ac tests, output current range for dc tests, energy discharge capability for impulse tests

(5) Power input requirements
(6) Weight and portability

4. Potential-Distribution Tests

4.1 Description. The potential-distribution test method requires the measurement of potential at or between various locations over an insulating unit. The method is most often applied to the testing of ac transmission line insulators while in service. In the application of this method to a string of suspension insulators, for example, the potential across each insulation may be measured.

4.2 Significance. A normal potential distribution is an indication that the insulating unit is in satisfactory condition. Any section of a unit across which the potential difference is lower than normal is considered to be in questionable condition.

4.3 Equipment

4.3.1 Safety. Safety is a primary requirement for potential-distribution testing devices to be used on energized transmission systems. The device must be so designed that it can be used without the possibility of creating a transmission outage from a short circuit or accidental ground.

4.3.2 High Impedance. A potential-distribution testing device must have high electrical impedance so that its use does not appreciably change an existing potential distribution.

4.3.3 Measurement of Potential. Measurements of potential may be obtained either as a meter reading or as a calibrated sphere-gap setting. The sphere gap is adjusted to the maximum setting at which a continuing discharge or sparking can be obtained. Discharge of the gap is monitored by listening to a telephone receiver in the gap circuit through a highly insulated stethoscope arrangement. A more recent method of monitoring a discharge is through the use of a remote detector responsive to electromagnetic radiations from the discharge.

4.3.4 One-Terminal Device. A one-terminal device has an exposed metallic tip for contacting some conducting part of the insulating unit, that is, cap, pin, or cement layer. The measuring circuit is completed by capacitance to ground but is also influenced by capacitance to nearby energized parts. Interpretation of results should be made by comparison of readings on similar units with the device similarly positioned, rather than on the absolute measured values.

4.3.5 Two-Terminal Devices. Two-terminal devices permit measuring the potential between two conducting parts of the insulating unit, one of which may be at ground potential. The measuring circuit between the two terminals includes the meter or gap-telephone system (see 4.3.3) and a high-voltage high-impedance element. A resistive element is usually used with a meter system and a capacitive element with a spark-gap system.

4.4 Comparison of Methods. Meter devices are difficult to read under adverse lighting conditions, while spark-gap devices are difficult to hear under noisy conditions. Voltage readings are more easily made with the meter device. The inconvenience of adjusting a gap for each insulator is commonly avoided by establishing a few fixed gap settings and using the setting most applicable to the insulator under test. The insulator passes or fails the test depending on whether or not it supports sufficient voltage to cause the gap to discharge.

4.5 Environmental Influences. The voltage distribution over an insulating unit or structure can be influenced by surface conditions. For comparison purposes voltage distribution tests should be made when surfaces are reasonably clean and dry.

The voltage distribution method may not be reliable for detecting cracks in porcelain insulation after prolonged exposure to low-humidity atmosphere, particularly when the operating voltage stress is low.

5. Partial-Discharge (Corona) Tests

5.1 General. Partial discharges in an insulation system are discharges that do not completely bridge the insulation between conductors. One form of partial discharge is corona, a term which more specifically describes discharges which emanate from a bare conductor into the surrounding air or gas. Of more concern to insulation life are partial discharges which occur in inadvertent gaseous inclusions (cavities) in otherwise solid insulation.

A discharge will occur in a cavity if the potential gradient exceeds a critical value. The discharge effectively short-circuits the cavity, dissipating stored energy into the surrounding insulation and causing a momentary increment in the capacitance of the system.

5.2 Significance

5.2.1 Reduction of Insulation Life. Partial discharges in an insulation system at operating voltage may result in a significant reduction in the life of the insulation. Some insulations are more susceptible to this type of damage than others.

5.2.2 Cavities. The presence of partial discharges in an insulation system may be an indication of the presence of cavities, particularly in composite or wound insulations.

5.2.3 Electromagnetic Radiation. Partial discharges in an insulation system may be a source of electromagnetic radiation which interferes with communication systems.

5.3 Measuring Methods

5.3.1 Test Voltage. Although some measurement of discharge activity is possible on apparatus while connected to the power system, in general it is preferable to disconnect the apparatus under test from the system and energize it by a test transformer. A separate test voltage supply minimizes interference from sources in the system and reduces the hazard to test personnel from accidental contact with system voltage. An adjustable supply permits observation of discharge activity as a function of test voltage. The test transformer and its connections must be free of partial discharge.

5.3.2 Power Loss

5.3.2.1 *General.* Measurement of partial-discharge power losses are usually based on the asumption that normal insulation losses vary as the square of the applied voltages. By measuring the loss in an insulation (see 6.6) at some voltage below the discharge inception voltage and calculating the loss at some higher test voltage according to the voltage-squared relation, the partial-discharge power loss at the higher test voltage is found as the difference between the observed and calculated losses. The assumption is often valid, but in some cases other nonlinear voltage effects may add to the loss increase.

A special bridge circuit may be used to present the discharge losses on an oscilloscope as the area of a pattern approximating a parallelogram (see ASTM Method D 3382-75, Measurement of Energy and Integrated Charge Transfer Due to Partial Discharges).

5.3.2.2 *Power Factor.* Using the preceding assumption, the measured power factor of an insulation should remain constant with increasing test voltage if no discharges are present. The observed power factor increase between a voltage below the discharge inception and some higher test voltage has been used as a measure of discharge activity at the higher voltage.

5.3.3 Measurement of Individual Pulses

5.3.3.1 *General.* Measurement of individual partial-discharge pulses may be desirable for insulation systems which are vulnerable to attack by partial discharges. Proper measurements of individual pulses can be made only when the pulses are sufficiently separated in time to make superposition improbable. Individual pulse measurements may be applicable when the total discharge power loss is too small to be accurately measured.

5.3.3.2 *Test Circuit.* The usual circuit for the measurement of individual discharge pulses in an insulation system includes an impedance coupled to the terminal of the system through a filter which removes the power frequency component of the voltage. The pulse voltages appear across the impedance where they can be observed by an oscilloscope or measured by a peak-reading voltmeter. The peak-reading voltmeter indicates the maximum pulse.

5.3.3.3 *Calibration Circuit.* A calibration circuit including a pulse generator may be added to the test circuit so that the detected pulses can be quantitatively evaluated. Oscilloscope deflections due to pulses are usually interpreted in terms of picocoulomb charges at the system terminals. The peak-reading voltmeter can also be calibrated in terms of charge.

5.3.3.4 *RIV Method.* Discharge pulses may be measured by the radio influence voltage (RIV) method. The measuring circuit consists of a filter as described in 5.3.3.2, with the pulses appearing across a noninductive resistor. A narrow band of high-frequency components of the pulses, usually centered about 1 MHz, is amplified and measured. The measurement is commonly expressed as the peak (or quasi-peak) voltage of the highest recurrent pulse. Calibration is based on the sine-wave output of a standard signal generator.

5.3.4 Electromagnetic Field Methods, Probes. Many insulation systems are not completely self-shielding, and in such systems partial discharges will produce an external electromagnetic field. Crude estimates of discharge activity have been obtained from the response of a radio receiver placed in the vicinity of such systems.

A probe may be used to localize the partial discharge sources in nonself-shielded systems such as used to insulate generator stator windings. A probe responsive to magnetic fields may consist of a few turns of wire on a ferrite core and be connected to a meter through a radio-frequency amplifier. A probe responsive to electric fields may be a miniature antenna, connected to a meter through an audio-frequency amplifier. For safety, a probe should be well insulated and used on insulation systems only when energized by a test transformer.

5.4 Environmental Influences. Partial-discharge measurements in the field are generally made in the vicinity of other equipment energized at high voltage. Partial discharges in the neighboring equipment, due to its pulse nature, may cause serious interference in the measuring circuit through capacitive coupling effects. Welding equipment, commutators, and radio stations are other sources of interference. When such interference is present, it may be desirable to schedule the test for a time when the interfering equipment is shut down.

6. Measurement of Dielectric Characteristics

6.1 General. An insulating structure has normal dielectric characteristics determined by its geometry and component materials. Dielectric characteristics commonly measured include insulation resistance and polarization index using a direct test voltage, and capacitance, dielectric loss, power factor, or dissipation factor using an alternating test voltage.

6.1.1 Normal Characteristics. The normal dielectric characteristics for a given insulating structure may be established from measurements made on similar structures which subsequent experience has shown to be in satisfactory operating condition. Where sufficient data exist, statistical methods are generally used in arriving at a norm. Normal characteristics of an insulating structure may often be closely approximated by a consideration of the design and materials employed.

6.1.2 Test Voltage. Measurements of dielectric characteristics are usually made at test voltages below the operating voltage of the insulation system under test. The tests are therefore categorized as nondestructive. Measurements at test voltages above operating value are used only for special information such as the prediction of failure during direct-voltage withstand tests (see 3.4.2) and the evaluation of partial-discharge activity (see 5.3.1).

6.1.4 Extent of Measurement. The effect of a local fault on the measured dielectric characteristics of an insulation system will be less pronounced when the total amount of insulation in the system is large. For this reason it is desirable to confine a measurement to a small amount of insulation. Test techniques have been established for the analysis of complex insulation systems, by which the characteristics of individual components of the system may be determined (see Appendix B).

6.2 Significance

6.2.1 Damage. Abnormal dielectric characteristics as determined from measurements on an insulating structure may indicate damage to, or a defect in, a component material, occurring during manufacture or from subsequent external causes.

6.2.2 Deterioration. Abnormal dielectric characteristics may be an indication of deterioration in one or more of the component materials in an insulation structure. Deterioration may be the result of absorption of contaminants, especially moisture, or chemical reactions within or between materials, accelerated by the temperatures and by electrical and mechanical stresses which occur in service.

6.2.3 Leakage. Abnormal dielectric characteristics in an insulating structure may be caused by leakage over insulation surfaces which are exposed to the deposition of moisture and particulate matter from the environment. Test results are sometimes used to indicate the necessity for cleaning the surfaces.

6.3 Insulation Resistance

6.3.1 Determination. Insulation resistance may be determined as the ratio of a direct test voltage applied to an insulation, as measured by a voltmeter, to the resulting current through the insulation, as measured by a current meter. Alternatively, the ratio may be determined by a single crossed-coil instrument. Bridge meth-

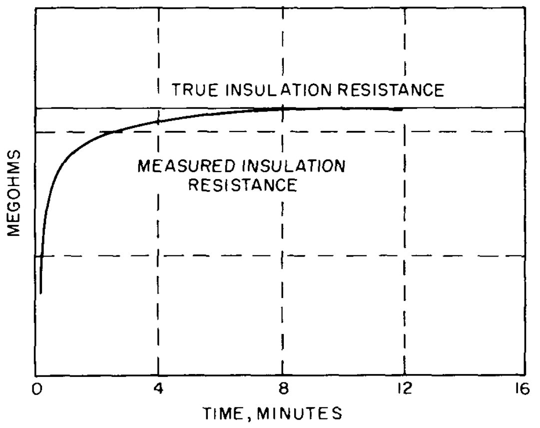


Fig 2
Effect of Absorption on
Measured Insulation Resistance

ods may also be used to measure insulation resistance by comparison with resistors of known value.

6.3.2 Time Dependence. Most high-voltage insulation exhibits dielectric absorption due to polarization processes which require time to complete. Because of absorption the measured insulation resistance appears to increase with the time of voltage application, approaching a steady value, which is the true insulation resistance. In practice, the resistance measured after a 1 min application of voltage is often considered the insulation resistance.

6.3.3 Example of Time Dependence. As an example of the time dependence of insulation resistance measurements, Fig 2 shows the change in measured resistance with time after applying a constant direct test voltage to an insulation specimen which exhibits absorption. The horizontal line indicates the true insulation resistance which the measured resistance is approaching.

6.4 Polarization Index

6.4.1 Determination. The polarization index (PI) of an insulation structure is found from insulation resistance measurements made at 1 and 10 min after application of the test voltage. The index is the ratio of the 10 min to the 1 min resistance value and is almost always greater than unity. The index is convenient for comparison purposes since it has no dimension.

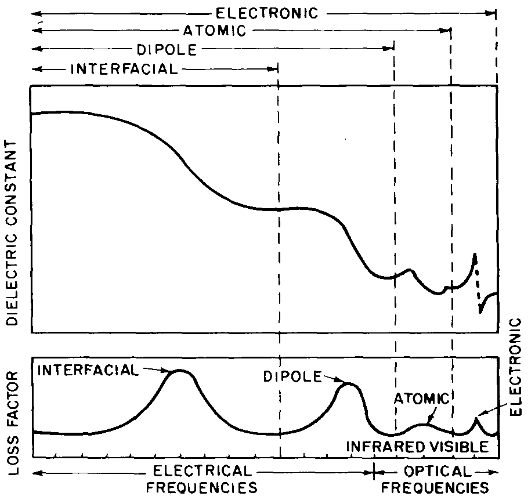
6.4.2 Use. The polarization index is useful in the determination of the condition of insulating structures for which the normal absorption characteristics are known. A PI lower than normal suggests excessive surface leakage or deteriorated insulation.

6.5 Capacitance

6.5.1 General. Capacitance in an insulating structure is present between any two conducting elements separated by a dielectric (insulating material). The capacitance value depends on the geometry of the structure and on the dielectric constant (permittivity) of the insulation. The dielectric constant in turn depends on the polarization processes in the insulation and is usually a constant only at a given frequency. The effect of frequency on the value of the dielectric constant is shown in Fig 3. Even at a given frequency the constant may vary with temperature and is influenced by the deterioration factors mentioned in 6.2.2.

6.5.2 Use. Capacitance measurements, while sometimes useful as an indication of insulation deterioration, provide other valuable types of information. For example, abnormal capacitance values may indicate incorrect test connections, floating shields or other breaks in conducting elements, or short-circuited portions of the insulation. Capacitance measurements are thus particularly important for insulation structures which are composed of a series of capacitor units such as coupling capacitors or condenser-type bushings.

Fig 3
Effect of Frequency on Loss Factor
and Dielectric Constant



6.5.3 Determination. Capacitance is commonly determined using an alternating test voltage and bridge techniques or charging current measurements.

6.6 Dielectric Loss

6.6.1 General. Measurable dielectric losses occur in all solid and liquid insulating materials, and in general, good insulating materials have low losses. Increased losses are usually caused by deterioration factors such as mentioned in 6.2.2.

6.6.2 Ionization. Dielectric losses in gaseous insulations are insignificant unless the applied voltage stress reaches or exceeds the critical value at which ionization of the gas is initiated. A possible source of ionization losses occurs in nominally solid insulation structures due to inadvertent gas inclusions in the structure.

6.6.3 Polarization. A substantial portion of the normal dielectric losses in solid and liquid materials under alternating voltage stress is due to polarization processes. The effect of the frequency of the applied voltage on the loss factor (product of dissipation factor and dielectric constant) is illustrated in the lower section of Fig 3.

6.6.4 Alternating Stress. The loss under alternating stress is always greater than under direct stress because of polarization losses and also because deteriorated areas of insulation which may not provide the continuous path necessary for a direct leakage current can reflect losses into an alternating voltage measurement through capacitive coupling.

6.6.5 Measurement. Losses under alternating voltage stress may be measured by use of a wattmeter, although for low-loss materials (power factor less than 0.5 percent) good wattmeter accuracy is difficult to obtain. Losses may be calculated as the product of the applied voltage and the in-phase component of the resulting current (component separation method). Losses may also be calculated from measurements of capacitance and dissipation factor, or power factor, as found by bridge techniques.

6.7 Power Factor, Dissipation Factor

6.7.1 General. Power factor and dissipation factor are dimensionless and can be used to compare the loss characteristics of insulation structure regardless of their geometry or size. All measurements used for comparisons should be made with test voltages having the same frequency, and for power apparatus insulation it is preferable to use a frequency at or near the power frequency.

6.7.2 Definition. The power factor and dissipation factor are the cosine and cotangent, respectively, of the phase angle between the applied test voltage and the resulting current through the insulation. Correspondence between these factors may be found by reference to trigonometric tables. For most insulations these factors fall in the range of 0 to 0.1 (or 0 to 10 percent). In this range the two factors are often used interchangeably, since they differ by less than 0.005 (0.5 percent).

6.7.3 Interpretation. Power factor, or dissipation factor, is the most widely used alternating-current characteristics for assessing the condition of insulation. The interpretation of insulation condition primarily depends on comparison of a measured value with a previously established normal value. Exceptions are insulating structures of very low capacitance, such as rods or tubes, where surface losses can have an exorbitant effect on the measured power factor.

6.7.4 Measurement. Power factor or dissipation factor can be obtained directly from many types of bridges. For test instruments that read out in terms of volts, current, and watts loss, power factor may be calculated using the following formula:

$$\text{power factor} = \frac{\text{watts}}{(\text{volts})\,(\text{amperes})}$$

6.8 Environmental Influences

6.8.1 Temperature

6.8.1.1 *General.* Temperature has a marked effect on the insulation resistance of most insulating materials. In some cases the insulation resistance decreases by a factor of 2 for each 10°C rise in temperature. When the resistance—temperature characteristic of an insulating material or structure is known, the measured resistance value can be corrected to a standard temperature base for comparison purposes.

6.8.1.2 *Polarization.* The temperature effect on alternating-voltage loss characteristics is greatly influenced by various polarization processes in the insulating material. Increasing temperature appears to decrease the relaxation time of a process, increasing the frequency at which the polarization effect peaks. Thus an increase in temperature tends to move the loss factor curve of Fig 3 to the right, in the direction of increasing frequency. Thus, depending on which side of a polarization peak the measurement is made, the losses may increase or decrease due to an increase in temperature. Loss-temperature characteristics for many materials and structures have been recorded.

6.8.1.3 *Water.* Characteristics of insulation structures subject to the adsorption of water should be tested at temperatures above 0°C. At lower temperatures any ice which forms will have a far different effect on the measurements than the water existing at higher temperatures.

6.8.2 Humidity. High humidity (above 50 percent RH) or surface moisture can have a significant effect on surface losses and consequently on the measured insulation resistance and loss characteristics of the insulation structure. Surface guarding techniques to remove the effect of surface losses are usually effective, especially for tests using direct test voltages.

6.8.3 Interference

6.8.3.1 *Electric/Magnetic Fields.* Measurements of insulation characteristics made in the field are generally subject to interference from electric and magnetic fields originating in neighboring energized equipment. The test equipment and connecting leads can be suitably designed and shielded to be immune from such fields (see Appendix A). The specimen itself, however, can seldom be shielded, and when in an electric field an interfering current will be introduced in any measuring circuit connected to it.

6.8.3.2 *Switch.* An important source of interference occurs at the switch which disconnects the test specimen from the energized system. The open switch constitutes a coupling capacitor through which the system voltage produces an interfering current in any measuring equipment connected to the test specimen. Such interference can be greatly reduced by grounding the specimen side of the switch and providing a second disconnection between the switch and the specimen. The second disconnection need only withstand the test potential to be applied to the specimen. This procedure, in addition to reducing interference, enhances safety (see 2.1.2).

6.8.3.3 *Power Frequency.* The effect of power-frequency interference on a power-frequency measurement of dielectric loss or capacitance (or, less precisely, charging current) can be nullified by a "reversal" procedure. A first measured value is obtained, then the phase of the test voltage is shifted by 180° (for example, by interchanging leads to the primary of the test voltage transformer) and a second measured value obtained. The desired value is the average of the two measured values.

6.9 Equipment. Commercial equipment is available for all types of dielectric characteristic measurements. Some of the most important features which must be considered are listed below.

Features applicable to all test sets are:

(1) Test voltage range
(2) Ability to measure grounded specimens
(3) Ability to measure ungrounded specimens
(4) Guard circuit for specimen analysis
(5) Ability to function in presence of interference
(6) Portability

Features particularly applicable to direct-voltage test sets are:

(1) Test voltage stability
(2) Test voltage rate-of-rise capability
(3) Output current range
(4) Measurement accuracy (voltage and current)

Features particularly applicable to alternating-voltage test sets are:

(1) Test voltage frequency
(2) Capacitance or output current range
(3) Ability to make accurate measurements in the presence of interference

7. Tests on Specific Apparatus

7.1 Rotating Machinery

7.1.1 Withstand Voltage Tests

7.1.1.1 *General.* Withstand voltage tests on rotating machinery insulation in the field are usually made at the time of installation or after repairs. They may be made when there is some reason to expect damage, as after involvement of a machine in a system fault, or after several years of normal operation. Withstand tests are usually confined to the ground wall insulation of the stator and rotor windings.

7.1.1.2 *Alternating Versus Direct Voltage.* No consensus exists in the choice of alternating or direct voltage for withstand tests on rotating machinery insulation. There are advantages and disadvantages to either method, and the choice is often a matter of convenience. The very low frequency test is an attempt to combine some advantages of both methods.

7.1.1.3 *Turn-to-Turn Tests.* Turn-to-turn insulation tests may be made by application of a high-frequency test voltage to a coil or winding. The voltage may be in the form of repetitively pulsed wave trains. The turn-to-turn test voltage should not exceed the ground wall withstand value, so that it may be necessary to limit a test to one or more coils of a winding. If direct connection to coils is not feasible, the test voltage may be induced in the coils. Detection of failure is often difficult and is usually accomplished by comparing voltage or current waveforms on similar coils or windings.

7.1.1.4 *Rotor Winding Exception.* Turn-to-turn withstand voltage tests of rotor winding insulation are seldom made. Tests are made, however, to determine if there are any shorted turns in a rotor winding. These tests involve impedance or flux measurements which are not considered dielectric tests and hence are not within the scope of this guide.

7.1.2 Partial-Discharge Measurements

7.1.2.1 *General.* Partial-discharge measurements on rotating machine stator insulation are usually made to indicate the amount of ionization energy available to deteriorate the stator insulation. Mica, the major ground wall insulation for high-voltage machines, is highly resistant to all but very concentrated discharges such as slot discharges (see 7.1.2.3). Other materials used, however, including those for strand and turn insulation, may be more susceptible to ionization damage. Failure of such insulation can develop into a ground wall failure.

7.1.2.2 *Dissipation or Power Factor.* An indicator of partial-discharge energy is the increment in dissipation factor or power factor (power factor tip-up) as the test voltage is raised from below the ionization inception voltage to the operating voltage. The indicator may be affected by materials in the insulation system which have nonlinear loss characteristics with voltage, such as some voltage-grading paints used in the end turn area.

7.1.2.3 *Slot Discharge.* Slot discharge is a special type of partial discharge which occurs when a coil side does not make intimate contact with a slot. Slot discharge may be detected by many of the methods listed in 5.3.

7.1.2.4 *Inception Voltage and Pulse Magnitude.* The partial-discharge inception voltage and pulse magnitude measurements may be used to monitor the condition and the tightness of mica-insulated stator bars in the machine slots. When a large number of pulses per cycle are encountered, the accuracy of individual pulse magnitude measurements may be questionable because of the possibility of pulse superposition.

7.1.2.5 *Probe Method.* Probe methods to indicate sites of severe partial-discharge activity as locations of incipient failures have met with limited success.

7.1.3 Dielectric Characteristics

7.1.3.1 *General.* Insulation resistance and polarization index measurements are often used to indicate the surface condition of machine insulation. Thus, these measurements may be used to determine when the surfaces need cleaning or drying before they become a flashover hazard. The measurements are also used during the drying of machine insulation which has been flooded or otherwise exposed to excessive water.

7.1.3.2 *Insulation Resistance.* Insulation resistance measurements may be made to ascertain that a machine insulation is in suitable condition for a withstand voltage test. Resistance measurements may be combined with direct-voltage withstand tests to provide possible warning of impending breakdown (see 3.3.2).

7.1.3.3 *Periodic Measurements.* Periodic measurements of insulation resistance, using a direct test voltage, or of capacitance and power factor, using an alternating test voltage, may be made to monitor the overall condition of the insulation. Alternating-voltage tests should be made at the operating voltage level to include ionization losses.

7.1.4 Analysis by Phases

7.1.4.1 *General.* For a three-phase machine more information on the condition of machine insulation can be obtained if the individual phases can be tested one at a time rather than all together. Separation of phases requires the opening of the neutral connection.

7.1.4.2 *Withstand Test.* Dielectric withstand tests may be made on each phase in turn, with the other two phases grounded. This procedure subjects the phase-to-phase (interphase) insulation to the test voltage.

7.1.4.3 *Dielectric Measurements.* Dielectric characteristic tests and partial-discharge tests on individual phases permit a comparison of results between phases. A localized fault will produce a greater change in the test results on a single phase than on a complete machine.

7.1.4.4 *Interphase Measurements.* Separation of phases permits the determination of dielectric characteristics on the interphase insulation. A three-phase generator may be treated as a four-electrode system (see Appendix B).

7.1.5 Water-Cooled Stators. Useful measurements of dielectric characteristics cannot be made directly on the stator insulation of water-cooled machines because low-resistance water paths shunt the insulation. An approximate measure of strictly alternating-voltage loss may, however, be obtained. Losses, including those in the water path, are first measured at a selected alternating voltage V (rms). Direct-voltage loss, which includes the water-path loss, is then calculated as V^2/R, where R is the direct-voltage resistance measured at the same terminals and preferably at direct voltage V. All measurements are made with normal water flow. The difference between the two losses is considered to be the alternating-voltage loss due to polarization and ionization. This differential loss can be used with the measured alternating current in the calculation of power factor and power-factor tip-up.

7.2 Transformers, Regulators, and Reactors

7.2.1 General. To avoid unnecessary wording in this section, only transformers are specifically mentioned. In general, the same material is also applicable to regulators and reactors. A reactor may be treated as a single-winding transformer. A regulator usually has shunt and series windings. When these windings can be separated, the regulator may be treated as a two-winding or multiwinding transformer; otherwise, it is treated as a single-winding transformer.

Transformers and regulators sometimes are equipped with internal surge arresters or other protective devices which may interfere with a dielectric test. The internal wiring diagram, usually found on the name plate, should be examined for this possibility before proceeding with the test.

7.2.2 Withstand Voltage Tests

7.2.2.1 *General.* It is not general practice to subject transformers in the field to withstand voltage tests. One reason for this situation is the difficulty of obtaining portable test-voltage sources which meet the test requirements. Normal overvoltage tests on a transformer require a source of alternating voltage at some higher than normal frequency and with sufficient capacity to supply the magnetizing current and core losses of the transformer. Impulse tests on a transformer require a high-voltage pulse generator which is not readily portable.

7.2.2.2 *Oil Samples.* Alternating voltage withstand or breakdown test may be made on samples of oil removed from the transformer. A special test cell is used for these tests (see 7.9).

7.2.3 Partial-Discharge Tests

7.2.3.1 *General.* Partial-discharge tests on transformers in the field usually must be made at normal system voltage, with the transformer energized by the connection of at least one winding to the power system. While a more effective test can be made using a separate voltage source to energize the transformer at some overvoltage, providing such a source (see 7.2.2.1) is usually impractical.

7.2.3.2 *Interference.* A normal connection to the power system does not include sufficient impedance to prevent discharges which occur elsewhere in the power system from interfering with the measurement, or to prevent the attentuation of those discharge pulses which originate in the transformer. Field measurements of partial discharges under such conditions are not accurate and are chiefly used to check for any intense discharge activity in a transformer in which trouble is suspected.

7.2.3.3 *Capacitance Taps.* Connection of partial-discharge measuring equipment to the transformer under test is facilitated when the transformer bushings are equipped with capacitance taps. The measuring equipment can be connected to a tap, thereby eliminating the necessity for a high-voltage coupling capacitor and any high-voltage connections.

7.2.4 Dielectric Characteristics

7.2.4.1 *General.* Insulation resistance using a direct test voltage, and power factor or dissipation factor using an alternating test voltage, are the characteristics most commonly used for the routine testing of transformer insulation. These tests are particularly sensitive to moisture absorption by the insulation and in oil-filled transformers to contaminants in the oil and to deterioration of the oil itself.

7.2.4.2 *Bushings.* The terminal bushings are an important but often small part of the total insulation system of a transformer. A separate test may be made on each bushing to determine its characteristics. Bushing tests are facilitated where the bushings are equipped with capacitance taps, test taps, or insulated draw leads (see 7.8).

7.2.4.3 *Oil.* The oil in an oil-filled transformer is often sampled on a routine basis and its dielectric characteristics measured in a special test cell (see 7.9).

7.2.4.4 *Temperature.* The measured dielectric characteristics of transformer insulation can be greatly influenced by the temperature of the insulation at the time of measurement. The effect of temperature varies greatly with different insulation systems; in general, the older systems are more greatly affected than modern systems. For comparison purposes the measurements should be converted to a common temperature base.

7.2.4.5 *Components.* The insulation system of a multiwinding transformer can be separated into components and the characteristics of each component found as described in Appendix B. The tank and core usually form the ground electrode. Each separate winding forms an additional electrode. A tapped winding, as in an autotransformer, must be treated as a single electrode. In the measurement or calculation of the components, it is sometimes found that a shield or winding placement is such as to practically eliminate one or more of the interwinding components. When the results indicate that a component has a near-zero capacitance, any calculated characteristic values should be discounted because of accuracy limitations (see B2.2, Appendix B).

7.2.4.6 *Interpretation.* The interpretation of the results of individual component characteristics may sometimes be facilitated by noting that the components involving the ground electrode include bushing insulation while the interwinding components include only the internal insulation of the transformer.

7.2.5 Special Tests

7.2.5.1 *Chemical.* A chemical analysis may be made on a sample of oil or the overlying gas in the oil-filled transformer to detect products of insulation deterioration. The composition and concentration of these products furnish information regarding the nature and severity of the condition causing the decomposition. Continuous or periodic checking for decomposition products in oil or gas is becoming a common practice for very large transformers.

7.2.5.2 *Core Grounds.* Core-to-ground insulation on core-type transformers may be checked for accidental grounds, particularly after shipment.

7.2.5.3 *Others.* A description of tests which indicate situations leading to insulation failure, but which are not tests on the insulation itself, is outside the scope of this guide. Some of these tests are listed by name only: winding resistance, turns ratio, and low-voltage impulse tests (to detect displacement of windings due to short circuits).

7.3 Insulated Conductors (Cables)

7.3.1 General. Power cable is subject to bending, tensile, and compression stresses during installation. Improper handling may result in damage to the cable insulation and its shielding systems. Insulation tests are often made on a cable after installation to reveal any such damage.

A complete cable assembly includes joints, when necessary, and terminations. Terminations and joints are generally assembled on site. Tests to check the insulation quality of termination or joint assemblies must therefore usually be made in the field.

Periodic tests may be made on the insulation of the cable during its service life. Cable insulation is exposed to several deteriorating influences in service including the effect of transient overvoltages and circuit overloads. Cable systems are subject to physical stresses due to load (temperature) cycling, and to damage from hostile environmental conditions including erosion by stray earth currents, as well as chemical, bacteriological, and rodent attacks.

7.3.2 Withstand Voltage Tests. Withstand voltage tests are generally considered the most reliable tests for exposing defects which originate during the installation of the cable, including those in joint and termination assemblies.

7.3.2.1 *Alternating Versus Direct Voltage.* Withstand tests on cable insulation may be made with either alternating or direct test voltages. Because of the high capacitance of the average cable run, direct test voltages are often used to avoid the high reactive power required by an alternating-voltage test. Resonating inductors in power-frequency alternating-voltage supply systems, or a very low frequency (for example, 0.1 Hz) may be used to reduce reactive power requirements.

7.3.2.2 *Withstand/Partial-Discharge Tests.* Withstand tests made with alternating test voltages are sometimes combined with partial-discharge (corona) tests (see 7.3.3.2), especially when testing extruded insulation systems.

7.2.2.5 *Determination of Test Voltage.* The rate of rise, the maximum value, and the duration of application of the withstand test voltage depend on the rating and on the type of cable insulation. Manufacturer's recommendations and published standards should be consulted in determining the test voltage to be used for a particular cable. Consideration should be given to the insulation level of terminations, joints, and any apparatus connected to the cable.

7.3.3 Partial-Discharge (Corona) Tests

7.3.3.1 *General.* Partial-discharge tests on cable insulation are preferably made with an alternating test voltage. A test voltage level somewhat higher than the normal operating value will activate any source of incipient ionization. Because of the difficulty of providing a suitable test voltage and controlling extraneous interference in the field, partial-discharge tests on installed cable are generally limited to short runs of cable and to cable systems with suspected ionization problems.

7.3.3.2 *During Alternating-Voltage Withstand Test.* Partial-discharge tests may be made during an alternating-voltage withstand test on the cable. In this case, the test voltage supply and test connections must be free of significant partial discharges, a requirement not necessary for a simple withstand test.

7.3.3.3 *Equipment Sensitivity.* Most cable insulation is susceptible to damage from low-level partial discharges. Discharge measuring equipment should therefore have sufficient sensitivity to detect charges in the picocoulomb range in high-capacitance specimens.

7.3.4 Measurement of Dielectric Characteristics

7.3.4.1 *General.* Measurements of dielectric characteristics are most often made to detect changes in the overall condition of cable insulation which occur with time as a result of service and environment. Measurements made to detect local weak spots are most successful on short lengths of low-voltage cable. In general, the ability of such measurements to detect local weak spots decreases with cable length.

7.3.4.2 *Time-Voltage Characteristics.* A series of insulation resistance measurements may be made while a cable is energized at various voltages to determine resistance as a function of voltage and time. These tests are sometimes combined with a withstand test. To facilitate comparison of test results, the test procedure should follow an established time—voltage schedule.

7.3.4.3 *Dielectric Loss, Power Factor, Dissipation Factor.* Measurements of dielectric loss or an associated dimensionless factor (power factor or dissipation factor) are sensitive indicators of the general condition of cable insulations. Measurements are preferably made at or near operating voltage and frequency, especially if ionization is suspected. Measurements to show changes in power factor or dissipation factor with variations in the applied test voltage may be used to evaluate nonlinear processes, including ionization, taking place in the cable insulation.

7.3.4.4 *Oil Samples.* Oil from pipe-type cables may be sampled and tested for supporting information on the effect of service conditions on the cable insulation.

7.3.4.5 *Terminations.* Dielectric characteristic measurements on installed terminations (potheads) may be made separate from those of the cable itself if the terminations are provided with test taps. For terminations not equipped with test taps, some information on the insulation characteristics may be obtained by applying one or more temporary external electrodes (collars) to the outer insulating surface of the termination and measuring between the electorde or electrodes and the conductor being terminated.

7.3.4.6 *Component Insulation.* Measurements on a belted multiconductor cable, in which the conductors are not individually shielded, may be made to obtain the dielectric characteristics of the insulation between any conductor and the lead jacket, or between any two conductors. Methods for analyzing the component insulations in a multiconductor cable are described in Appendix B.

7.4 Switchgear

7.4.1 General. Switches for power circuits are made in a wide variety of design. Only a very general discussion of their insulating structures, as they affect insulation testing, can be given in this guide.

7.4.2 Tests. Tests on switch insulation are usually confined to the measurement of dielectric characteristics such as insulation resistance, power factor, or dielectric loss. Many other types of tests are made to check the operation of a switch, including mechanism-motion analysis and contact-resistance measurements, but these tests are beyond the scope of this guide.

7.4.3 Terminals. A switch must have two terminals across which a circuit is closed or opened by the switching mechanism. Each terminal must be insulated for system voltage. When the switch is open, the terminals must be insulated from each other for a higher voltage in the event that there are system voltages at the two terminals that are not in phase or in synchronism. The basic test procedure for switch insulation requires a test or measurement to be made on each terminal of the open switch, with the other terminal at or near ground potential. Each of these tests, therefore, involves both insulation to ground and insulation between terminals. A supplementary test with the switch closed removes the direct effect of insulation between terminals and is helpful in the analysis of test results.

7.4.4 Opening and Closing. The opening and closing of a switch requires mechanical force, which is usually generated at ground potential. Insulation is required in transmitting this force to the switching element. A common means for transmitting this force is an insulating rod or a column of insulating fluid confined in an insulating tube. This insulating rod or tube may be included in the test of one or both terminals, but in some switches the insulation is not directly in the test circuit unless the switch is closed. For such switches, a closed-switch test is particularly important.

7.4.5 Operating Means. Switches designed to open a circuit under load may use an insulating structure designed to quench the arc. This structure is usually associated with a switch contact and in some cases extends to a grounded support. Arc products and moisture may affect the insulation characteristics of these structures, and the condition of the insulation is reflected in measurements made at the switch terminals.

7.4.6 Arc-Quenching Structure. Switches for use on the higher range of power-system voltages open the circuit by a series of gaps, usually in an environment of air of SF_6 at high pressure. The voltage to be interrupted is distributed among the gaps by grading capacitor assemblies. Such switches are usually designed in a module arrangement which permits each grading capacitor to be measured separately. Capacitance measurements on these assemblies are of particular value in locating deteriorated capacitors, since the measured capacitances may be compared with each other and with the design value which is generally known.

7.4.7 Oil Circuit Breaker. A common type of switch is the oil circuit breaker in which the circuit is broken within a tank of oil. The tank may be "dead" (at ground potential), in which case the circuit is brought into the tank by bushings similar to those of a transformer. A contact assembly, including an arc suppression device, is fastened to the lower end of each bushing, and a conducting crosspiece is lifted or rotated by an insulated operating member to engage the contacts and complete the circuit. Insulation in the tank in addition to the bushings, arc suppressor, operating member, and oil may include guides for the operating member and a tank liner. Information on the condition of the tank insulation may be deduced from open- and closed-breaker tests. Separate tests may be made on the bushings by techniques described in 7.8. Also, oil samples may be taken from the tank for tests specifically applicable to oil (see 7.9).

7.5 Lightning Arresters

7.5.1 General. Withstand tests, in the usual meaning of the term, cannot be made on a lightning arrester, since the protective function of the arrester inhibits overvoltages beyond a specified value. The application of overvoltages to check the operation of an installed arrester is not generally practiced, although some testing has been done at lower transmission voltages for which impulse generators are more easily transportable. The energy output of any impulse generator used for lightning-arrester tests should not be sufficient to damage the arrester.

7.5.2 Insulation Measurements. Measurements of the insulation characteristics of an arrester may be made to assess the ability of the arrester to withstand continued normal system voltage. Such measurements have also revealed conditions which could affect the protective function of the arrester. Measurements of particular value include insulation resistance using a specified direct test voltage and power loss at a specified alternating test voltage. Since nonlinear elements may be included in lightning arrester measurements, accurate adjustment of the test voltage is necessary for comparable results. Normal test values for a specific type of arrester are usually obtained by statistical analysis from a large number of tests.

7.5.3 Gaps. Some arresters include in their internal circuits a gap or series of gaps which may be shunted by resistors. Corrosion products may short-circuit a gap, a condition which is reflected in test measurements by decreased resistance and increased loss. An open shunting resistor, on the other hand, causes an increase in resistance and a decrease in loss. Partial-discharge tests may be useful in identifying these types of deterioration.

7.6 Capacitors

7.6.1 General. Capacitors are used in high-voltage power systems as couplers for carrier current circuits and as components of potential devices. Such capacitors are seldom subject to withstand tests in the field, but are readily tested for insulation characteristics such as capacitance, power factor, and insulation resistance.

7.6.2 High Voltage. High-voltage capacitors may consist of two or more lower voltage units stacked in series. In this case, measurements should be made on each individual unit.

7.6.3 Capacitance Measurements. Capacitance measurements are important, since an increase in capacitance suggests the failure of one or more sections of a capacitor. For capacitors used with coupling-capacitor voltage transformers, a change in capacitance or power factor can affect the accuracy of the output voltage. An increase in measured power factor indicates a possible incipient fault.

7.6.4 Power Factor Correction. Capacitors are also used to correct the power factor of a system load. Tests on this type of capacitor to determine incipient faults are economically questionable. Internal discharge resistors which shunt the capacitance may interfere with the interpretation of insulation resistance measurements. Capacitors in which one or more sections have been punctured and short-circuited may be found by measurements of capacitance or charging current made at a low test voltage.

7.7 Insulators

7.7.1 Line and Station. Line and station insulators in general have such a good service record that testing is usually limited to spot checks or to the few designs that have a significant failure rate. Tests are usually made by the voltage-distribution method (see Section 4) while the insulators are in service.

7.7.2 Single Piece. Single piece insulators located between an energized line and ground cannot be effectively tested by the voltage-distribution method. One method of testing such insulators requires the line to be grounded, a temporary electrode applied around the center of the insulator, and an insulation measurement made between the electrode and ground.

7.7.3 Insulator Stack. An insulator stack supporting a conductor from ground may be tested by grounding the conductor and testing the insulators in pairs, applying the test voltage to the connection between the insulators and grounds to the outer connections. The test may be a measurement of insulation characteristics. If the test voltage exceeds the voltage normally impressed on each insulator in service, the test may also be considered as a sort of withstand test.

7.7.4 Corona. While not strictly an insulation problem, corona may occur at tie wires or insulator hardware and cause objectionable radio or television interference. Sources of corona may be located by ultrasonic detectors or by test equipment, receivers, or detectors which operate in some frequency band between ordinary radio frequencies and a frequency beyond that of visual light. Details of corona location are beyond the scope of this guide.

7.8 Bushings

7.8.1 Spares. Spare bushings are usually crated and stored in confined spaces. Satisfactory withstand tests on a spare bushing usually require that the bushing be removed to an open space, uncrated, and mounted on a metal stand with its lower end in oil to a level representing the normal operating environment. Measurements of the insulation characteristics of spare bushings can be adversely affected by the crate and other surrounding material. Removal of the crate and use of the ungrounded-specimen test mode (grounded-guard circuit; see A2.1.3, Appendix A) are often helpful in obtaining a satisfactory reading.

7.8.2 Connection to Other Components. A bushing installed in power apparatus is connected within the apparatus tank to some other circuit component such as a transformer winding. Isolating the bushing by disconnection within the tank is usually impractical, so that it is impossible to confine a test measurement to the bushing insulation with certain exceptions.

7.8.2.1 *Test Tap.* Some bushings are constructed with an electrode positioned near the ground flange so that the main insulation of the bushing appears between the electrode and center conductor. An insulated tap brought through the ground flange of the bushing permits connection to the electrode for energizing a potential device or for a test connection. This construction feature is referred to as a potential tap or test tap. An ungrounded-specimen test made between the center conductor of the bushing and the tap will confine measurements of insulation characteristics to the main insulation of the bushing.

7.8.2.2 *Draw Lead Bushing.* Some bushings and transformers are designed so that an insulated lead from the transformer winding is brought through the hollow center conductor of the bushing to the top or cap of the bushing where connection is made. By opening this connection, the center conductor of the bushing is isolated from the transformer winding. A test may then be made between the center conductor and the bushing flange. To confine the measurement to the bushing insulation and to exclude the insulation of the transformer lead, the lead must be connected to the guard terminal of the measuring circuit. Because the clearance at the cap and the lead insulation will withstand only a few volts, the test voltage using a "cold-guard" circuit must be kept very low. The voltage limitation may be avoided by use of the "hot-guard" circuit, which is recommended for this type of test. (See A2.1.4, Appendix A).

7.8.3 Test on Local Area. A test may be made on a local area of insulation above the flange by applying a temporary electrode (conducting band or collar) around the insulating surface of the bushing at a point nearest to the area in question. The test measurement is usually made between the electrode and the grounded center conductor of the bushing.

7.8.4 Correspondence with Nameplate Values. Many high-voltage bushings have capacitance and power factor values as measured at the time of manufacture recorded on a nameplate. Test measurements should show a reasonable correspondence with the nameplate values.

7.9 Insulating Fluids

7.9.1 General. Insulating fluids are usually sampled for test and introduced into a test cell having a specific electrode configuration. While samples can be sent to a testing laboratory, tests in the field at the time of sampling avoid misleading results due to changes in the sample from handling and transportation.

7.9.2 Dielectric-Strength Test. A common test for an insulating fluid is the dielectric-strength test, in which the test voltage applied to the electrodes is raised at a specified rate until rupture occurs. The dielectric strength of common insulating liquids is only moderately influenced by temperature over ordinary operating ranges. The dielectric strength of gases, however, is influenced by temperature and pressure. The temperature and pressure of the gas in the test cell at the time of test should be included in the test report.

7.9.3 Conducting Contaminants. Low dielectric-strength values obtained on insulating fluids may usually be traced to conducting contaminants. Water in one or more of its phases is a common contaminant. Gases are sometimes checked for moisture contamination by means of dew-point measurements. An additional cause of low dielectric-strength values for liquids are gas bubbles which may have been introduced in pouring the sample into the test cell. This problem can be avoided by permitting the sample to remain in the cell for sufficient time to allow the bubbles to surface and disappear before the test voltage is applied.

7.9.4 Test Methods. Measurements of the insulation characteristics of insulating fluids are usually confined to liquids. A test cell is used in which the electrodes form the plates of a capacitor and the liquid constitutes the dielectric. For accurate tests on low-loss liquids, the electrode system includes guard electrodes to avoid measurement of edge effects and the insulation of the electrode supports. The capacitance of the cell with air as the dielectric is used in conjunction with a test measurement to obtain the dielectric constant (permittivity) or resistivity of the sample.

7.9.5 Temperature. The insulation characteristics of many liquids are sensitive to temperature, so that the temperature of the liquid at the time of test should be included in the test report. Low-loss liquids which may be used at high temperatures (for example, 100°C) are often tested at high temperatures, since increased losses provide more accurate test results.

7.9.6 High Power Factors, Dissipation Factors, Low Resistivity. Abnormally high power factors or dissipation factors, or abnormally low resistivity values, may usually be traced to contaminants such as resins which dissolve in the liquid and cause extra polarization losses.

7.9.7 Other Tests. Many other tests are applied to insulating liquids which are not primarily electrical and which are outside the scope of this guide. Such tests include viscosity, fire and flash points, identification and evaluation of dissolved gases, etc, and are usually made in a laboratory rather than in the field.

8. Applicable Documents

8.1 Withstand Voltage Tests

IEEE Std 4-1978 IEEE Standard for High-Voltage Testing Techniques

ASTM D 149-75, Tests for Dielectric Breakdown Voltage and Dielectric Strength of Electrical Insulating Materials at Commercial Power Frequencies[1]

8.2 Partial-Discharge (Corona) Tests

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

ASTM D 1868-73, Detection and Measurement of Corona Pulses in Evaluation of Insulation Systems

NEMA Std 107-1964 (R 1971), Methods of Measurement of Radio Influence Voltage of High-Voltage Apparatus[2]

ASTM D 3382-75, Measurement of Energy and Integrated Charge Transfer Due to Partial Discharges (Corona) Using Bridge Techniques

8.3 Dielectric Characteristics

ASTM D 257-76, Tests for D-C Resistance or Conductance of Insulation Materials

D 150-74, Tests for A-C Loss Characteristics and Dielectric Constant (Permittivity) of Solid Electrical Insulating Materials

8.4 Rotating Machinery Insulation

ANSI/IEEE Std 43-1974 Recommended Practice for Testing Insulation Resistance of Rotating Machinery

ANSI/IEEE Std 56-1977 Guide for Insulation Maintenance for Large AC Rotating Machinery

ANSI/IEEE Std 95-1977, Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage

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

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

8.5 Transformer Insulation

ANSI/IEEE Std 93-1968, Guide for Transformer Impulse Tests

8.6 Conductor (Cable) Insulation

IEEE Std 82-1963 (Reaff 1971), Test Procedure for Impulse Voltage Tests on Insulated Conductors

IEEE Std 83-1963 (Reaff 1971), Test Procedure for Radial Power Factor Tests on Insulating Tapes in Paper-Insulated Power Cable

IPCEA T-24-380 (1974), Partial-Discharge Test Procedure (Corona)[3]

8.7 Capacitors

ANSI/IEEE Std 18-1968 Shunt Power Capacitors

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[1] ASTM documents are available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pa. 19103.

[2] NEMA documents are available from National Electrical Manufacturer's Association, 2101 L Street, N.W., Suite 300, Washington, D.C. 20037.

[3] IPCEA documents are available from National Electrical Manufacturer's Association.

8.8 Liquid Insulation

ANSI/IEEE C57.106-1977, Guide for Acceptance and Maintenance of Insulating Oil in Equipment

IEEE Std 76-1974, Guide for Acceptance and Maintenance of Transformer Askarel in Equipment

9. Applicable Documents in Preparation[4]

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[4] When the following documents are completed, approved and published, they become a part of this listing.

IEEE Guide for Installation of Oil-Immersed Transformers (10 000 kVA and larger, 69-287 kV Voltage Rating) (To be published in ANSI C57 Series).

IEEE Standards Project P400 (in preparation) High Potential Direct Voltage Dielectric Tests on Insulated Conductors

IEEE Standards Project P510 (in preparation), Recommended Safety Practices in High-Voltage

Appendixes

(These Appendixes are not a part of IEEE Std 62-1978, Guide for Field Testing Power Apparatus Insulation.)

Appendix A

Shielding of Equipment for the Measurement of Insulation Characteristics

A1. General

A1.1 Shielding Against External Interference

A1.1.1 General. Measurement of insulation characteristics must often be made on apparatus located near conductors operating at high voltage and carrying heavy currents. The electric and magnetic fields emanating from these conductors may extend to the measuring circuit, inducing voltages and currents therein which interfere with measuring accuracy.

A1.1.2 Loops. Magnetic fields induce voltages in any wiring loops in the measuring circuit. Usually wiring can be arranged to avoid loops. Certain components, however, such as inductors and some wire-wound resistors, contain many loops. Magnetic interference induced in these components can be minimized by enclosing them in a shield made of a material having high initial permeability.

A1.1.3 Electric Fields. Electric fields induce currents in the measuring circuit, an effect which may be described as due to capacitive coupling between the interfering conductor and the circuit. This type of interference can be effectively eliminated by enveloping the measuring circuit in a conductive shield connected to ground.

A1.1.4 Test Specimen. The test specimen, an external part of the measuring circuit, should be included in the ground shield. It is seldom feasible, however, to apply shielding to high-voltage power apparatus for test purposes. Interference induced in the test specimen by external voltage sources can be dealt with by special test techniques (see 6.8.3).

A1.1.5 Safety of Personnel. For protection of personnel, a conducting shield connected to ground may be placed over any parts of the test circuit energized by the test voltage source.

A1.2 Shielding Against Internal Interference

A1.2.1 Guard Shield. A shielding system is used to prevent the measurement of the circuit insulation along with the insulation of the test specimen. This system is often designated the "guard" shield and is usually so located and connected as to return all currents, produced in the insulation of the measuring circuit by the test voltage source, directly back to the source without passing through any measuring element.

A1.2.2 Test Specimen. The guard shielding system may be extended to the test specimen to aid in the analysis of complex insulation systems. Details of this use are discussed in Appendix B.

A1.2.3 Surface Leakage. An extension of the guard shielding system in the form of a wire or band around the insulating surface of a test specimen may be used for the purpose of excluding surface leakage from the measurement. Surface guards are more efficacious for direct test voltages than for alternating voltages.

A2. Basic Shielding Systems

A2.1 Guard Shields

A2.1.1 General. The need for a guard shield (see A1.2.2) is illustrated by the circuit of Fig A1, in which the specimen insulation resistance R_x is to be measured by the current which flows through it into the meter in response to the test voltage. The measuring circuit has three conductors, A, B, and C, with associated insulation resistances R_{ab}, R_{bc}, and R_{ac}. R_{ab} shunts the voltage source but does not affect the measurement. R_{bc} shunts the meter but has such a high value in comparison with the meter resistance that the shunting effect is insignificant. R_{ac} shunts the test specimen, and the current which the test voltage produces in it is measured by the meter along with the test specimen current. The meter then does not give a true indication of the current through the specimen.

A2.1.2 Elimination of Leakage Path. The leakage path R_{ac} can be eliminated by means of the guard shield shown by broken lines in Fig A2. With the path eliminated, the meter now reads only the leakage current through the test specimen. Leakage from conductor A to the shield adds to that through R_{ab} of Fig A1 and returns to the voltage source without passing through the meter. In Fig A2 the combined leakage path is represented by Z_{ab}. For alternating-current measuring circuits, charging currents due to capacitance as well as to leakage currents must be considered (see A2.3).

A2.1.3 Grounded-Guard Shield. Conductor C in the shielding system of Fig A2 cannot be grounded, or the shielding system would theoretically have to cover the entire earth. A ground can be placed on conductor B as shown, which restricts the circuit to the measurement of ungrounded test specimens. The ground on conductor B puts the meter conveniently in the ground circuit, and also puts the shield at ground potential. In this case the shield may be called a grounded-guard shield.

A2.1.4 Hot-Guard Shield. Conductor A of Fig A2 can be grounded instead of conductor B, as shown. If one terminal of the test specimen is grounded, the test specimen is placed in the circuit with its grounded terminal connected to conductor A. Fig A3 is an inversion of Fig A2 to show the connections in a more conventional manner. Both the meter and the shield are at test potential, and in this case the shield may be called a hot-guard shield. There is an obvious difficulty in reading or adjusting a meter which is inside a shield at test potential.

A2.1.5 Cold-Guard Shield. A more convenient circuit when one terminal of the test specimen is grounded is shown in Fig A4. The shield is connected to conductor B as in Figure A2, but extends in the opposite direction to enclose the voltage source and conductor A. The shield is slightly above ground potential by the voltage drop across the meter, which is conveniently in the ground circuit. In this case the shield may be called a cold-guard shield.

A2.2 Ground Shields

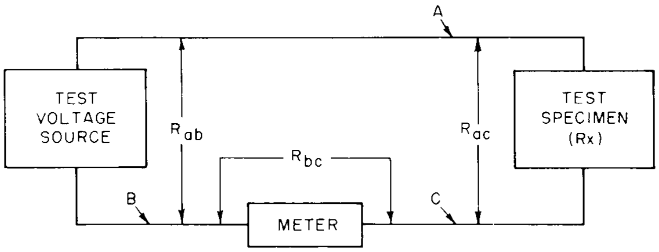
A2.2.1 Safety Use. In the circuits of Fig A2 and A3, the addition of ground shields is necessary only for safety. Any currents picked up by the measuring circuit due to capacitive coupling with external voltage sources will flow to ground either directly or through the low-impedance voltage source without passing through the meter.

A2.2.2 Protection of Guard Shield. In the circuit of Fig A4, currents from external sources picked up on the guard shielding system will flow to ground through the meter and thus cause erroneous readings. To prevent the error, the guard shield must be entirely covered by a ground shield. The circuit with both shields is shown in Fig A5. Note that the test voltage source is shown as a transformer and that the primary winding is treated as an external voltage source. The ground shield is interposed between the primary winding and the guard shield.

A2.3 Effect of Shielding System Capacitance

A2.3.1 Phase Shift. For measurements using an alternating test voltage, the effect which test circuit capacitances have on the measurement must be considered in addition to the effect of the resistances discussed in A2.1. The

Fig A1
Elementary Measuring Circuit



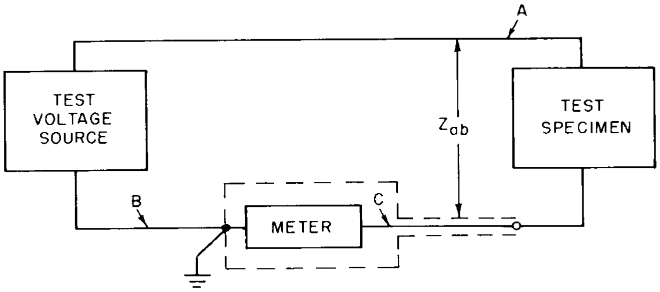


Fig A2
Grounded-Guard Shield

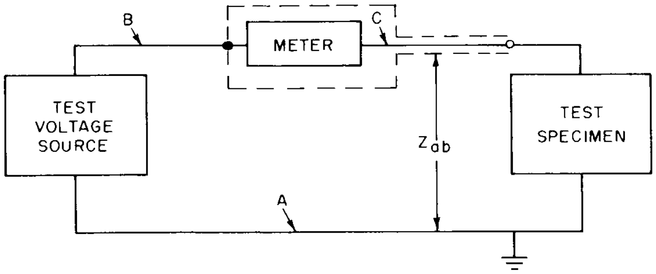


Fig A3
Hot-Guard Shield

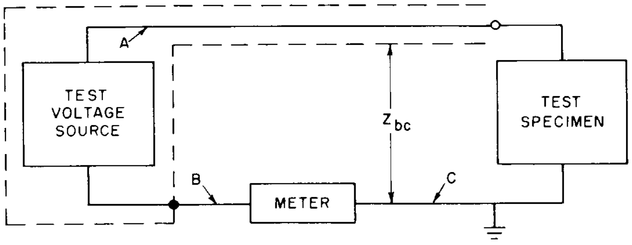


Fig A4
Cold-Guard Shield

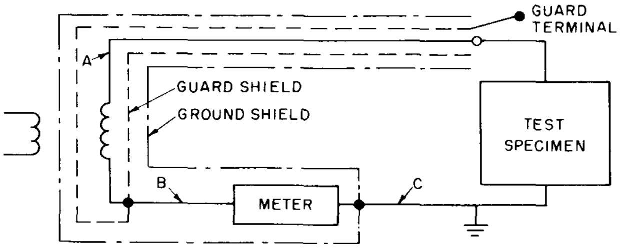


Fig A5
Double-Shielded Circuit

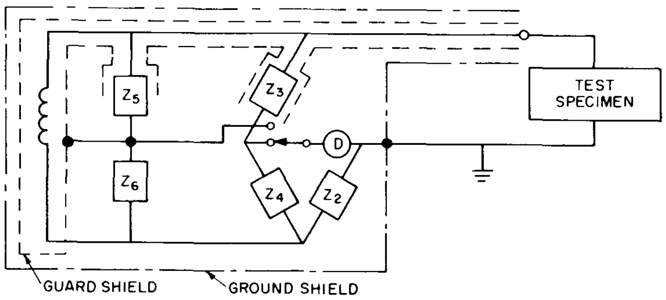
capacitance which shunts the meter or measuring element is that between conductors B and C of Fig A1 and is enhanced by the shielding system of Figs A2, A3, A4, or A5. The effect of this capacitance on a resistive measuring element is to shift the phase of the current through the element and thus cause an error in the measured loss characteristic, for example, dielectric loss, or power factor or dissipation factor.

A2.3.2 Shunting Capacitance. Additional shunting capacitance may be present when measuring components of a complex insulation system by method B or C described in Appendix B. The test connections required by these methods place the capacitance of one or more of the components of the insulation system in shunt with the measuring element.

A2.3.3 Loss Error. The error in a loss characteristic measurement due to the effect of capacitance shunting the measuring element is proportional to the resistance of the measuring element. The error will be insignificant if the resistance of the measuring element is sufficiently low.

A2.3.4 Guard Balance. In bridge circuits, when the capacitance shunting the measuring element is that between the guard and ground shields, the effect of the capacitance on the measurement may be nullified by bringing the potential of the guard shield to ground. The procedure is referred to as a guard balance. A bridge circuit incorporating a guard balance feature is shown in Fig A6. In this circuit, Z_2 is the measuring element, Z_3 and Z_4 are the standard arms used in the main balance of the bridge, and Z_5 and Z_6 are the guard balance arms.

Fig A6
Shielded Bridge Circuit with Guard Balance



Appendix B

Measurement Techniques for the Analysis of Complex Insulation Systems

B1. Simple and Complex Systems

B1.1 Simple System. A simple insulation system consists of two electrodes separated by insulation, and can be represented as a single capacitor. An example of a simple system is an apparatus bushing, with its center conductor and mounting flange as the two electrodes.

B1.2 Complex System. A complex insulation system has three or more electrodes insulated from each other. Capacitance may exist between any pair of terminals. A three-electrode system may therefore be represented by a network of three capacitors, a four-electrode system by six capacitors, and an *N*-electrode system by $\frac{1}{2}N(N-1)$ capacitors. An example of a complex system is a multiconductor belted cable, in which each conductor and the lead sheath are electrodes.

B1.3 Grounded Electrode. In a practical system, one of the electrodes is at ground potential. Thus in an *N*-electrode system there are *N*-1 ungrounded electrodes, each insulated from ground. Consequently, there are *N*-1 component capacitors representing insulation from ground. The remainder of the $\frac{1}{2}N(N-1)$ components represent insulation between ungrounded electrodes.

B2. Determination of the Characteristics of an Individual Component

B2.1 Methods of Measurement. The determination of the characteristics of the individual components of a complex insulation system is of value in the detection and location of defective insulation within the system. The characteristics of any component may be determined from measurements made at the electrode terminals. Three methods for accomplishing the determinations are described in the following subsections, and for convenience in this Appendix they are denoted methods A, B, and C. The choice of method is limited by the facilities provided by the measuring equipment.

B2.2.1 Method A. Method A requires calculation involving three or more measurements to determine the characteristic of any one component. Method A may be used by measuring equipment capable of measuring insulation to ground.

B2.1.2 Method B. Method B permits a direct measurement on each component representing insulation to ground. The characteristics of the remaining components are found by calculation similar to that of method A. Method B requires the measuring equipment to have the additional facility of a usable guard circuit, that is, a guard circuit to which some components of the insulation system can be connected with no appreciable effect on the measurement accuracy.

B2.1.3 Method C. Method C permits a direct measurement of any component. In addition to facilities required by method B, method C requires the further facility of adapting the measuring circuit to measure between ungrounded electrodes. In the ungrounded measurement mode it must have a usable guard circuit at ground potential.

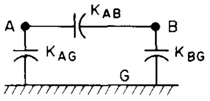
B2.2 Direct Measurement. In general, greater accuracy is afforded by direct measurement. The accuracy of a determination calculated from several readings is subject to cumulative error and is poor when the result represents a small difference between two large quantites.

B3. Method A

B3.1 Individual Components. A characteristic of an individual component cannot be directly

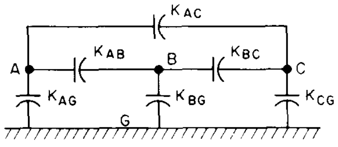
Table B1
Method A

Three-Electrode System



Test Connections			Calculations
To Measure	Energize	Ground	Component Formula
K_1 (= K_{AG} + K_{AB})	A	B,G	$K_{AB} = 0.5\,(K_1 + K_2 - K_3)$
K_2 (= K_{BG} + K_{AB})	B	A,G	$K_{AG} = 0.5\,(K_1 + K_3 - K_2)$
K_3 (= K_{AG} + K_{BG})	A,B	G	$K_{BG} = 0.5\,(K_2 + K_3 - K_1)$

Four-Electrode System



To Measure	Energize	Ground	Component Formula
K_1 (= K_{AG} + K_{AB} + K_{AC})	A	B,C,G	$K_{AB} = 0.5\,(K_1 + K_2 - K_4)$
K_2 (= K_{BG} + K_{AB} + K_{BC})	B	A,C,G	$K_{AC} = 0.5\,(K_1 + K_3 - K_5)$
K_3 (= K_{CG} + K_{AC} + K_{BC})	C	A,B,G	$K_{BC} = 0.5\,(K_2 + K_3 - K_6)$
K_4 (= K_{AG} + K_{BG} + K_{AC} + K_{BC})	A,B	C,G	$K_{AG} = 0.5\,(K_1 + K_7 - K_6)$
K_5 (= K_{AG} + K_{CG} + K_{AB} + K_{BC})	A,C	B,G	$K_{BG} = 0.5\,(K_2 + K_7 - K_5)$
K_6 (= K_{BG} + K_{CG} + K_{AB} + K_{AC})	B,C	A,G	$K_{CG} = 0.5\,(K_3 + K_7 - K_4)$
K_7 (= K_{AG} + K_{BG} + K_{CG})	A,B,C	G	

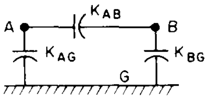
measured by this method. Measurements on various combinations of components can be made, however, and from these measurements the characteristic of an individual component can be calculated.

B3.2 Calculation Formulas. In the right-hand side of Table B1 formulas are given for the calculation of a characteristic of each individual component of three- and four-electrode systems. The characteristic to be calculated is denoted by the letter K, and the location of the component in the system is identified by letter subscripts and also shown in diagrams. The calculation requires the measurement of K for certain combinations of components identified by numerical subscripts. Thus to be able to calculate the characteristic K_{AB} in a three-electrode system, it is necessary to have measured values for combinations K_1, K_2, and K_3.

B3.3 Test Connections. Test connections for measurement of the characteristic K for a particular combination of components, as identified by a numerical subscript, are shown on the left-hand side of Table 1. The individual components involved in the combination are shown in parentheses, for information only. Thus, to measure K_1 in a three-electrode system, the test voltage is applied between electrode A and ground with electrode B also

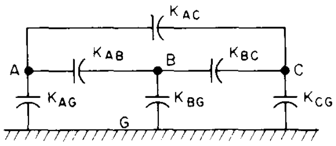
Table B2
Method B

Three-Electrode System



To Measure	Energize	Guard	Ground	Component Formula
K_{AG}	A	B	G	—
K_{AG}	B	A	G	—
K_1 (= K_{AG} + K_{AB})	A	—	B,G	$K_{AB} = K_1 - K_{AB}$

Four-Electrode System



To Measure	Energize	Guard	Ground	Component Formula
K_{AG}	A	B,C	G	—
K_{BG}	B	A,C	G	—
K_{CG}	C	A,B	G	—
K_1 (= K_{AG} + K_{AB})	A	C	B,G	$K_{AB} = K_1 - K_{AG}$
K_2 (= K_{AG} + K_{AC})	A	B	C,G	$K_{AC} = K_2 - K_{AG}$
K_3 (= K_{BG} + K_{BC})	B	A	C,G	$K_{BC} = K_3 - K_{BG}$

grounded. It may be noted that the measurement is on the parallel combination of components K_{AG} and K_{AB}.

B3.4 Measurable Characteristics. The characteristic K in Table B1 is restricted to capacitance or a quantity generally proportional to capacitance. A list of characteristics which K can represent includes:

C capacitance
A charging current at a specified voltage
I leakage current at a specified voltage
G insulation conductance
W loss (watts) at a specified voltage
P product of capacitance and dissipation factor.

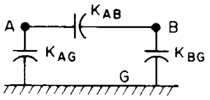
P is calculated from a simultaneous measurement of capacitance and dissipation factor for a given component or combination of components. For example, $P_1 = C_1 D_1$.

B3.5 Power Factor or Dissipation Factor. Power factor or dissipation factor of an individual component cannot be directly calculated from Table B1, since these characteristics are independent of capacitance. It is necessary to use the table twice for the same component, once with $K = C$ or A, and again with $K = W$ or P.

B3.5.1 Power Factor. If W and A (at specified voltage V) have each been calculated for a certain component according to the appropri-

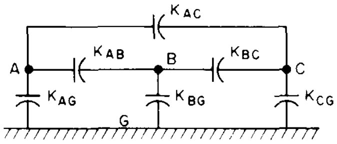
Table B3
Method C

Three-Electrode System



To Measure	Energize	Ungrounded Test Mode Measure	Ungrounded Test Mode Ground	Grounded Test Mode Guard	Grounded Test Mode Ground
K_{AB}	A	B	G	—	—
K_{AG}	A	—	—	B	G
K_{BG}	B	—	—	A	—

Four-Electrode System



To Measure	Energize	Ungrounded Test Mode Measure	Ungrounded Test Mode Ground	Grounded Test Mode Guard	Grounded Test Mode Ground
K_{AB}	A	B	C,G	—	—
K_{AC}	A	C	B,G	—	—
K_{BC}	B	C	A,G	—	—
K_{AG}	A	—	—	B,C	G
K_{BG}	B	—	—	A,C	G
K_{CG}	G	—	—	A,B	G

ate component formula, the power factor of that component can then be calculated as

$$PF = W/VA$$

B3.5.2 Dissipation Factor. If P and C have each been calculated for a certain component according to the appropriate component formula, the dissipation factor of that component can then be calculated as

$$D = P/C$$

As an example, having calculated P_{AB} and C_{AB} of a three-electrode system, $D_{AB} = P_{AB}/C_{AB}$. Expanding,

$$D_{AB} = 0.5\,(P_1 + P_2 - P_3)/0.5\,(C_1 + C_2 - C_3)$$

and

$$D_{AB} = (C_1D_1 + C_2D_2 - C_3D_3)/C_1 + C_2 - C_3)$$

B3.6 Insulation Resistance. The determination of the insulation resistance of a component requires that the calculations be made with K representing conductance (the inverse of resistance), or the leakage current at a specified test voltage. The insulation resistance in ohms

(R) for a certain component may be found from the calculated conductance in mhos (G) by the relation $R = 1/G$, or from the calculated leakage current in amperes (I) and the test voltage (V) by the relation $R = V/I$.

B4. Method B

B4.1 General. The characteristics of a component of a complex system which exists between any ungrounded electrode and ground may be measured directly by connecting all other ungrounded electrodes to the guard circuit of the measuring circuit. Test connections for three- and four-electrode systems are listed in Table B2.

B4.2 Methods of Calculation. The characteristics of those components of a complex system which exist between ungrounded electrodes may be individually determined by calculations similar to those described in method A. Test connections and calculation formulas for three- and four-electrode systems are listed on Table B2. The restrictions on K described in B3.4, and the methods for finding power factor, dissipation factor, or insulation resistance described in B3.5 and B3.6 also apply.

B5. Method C

B5.1 General. The characteristics of any component of a complex system may be measured directly by use of test equipment which provides facilities for measuring both insulation to ground and insulation between ungrounded electrodes. Test connections for three- and four-electrode systems are listed in Table B3.