



IEEE Guide for the Dielectric Frequency Response Measurement of Bushings

IEEE Power and Energy Society

Developed by the
Transformers Committee

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STANDARDS

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Transformers Committee
of the
IEEE Power and Energy Society

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Abstract: Bushings are critical components for power apparatus as their main role is to conduct current at high voltage through a grounded barrier. Statistical studies have shown that bushing defects such as water ingress and partial discharge are among the most important causes for unexpected failures. Dielectric frequency response (DFR), sometimes also known as frequency domain spectroscopy (FDS), which involves measurement of the bushing capacitance and dielectric losses over a frequency range, is an effective method to detect deterioration of bushing insulation. This guide applies to the DFR measurement of various types of bushings either in the field or in the factory except for gas-insulated bushings.

Keywords: dielectric frequency response (DFR), dissipation factor, moisture, frequency domain spectroscopy (FDS), IEEE C57.12.200™, OIP bushing, power factor, RIP bushing, RIS bushing, transformer bushing

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Introduction

This introduction is not part of IEEE Std C57.12.200–2022, IEEE Guide for the Dielectric Frequency Response Measurement of Bushings.

Bushings are critical components for power apparatus as their main role is to conduct current at high voltage through a grounded barrier. Statistical studies have shown that bushing defects such as water ingression and partial discharge are among the most important causes for unexpected failures. Dielectric frequency response (DFR), sometimes also known as frequency domain spectroscopy (FDS), which involves measurement of the bushing capacitance and dielectric losses over a frequency range, is an effective method to detect deterioration of bushing insulation. This guide applies to the DFR measurement of various types of bushings except gas-insulated bushing either in the field or in the factory.

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IEEE Guide for the Dielectric Frequency Response Measurement of Bushings

1. Overview

1.1 Scope

This document provides guidelines for performing a bushing dielectric frequency response (DFR) measurement either in the field or in the factory. The measurement technique, measuring equipment requirement, and interpretation of results based on comparison are included in the normative text.

Additional theories related to DFR such as temperature correction using the Arrhenius equation, influence of voltage, and a few case studies are described in the annexes.

1.2 Purpose

The purpose of this guide is to provide a diagnostic tool for bushing condition evaluation in the field to reduce unexpected transformer failures and unplanned outages. Bushing manufacturers performing the DFR measurement on a bushing during the factory acceptance or transformer commissioning test could act as a baseline signature that is compared with the results obtained later. Given the same test conditions, the trending of the insulation condition can be observed through comparison. This process gives the test engineers an additional way to identify defects in the bushing insulation system at an early stage.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall equals is required to*).^{6, 7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should equals is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may equals is permitted to*).

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

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The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 510™, IEEE Recommended Practice for Safety in High-Voltage and High-Power Testing.^{8,9}

IEEE Std C57.152™, IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹⁰

bushing: An insulating structure, including a through conductor or providing a central passage for such a conductor, with provision for mounting on a barrier, conducting or otherwise, for the purpose of insulating the conductor from the barrier and conducting current from one side of the barrier to the other.

bushing test tap (tanδ tap): A connection to a conducting layer of a capacitance-graded bushing for measurement of partial discharge, power factor, and capacitance values.

bushing voltage tap: A connection to a capacitance layer that divides the layers into sections C_1 and C_2 such that the capacitance-graded internal insulation forms a voltage divider, which when connected to other equipment to safely control the output voltage, can be used to measure the voltage applied to the bushing's high-voltage terminal.

NOTE—Additional equipment can be designed, connected to this tap, and calibrated to indicate the voltage applied to the bushing. This tap can also be used for measurement of partial discharge, power factor, and capacitance values.¹¹

composite bushing: A bushing with an insulating envelope consisting of a resin impregnated fiber tube with or without a rubber compound covering.

dielectric frequency response (DFR): The representation of dielectric response in the frequency domain.

NOTE—See IEEE Std C57.161™-2018 [B6].¹²

dissipation factor (dielectric): The tangent of the phase angle between a pure capacitive current component that leads the sinusoidal voltage applied across a dielectric (or combinations of dielectrics) by 90 degrees and the resulting current through the dielectric system.

⁸The IEEE standards or products referred to in [Clause 2](#) are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

⁹IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹⁰*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹¹Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

¹²The numbers in brackets correspond to those of the bibliography in [Annex H](#).

frequency domain spectroscopy (FDS): Response curves of dielectric parameters such as dielectric coefficient and power factor with frequency.

main capacitance (of a capacitance graded bushing) C_1 : Capacitance between the high-voltage conductor and the voltage tap or the test tap (if no voltage tap is present).

oil-impregnated paper-insulated bushing (OIP): A bushing in which the internal insulation consists of a core wound from paper and subsequently impregnated with oil. The core is contained in an insulating envelope, the space between the core and the insulating envelope being filled with oil.

power factor (of insulation): The ratio of the power dissipated in the insulation, in watts, to the product of the effective voltage and current, in volt-amperes, when tested under a sinusoidal rms voltage and prescribed conditions.

NOTE—The insulation power factor is equal to the cosine of the phase angle between the voltage and the resulting current when both the voltage and the current are sinusoidal.

resin-bonded paper-insulated bushing (RBP): A bushing in which the internal insulation consists of a core wound from resin-coated paper. During the winding process, each paper layer is bonded to the previous layer by its resin coating, and the bonding is achieved by curing the resin.

NOTE—A resin-bonded paper-insulated bushing may be provided with an insulating envelope; in which case, the intervening space may be filled with another insulating medium.

resin-impregnated paper-insulated bushing (RIP): A bushing in which the internal insulation consists of a core wound from untreated paper and subsequently impregnated under vacuum with a curable resin.

NOTE—A resin-impregnated, paper-insulated bushing may be provided with an insulating envelope; in which case, the intervening space may be filled with another insulating medium.

resin-impregnated synthetic—insulated bushing (RIS): A bushing in which the internal insulation consists of a wound core of synthetic polymer and (subsequently) impregnated with a filled or an unfilled curable resin.

tap capacitance (of a capacitance graded bushing) C_2 : The capacitance between the voltage tap or test tap and the flange (ground) and typically referred to as C_2 .

3.2 Acronyms and abbreviations

DF	dissipation factor
DFR	dielectric frequency response
DGA	dissolved gas analysis
FDS	frequency domain spectroscopy
GST	grounded specimen test
HV	high voltage
LV	low voltage
OIP	oil-impregnated paper
PF	power factor
RBP	resin-bonded paper bushing
RIP	resin-impregnated paper
RIS	resin-impregnated synthetic

rms	root mean square
UST	ungrounded specimen test

4. Principle and application of the DFR measurement

4.1 Overview

The dielectric response measurement is a nonintrusive, nondestructive off-line testing technique developed as an advanced insulation diagnostic tool for power apparatus. The representation of dielectric response in the frequency domain is termed DFR, also known as FDS. The results can be displayed as capacitance and power factor as a function of frequency. The power factor reflects the loss characteristics determined by polarization and conduction phenomena of insulating materials. The DFR measurement on power transformers has been widely used to determine the moisture content of solid insulation and the conductivity of liquid insulation. It has also been used to detect other anomalies.

Application of DFR measurement on bushings has been successful in many cases where defects were not detected by other methods. The bushing insulation system consists of a composite dielectric media, oil-paper, resin-paper, or resin-synthetic material. Thorough research activities have been carried out, and extensive experiences have been gained for DFR testing on OIP bushings. The defects of other bushing types (e.g., RBP, RIP, and RIS bushings) may also have significant influence on the DFR results. More studies are required to verify such influence.

4.2 Use of DFR

In principle, the DFR testing is like the well-known capacitance and power factor testing. The power factor testing measures the capacitance and loss at one specific frequency (or frequencies close to line frequency 50/60 Hz). For a DFR measurement on bushings, the capacitance and power factor are measured over a wide frequency range, typically from an upper limit of 1 kHz down to a lower limit of 10 mHz.

The frequency range may be subject to change depending on the thermal conditions of the insulation under test, as well as on the environmental interferences. One can obtain the same amount of insulation condition information with an increased low-frequency limit at higher insulation temperatures so that time can be saved, and the results are less affected by interference. However, more experience is still needed to determine the optimum frequency range in various conditions.

Condition trending of the bushing insulation systems, regardless of single or composite insulating materials, can be more clearly observed from the change of DFR traces than a single point (line frequency). In addition, some defects have more dramatic influence on power factors at lower frequencies, which is difficult to identify at line frequency.

4.2.1 Theoretical basis for measured parameters

The capacitance of a parallel-plate capacitor with vacuum in between can be expressed as in [Equation \(1\)](#).

$$C = \frac{\varepsilon_0 \times S}{d} \quad (1)$$

where ε_0 is the permittivity of vacuum and its value is $8.854 \times 10^{-12} F/m$. S is the area of the plate, and d is the distance of two plates. If the vacuum space is filled with some dielectric material, the capacitance value will change accordingly, which is given by [Equation \(2\)](#).

$$C = \frac{\varepsilon_0 \times \varepsilon_r \times S}{d} \quad (2)$$

where the term ϵ_r is the relative permittivity of the insulating material representing the ratio of permittivity of the material, relative to the permittivity of the vacuum (see [Annex A](#)). The relative permittivity, and the capacitance according to [Equation \(2\)](#), vary with frequency and aging. The change of capacitance is an important property in terms of DFR assessment of bushings. Relative permittivities of some typical insulating materials are 1.0 for vacuum/air, 2.2 for mineral oil, and 80 for water (20 °C). The relative permittivities of oil-and/or resin-impregnated paper are typically in the range of 2 to 4, which are dependent on the manufacturing processes.

In addition to the capacitive characteristic, loss occurs when the insulating material is subjected to an electric field. This field is due to conduction of free charge and movement of electric dipoles constructed by positive and negative charges of atoms. Dielectric loss explains how fast electrical energy is transformed into heat and often represents the quality of the insulating material. In the presence of an external electric voltage, the capacitive current component I_C starts to flow, which leads the test voltage by 90°. The resistive current component I_R represents the dielectric loss of the insulating material, and it is in phase with the test voltage ([Figure 1](#)).

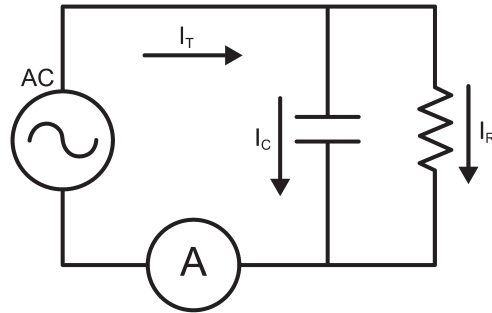


Figure 1—Equivalent electric circuit model of the insulating material

The capacitive current component can be calculated as shown in [Equation \(3\)](#).

$$I_C = V \times \omega \times C = 2\pi f \times C \times V \quad (3)$$

An increase of voltage or frequency requires higher output current from the test instrument. The magnitude of I_R component is very small compared with I_C for bushing insulations. A variety of factors such as aging, chemical contamination, moisture ingress, high oil conductivity, and carbon tracking may contribute significantly to the I_R component.

The definitions of PF and DF, and their relationship, are readily understood with reference to [Figure 2](#). The mathematical expressions for PF and DF are as follows in [Equation \(4\)](#) and [Equation \(5\)](#).

$$\text{Power factor} = \cos \theta = \frac{I_R}{I_T} \quad (4)$$

$$\text{Dissipation factor} = \tan \delta = \frac{I_R}{I_C} \quad (5)$$

where

$$\delta = (90^\circ - \theta)$$

PF, DF, and capacitance can be obtained whenever a single-frequency power factor or multi-frequency DFR test is performed. For insulating materials, PF and DF values are close in magnitude if the angle δ is very small (< 5 degrees or DF and PF values are below 10%).

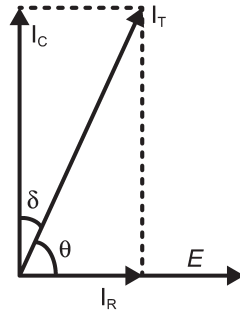


Figure 2—Vector diagram for power factor and dissipation factor

4.3 Differences between DFR and single-frequency PF testing techniques

The power factor is typically performed in the field as a routine test at 10 kV or sometimes at a voltage lower than rated voltage of the insulation system under test. The trending of the power factor value is usually monitored to assess the degree of contamination or deterioration of the insulation. Most OIP bushings in good condition show the power factor at line frequency not exceeding 0.5%. Some polymer bushings may exhibit higher power factor values than oil-impregnated bushings. Values showing accelerated increase of losses or above limits recommended by standards require further investigation. Table 1 enumerates some differences between single-frequency PF and DFR testing.

Table 1—Differences between single-frequency PF and DFR testing

Items	PF testing	DFR testing
Frequency	Line frequency or close to line frequency (50/60 Hz)	Variable frequency Typically from 1 kHz down to 10 mHz
Voltage	10 kV or below apparatus rated voltage	Not lower than 140 V rms
Measurement time	< 1 min	Typically several minutes, dependent on stop frequency
Analysis	Trending, compare with references	Compare with baseline signature and trending
Objective of test	Used to identify general deterioration of insulation	Used to detect insulation degradation or moisture ingress at an early stage

4.4 DFR measurement on bushings

DFR measures capacitance and the power factor of the bushing insulation system, and these parameters are plotted as the measurement result as shown in Figure 3. It is recommended to use logarithmic scale for both x and y axis for better presentation of the overall response. The capacitance curve usually exhibits less variation over the measured frequency range compared with that of the power factor curve.

The setup and procedure of the DFR measurement is like the power factor measurement at power frequency described in IEEE Std 62™-1995 [B3] except that measurement is performed at multiple frequencies. The advantage of frequency sweep is that it contains more information than a single-frequency point measurement. Insulation degradation or moisture ingress can be better observed from changes of the power factor trace pattern and magnitude.

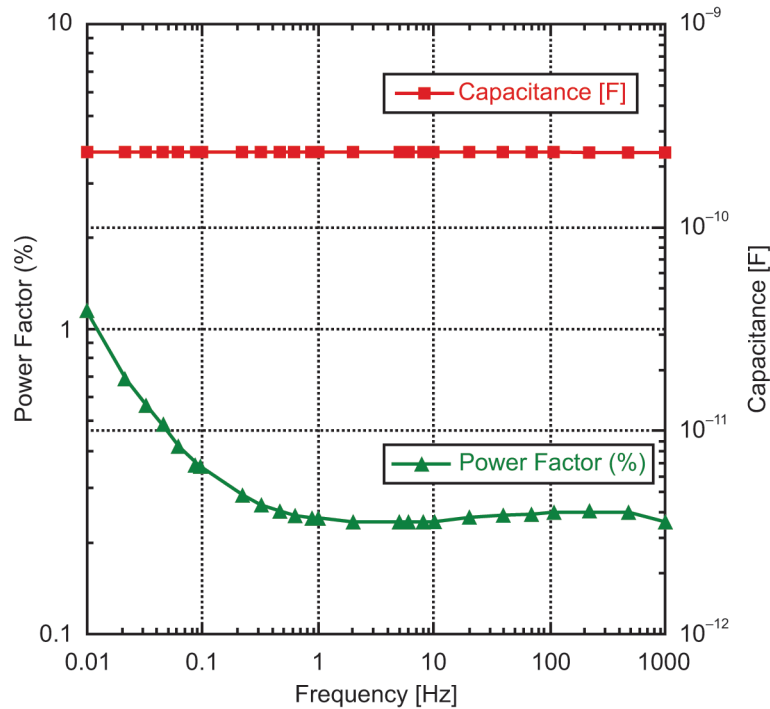


Figure 3—Typical DFR measurement result of an OIP bushing

The measurement can be performed on all types of bushings with test or voltage taps. Comparison with the reference can reveal the change of overall insulation condition. The impact of contamination and degradation is more prominent in the low-frequency range for bushings with paper insulation. Analysis of results to find the deterioration source based on the modeling of insulation materials and bushing structure is still in the research stage.

5. Safety recommendations

5.1 General safety instructions

The ground connection on the test set should be the first connection made and the last removed. Considerations of safety in bushing DFR testing apply not only to personnel but also to the test equipment and bushings being tested. This document will cover some important aspects that have to be strictly followed in practice. In addition, always comply with local and company safety regulations, such as referring to, for example, IEEE Std 510 and IEEE Std C57.152 for further information.¹³

5.1.1 Instrument safety and grounding

Before making any connections to the test object, use ground cables to ground both the test instrument and the test object to the closest substation ground. This is important for both safety and reliable measurements.

The external power source used by the test instrument should match with the specification. Do not bypass the grounding connection. Any interruption of the grounding connection may create an electric shock hazard.

5.1.2 Safety instructions in the field

The test set and the specimen to which it is connected are a possible source of high-voltage electrical energy. All personnel performing or assisting in tests shall use all practical safety precautions to prevent contact with energized parts of the test equipment and related circuits.

¹³Information on references can be found in [Clause 2](#).

Personnel engaged in the test shall stand clear of all parts of the complete high-voltage circuit. This includes all connections, unless the test set is deenergized, and all parts of the test circuit are grounded. Personnel not directly involved with the work shall be kept away from test activities by suitable barriers, barricades, or warnings.

Treat all terminals of high-voltage power equipment as a potential electric shock hazard. There is always the potential of voltages being induced at these terminals because of proximity to energized high-voltage lines or equipment.

5.1.3 Training and local regulations

All personnel performing or assisting in tests should be trained and qualified for the tests they are performing. Local safety requirements shall be followed at all times. Safety is the responsibility of the tester.

5.1.4 Grounding

The bushing flange should have very low contact resistance with the transformer tank, which should be securely grounded. The protective ground of the power source should be at the same potential with the substation ground. If a voltage potential is found between two ground systems, then additional measures described in local safety standards should be applied for personnel safety considerations. Only the bushing tap cap on the bushing being tested should be removed. All other test or voltage taps shall remain grounded during test. It is important to reinstall the cap on the bushing tap after testing.

5.1.5 Potential hazards

It is not possible to eliminate all potential hazards in electrical tests. For this reason, it is not possible to foresee every hazard that may occur in the various applications of this test. Therefore, it is essential that the tester, in addition to following the safety rules, also carefully considers all safety aspects of the test before proceeding.

5.1.6 Pacemakers

High-voltage discharges and other sources of strong electric or magnetic fields may interfere with the proper functioning of heart pacemakers. Persons with heart pacemakers should obtain expert advice on the possible risks before testing or being close to the equipment during operation.

5.2 Test safety

5.2.1 Environment

The DFR measurement can be performed both indoors and outdoors, but it is not advisable to perform the test in wet, or extreme, weather conditions (e.g., storm, rain, snow, or high humidity). Dirty and dusty environments, especially in combination with high relative moisture, may affect the DFR measurement significantly. However, if the test must be performed, it is highly recommended to clean the bushing surface thoroughly.

5.2.2 Test connections

The test object should be deenergized, isolated, and grounded before making any connections. The ground connection on the test set should be the first connection made and the last removed. Never connect the test instrument to the energized apparatus. Always disconnect test leads from the test object before attempting to disconnect them at the test set. Always use a safety ground stick to ground the high-voltage conductor. A safety ground jumper shall be installed between all terminals of apparatus under test and ground. Wearing personal protection equipment can further improve safety.

5.2.3 Voltage application

Before applying voltage, the instrument operator should call attention to others. Confirm the applied test voltage by observing the instrument or oscilloscope while testing. Use suitable means to confirm that no voltage is present when someone is connecting or disconnecting the test leads. The instrument operator should be ready to cut off the power supply at any time in case of unpredictable situations.

6. Best practices for DFR testing

6.1 Test object

This clause provides a few instructions to help ensure the measurement reliability and accuracy. It is important to record ambient conditions such as weather, altitude, relative humidity, and temperature before carrying out the measurement. It is also important to confirm that there is no crack on the bushing surface and it is free of moisture and contamination so that the surface leakage can be kept to a minimum. To obtain valid bushing DFR results, the bushing surface should be dry and clean. The cleaning procedures should follow bushing manufacturers' instructions.

Temperature has significant influence on the DFR results. In case of bushings mounted on transformers, the bushing temperature (insulation temperature) is approximated by taking the average of the ambient and transformer top-oil temperatures.

6.2 Measuring instrument

For DFR measurement instruments, the following items are recommended:

- a) The DFR test can be performed at any voltage within the normal operation range of the bushing. For power transformers, 140 V rms is typically used. However, for bushing measurement in high-interference environments, a higher test voltage is recommended to improve the noise immune performance, especially at lower frequencies (< 0.1 Hz). Refer to [Annex D](#) for more details.
- b) The typical frequency range of the measurement instrument is from 0.1 mHz to 1 kHz. Since it is time consuming and noise sensitive to perform a very low frequency measurement, a narrower frequency range (e.g., 10 mHz to 1 kHz) could be used in the field. Empirical evidence has suggested that setting the lowest frequency to 10 mHz is sufficient to detect the deterioration of bushings with paper insulations. But a DFR measurement with a broader frequency range is sometimes helpful for better detection of bushing defects. Experience has shown that a more limited frequency range in many cases was sufficient to identify changes in the bushing insulation condition. Avoid measuring at the line frequency and its harmonics. Increase of temperature helps to reveal the information below the lower frequency limit (refer to [Annex B](#)). Therefore, the stop frequency can be set higher in cases of high ambient or object temperature to save measurement time.
- c) The instrument should be able to supply enough current as per [Equation \(3\)](#). If the bushing is installed on power apparatus, the capacitance in the equivalent electric circuit may consist of both the bushing and the power apparatus. Output capability higher than 20 mA rms at power frequency is recommended.
- d) Internal protection should be provided so that instrument will not be damaged if test leads are shorted by accident.
- e) Measurement accuracy around line frequency (45 Hz to 65 Hz) should be equivalent or higher than the 10 kV power factor measurement instrument, which is 1% of reading ± 1 pF for capacitance measurement and 1% of reading $\pm 0.04\%$ for power factor measurement for capacitance above 200 pF. The instrument is supposed to be used in high-voltage substations so good interference suppression capability is recommended. Detailed calibration procedures can be referred to instrument manufacturers.

- f) Software should be equipped with selectable test configurations and connection diagrams that simplify the testing of a complex insulation system. The configurations should include ungrounded specimen test (UST) mode. The grounded specimen test (GST) mode, with and without guard, is optional for a bushing DFR measurement. Display of voltage and current waveforms by human-machine interface is a useful tool to monitor the measurement process, as well as environmental interference.

6.3 Test setup

Before the test, ambient temperature should be recorded. If the bushing is mounted on a transformer or other apparatus, the top oil temperature should be recorded as well. In addition, other environmental conditions such as humidity and weather (if the measurement is performed outside) should also be recorded.

The windings on which the tested bushings are installed shall be short-circuited including the neutral, if available. All other windings accessible through bushing terminals shall be shorted and grounded. As an example, if an HV side bushing is being tested on a two-winding transformer, the HV side shall be shorted, and the LV side shall be shorted and grounded. For an autotransformer, windings that have internal electrical connections should be shorted together. Failure to short the windings correctly may introduce interference or resonance effects that might lead to erroneous results.

If a bushing to be tested is not mounted on any apparatus, an appropriate measurement setup for the particular bushing design may be advised by the test set manufacturer or the bushing manufacturer. Bushings should not be tested in the shipping container. Generally, it is advisable to mount the bushing vertically on an oil vessel to suppress surface leakage currents on the oil side. It should not be placed horizontally or adjacent to ground. If the oil vessel is not available in the field, mount it vertically on a metallic rack and ground the bushing flange to a solid station ground. In addition, under some special circumstances, a guard ring may be needed to improve the results. It is important to record the test conditions for comparison purpose.

7. Test connection

7.1 Test mode

The main capacitance C_1 of a bushing is the capacitance between the high-voltage conductor and the voltage tap or the test tap. The capacitance C_2 of a condenser bushing is the capacitance between the voltage tap and the outermost grounded condenser layer or the test tap and the mounting flange (ground). In most cases, only the main capacitance C_1 is recommended to be used for bushing insulation condition assessment. The reason is that the dielectric property of C_1 is strictly controlled by design and mainly dependent on the condition of the bulk insulation, whereas the dielectric property of the tap capacitance C_2 is not dependent only on the insulation condition.

7.1.1 Ungrounded specimen test

The UST configuration is used to measure a test specimen with both terminals ungrounded, or that can be removed from ground. In the UST configuration, voltage is applied to the generator lead and current flowing through the measurement lead is measured for capacitance and loss calculation as shown in [Figure 4](#).

A stray capacitance C_s might be present due to external factors such as capacitively coupled resistive paths from bushing terminal to ground. By connecting the bottom terminal of C_2 to instrument guard (GND terminal for the UST configuration), stray current can be excluded from the measuring circuit and thus only C_1 is measured.

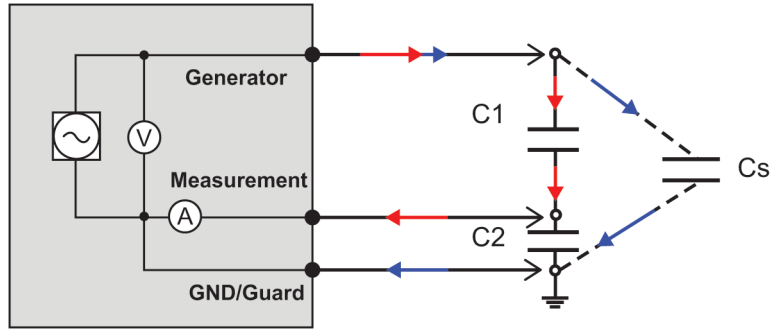


Figure 4—UST with guard measurement configuration

7.1.2 Grounded specimen test

The GST configuration is used to measure a test specimen with an ungrounded terminal and a grounded terminal(s). In GST without guard configuration, currents flowing through the GND lead and measured by the instrument include a stray component (see Annex C).

In GST with guard configuration, the guard lead allows the unwanted current component to bypass the measuring circuit. Only the grounded capacitor C_2 is measured while the stray current component flowing through the guard lead is not measured, as shown in Figure 5.

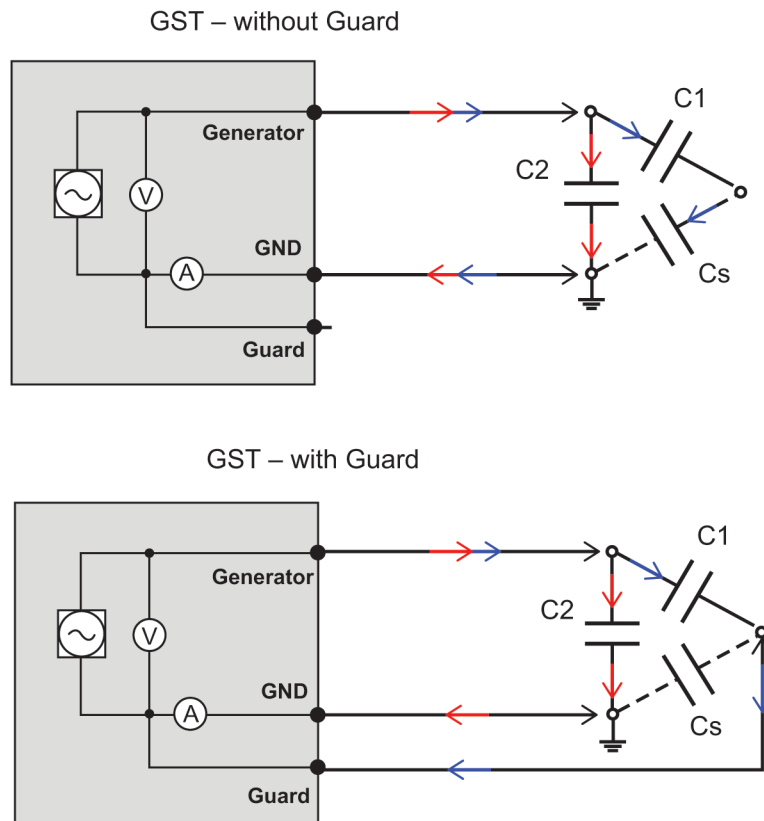


Figure 5—GST measurement configurations, with and without guard