Best Practices for HV Bushing Condition Assessment

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Introduction

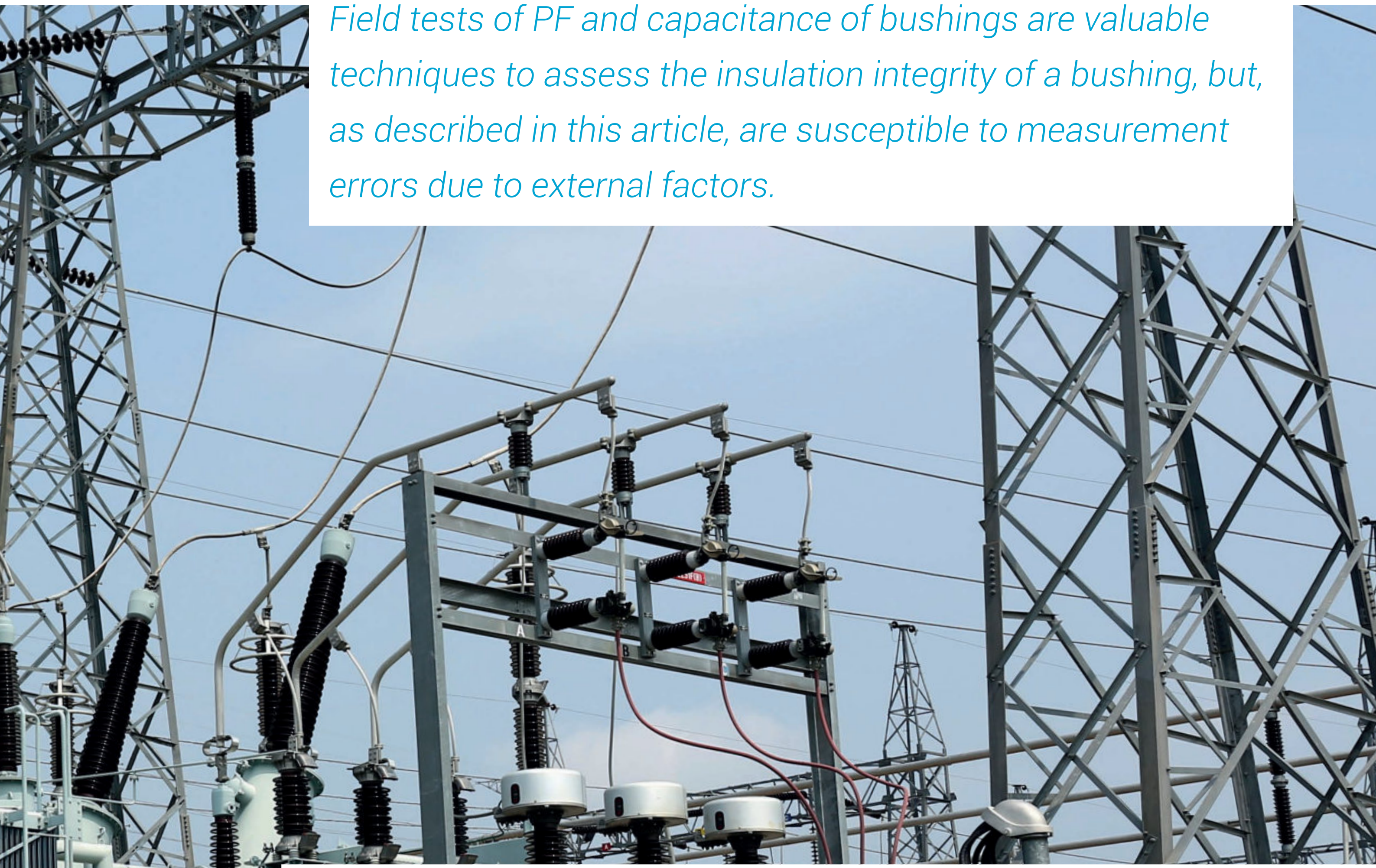
Bushings are the means by which electric power passes to and from different electrical devices, as they provide a point of interface for electrical voltage to be applied and current to pass to and from an electrical apparatus. The bushing's main function of allowing the current to pass through the apparatus cannot be achieved without the bushing's ability to insulate the main conductor from ground.

Construction of bushings includes condenser and non-condenser types. Most high voltage bushings today are of the condenser oil impregnated paper (OIP) type. OIP type bushings are susceptible to failure due to aging, contamination and deterioration of its composite insulation system, therefore a non-intrusive and non-destructive testing technique capable to evaluate changes of the dielectric properties in the inner insulation of the bushing is vital for power system operators and manufacturers of HV equipment.

In general terms the tests that are performed on bushings during maintenance include conductor and connections integrity (low resistance measurements), infrared inspections–usually to determine the oil level of the bushings and insulations tests, including Power Factor (PF), capacitance measurements, Dielectric Frequency Response (DFR), and in some specific cases, Dissolved Gas Analysis (DGA) and Partial Discharge (PD).

This article covers exclusively best practices to carry out PF and capacitance tests on OIP type bushings.

> *Field tests of PF and capacitance of bushings are valuable techniques to assess the insulation integrity of a bushing, but, as described in this article, are susceptible to measurement errors due to external factors.*



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Power Factor Testing and Setups

OIP bushings are designed as a capacitive divider with many capacitors, grouped by a tap connection, in two main capacitances or as two capacitors C1 and C2, which values are usually indicated by the manufacturer on the bushing nameplate. The tap connection, depending on its constructive characteristic, is classified as a test tap or a voltage tap.

Lower voltage bushings do not require a tap and the capacitance, C, of a bushing without a voltage or test tap is the capacitance between the high voltage conductor and the mounting flange (ground).

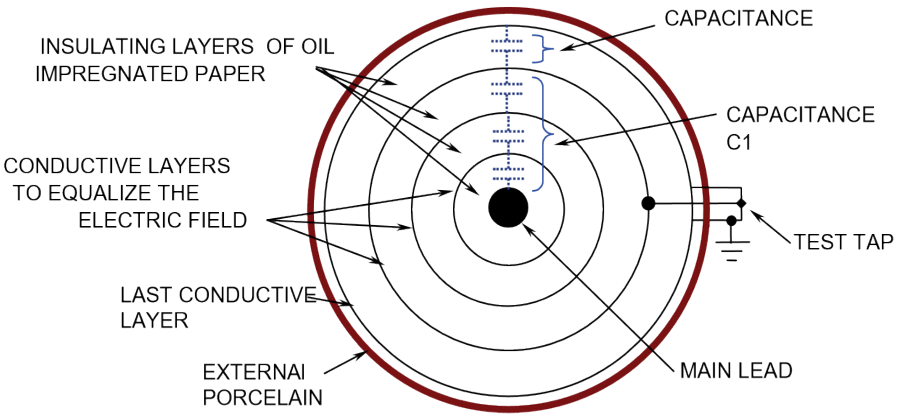

Figure 1. Modeling the OIP bushing as a set of capacitive layers

The C1 capacitance, is the main insulation of the bushing and is measured between the high-voltage conductor and the voltage tap or the test tap. The capacitance C2, is the insulation layer between the tap and mounting flange (ground), and it is regularly shorted during normal operation or connected to a potential measurement device for online monitoring or as auxiliary power. If there is no tap, the PF testing is performed using the hot collar technique, described hereinafter.

PF and capacitance measurements of C1 and C2 are performed sharing the same test setup: all the bushings of each side (voltage level of the transformer) should be isolated and shorted. All groups of untested bushings should be grounded.

The test is typically done at line frequency, at 10kV for C1, and 500-2000V for C2, or at the voltage suggested by the bushing manufacturer depending on the application. Before applying a test voltage to the tap, the maximum safe test voltage must be known and observed. Only the tap cover for the bushing to be tested should be removed.

For C1 measurements, the test is conducted in the UST test mode which eliminates the losses leaking to grounded portions of the bushing.

Measurements on C2 use GST-g test, energizing the tap and measuring the losses leaking from the tap to ground.

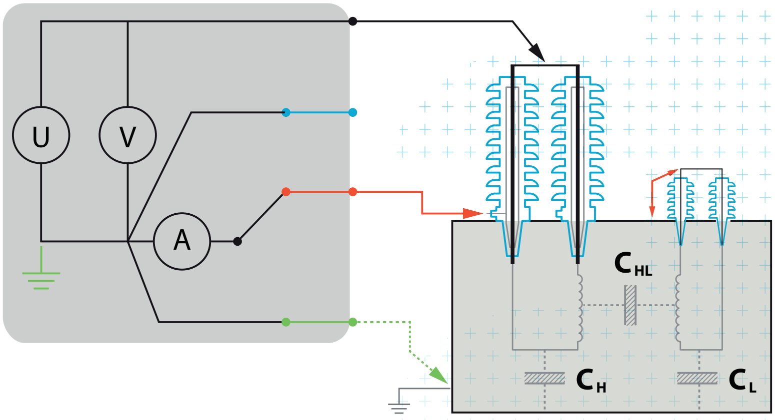

Figure 2. Setup for C1 power factor and capacitance measurement using UST-R test mode

This measurement is not appreciably affected by connections to the bushing center conductor.

For bushings not equipped with either a test tap or a voltage tap, the main field measurement which can be performed is the hot collar test which generates localized high-voltage stresses through the various sections of any bushing or pothead, so the dielectric losses can be measured. This is accomplished by applying the voltage to a conductive collar band designed to fit closely to the porcelain surface, usually directly under the top petticoat. The bushing center conductor is grounded by connecting it to the red cable and using the GST-GND test mode, which measures the overall losses leaking to both, the center conductor and ground.

The test provides a measurement of the losses in the section directly beneath the collar and is especially effective in detecting conditions such as voids in compound filled bushings or moisture penetration since the insulation can be subjected to a higher voltage gradient than can be obtained with the normal bushing tests.

Following the best practices outlined in this article will help an individual to either find the cause of an abnormal reading or to ensure those results are an indication of a deteriorated insulation system, or an actual failure.

Analysis of PF & Capacitance Results

The evaluation of the results of power factor measurements is done by comparison with standard defined limits or trending of historic values. Such limits are different depending on the type of bushing and are defined at a specific test voltages and frequency. Table 1 shows the accepted IEEEC57.19.01 and IEC 60137 standard limits for PF values for OIP bushings. Typical values for new bushings range between 0.2 and 0.4%

A change of the PF can indicate problems such as moisture ingress, degradation, carbonized parts or bad contacts. According to CIGRE 445 a doubling of the initial PF value warrants either more frequent monitoring or replacement.

A change in capacitance could indicate a breakdown between capacitive layers. An increase of 10% in the value of capacitance from the nameplate value could warrant replacement of the bushing.

IEEE C57.19.100 indicates that any bushing exhibiting progressive increase of PF values should be considered for investigation and potential removal from service. The guide also states that some bushing manufacturers consider an increase between 1.5 and 2 times the initial reading to be significant. Therefore, it is good practice to address a progressive increase of PF values with the manufacturer. Regarding capacitance, the guide considers an increase in capacitance of 5% or more over the initial/nameplate value to be cause of investigation.

Field Challenges

Testing in the field brings a number of challenges and it is not uncommon to obtain unexpected results. Typically, the first suspect is the test instrument. One common troubleshooting technique, if there is any doubt about the PF test set, is to perform an open-air test, which is commonly described in the user manual of the instrument and includes expected results. An additional test to verify the instrument is to measure a reference capacitor.

Once the test set has been verified and confirmed its optimal operation, the next step is to verify the test modes utilized in PF testing: UST, GST-g, and GST-GND.

Finally, the field is not always an ideal place for testing and external factors influencing the measurements must be considered, especially: temperature, moisture, contamination, and handling of the tap.

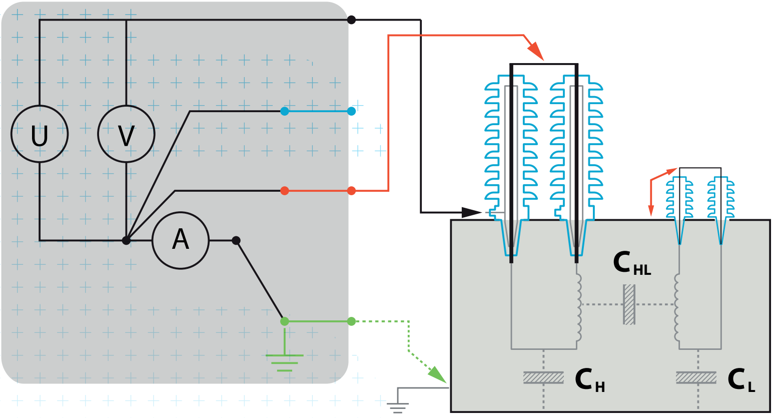

Figure 3. Setup for C2 power factor and capacitance measurement using GST-g test mode

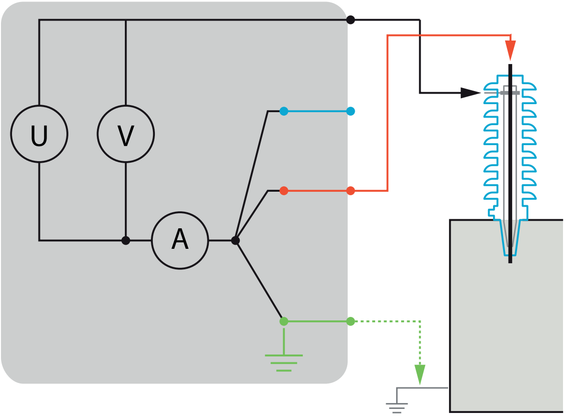

Figure 4. Setup for hot collar measurement using GST-GND test mode

REFERENCE	Test Voltage	Maximum acceptance PF/DF value %	Temperature (°C)
IEC 60137	1.05*Um/(1.73) and Um	0.7	10 to 40
IEEE C57.19.01	Typically 10 kV for C1	0.5	Corrected to 20°C

Table 1. International standards PF acceptance limits

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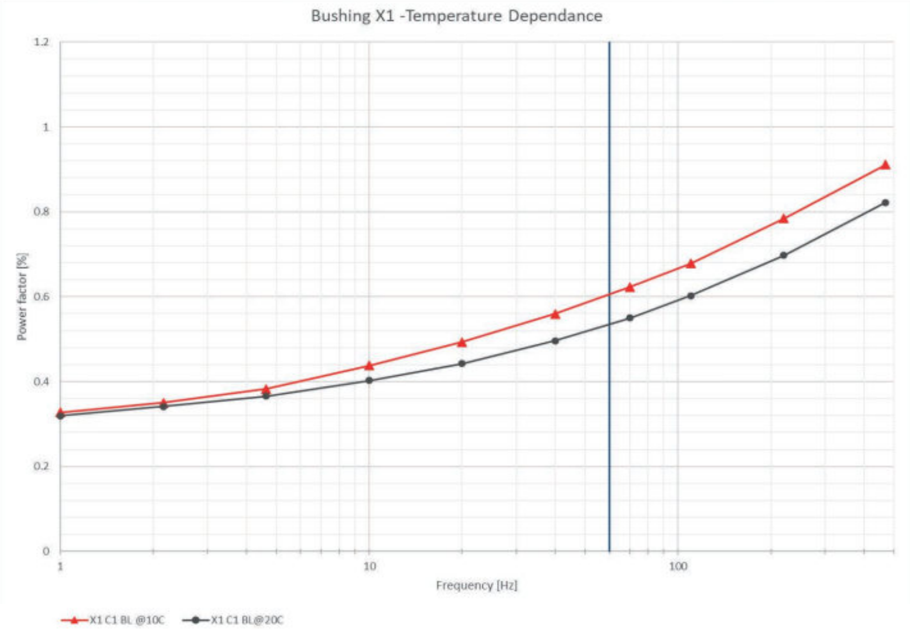


Figure 5. Example of bushing PF temperature dependence

Estimating the Temperature of the Bushing

Although PF measurements are obtained from accurate instruments, results need to be corrected to 20°C for trending analysis and comparison against nameplate data. Temperature correction is highly dependent on insulating material and its structure, ageing condition, presence of moisture or contamination, so that a fixed correction factor from a reference table may introduce some error in the corrected value by over or undercompensating. An alternate correction method is the Individual Temperature Compensation (ITC), which calculates an accurate correction factor based on a variable frequency PF measurement and

> *Another important source of measurements error is the temperature dependency of PF, which can be accurately corrected using the ITC method.*

the fact that a power factor at a certain temperature and frequency corresponds to a measurement made at different temperature and frequency.

Despite the method, proper determination of the bushing temperature is required to avoid introducing a higher error in the corrected value. Since there is no direct measurement of the bushing temperature, it must be estimated, and the recommended approach is calculating the average from the transformer top oil temperature and the ambient temperature.

It is common practice to consider 0°C (32°F) to be the lowest temperature acceptable for testing. Dielectric testing has been performed below this value, but special attention must be given to the results obtained. It is always recommended to discuss results with the manufacturer.

Temperature correction factors for specimens at high temperatures (above 40°C) may be limited by the reference tables; however, ITC provides accurate correction of C1 PF at a wide range of temperatures, even greater than 55°C.

Correct Handling of the Capacitance Tap for C1 and C2 Measurements

In a capacitance graded bushing, the test tap is a component which main purpose is to provide access to measure the bushing capacitance and power factor. The voltage tap, in addition, can be used for permanent voltage measurement or online monitoring of PF or partial discharge.

When testing the bushings of a transformer, it is advised that all bushing tap caps remain installed (closed), except for the bushing or bushings under test. Since the test voltage is applied to a group of bushings, any unused test tap will have a potential difference if not grounded; the voltages that can be developed at open test taps may generate leakage current that not only can affect the PF results but severely damage a bushing and pose a safety hazard for the individuals performing the tests.

Special care should also be observed to properly connect the test leads to the capacitance tap, as in some cases, adapters are needed to be able to achieve a suitable connection while maintaining isolation from ground. These adapters are usually provided by the test set and/or bushing manufacturer.

In addition to that, make sure that the tap is properly connected, and it is not loose.

Effective Grounding and Shorting Techniques

When performing power factor and capacitance measurements on bushings of a transformer—both single and three-phase—it is a well known practice to short all the bushings of the same group (same voltage level) together, to form an equipotential section of the transformer with each winding group when performing a test. See shorts (a) an (b) in Figure 6.

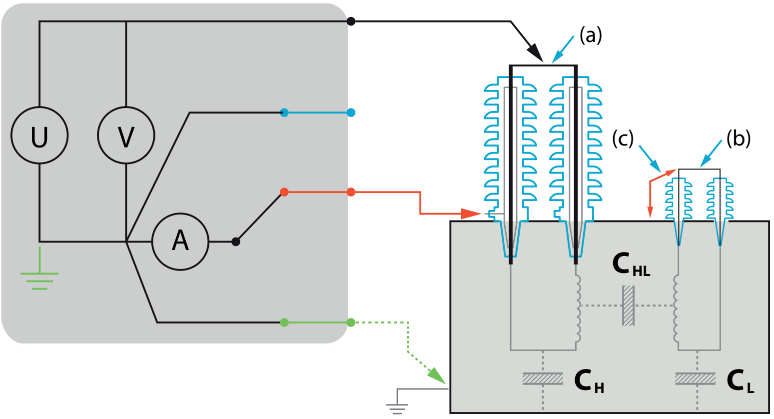


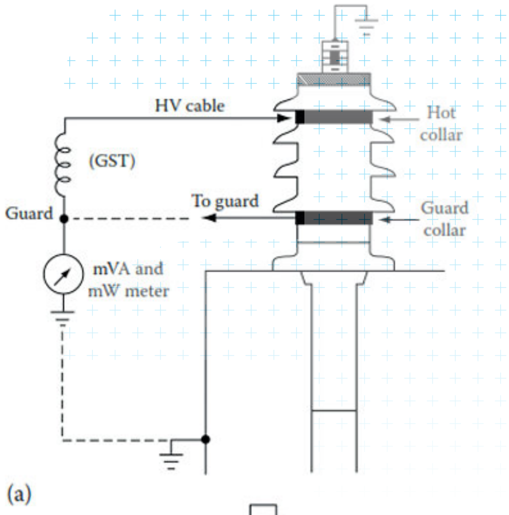
Figure 6. Effective shorting and grounding techniques

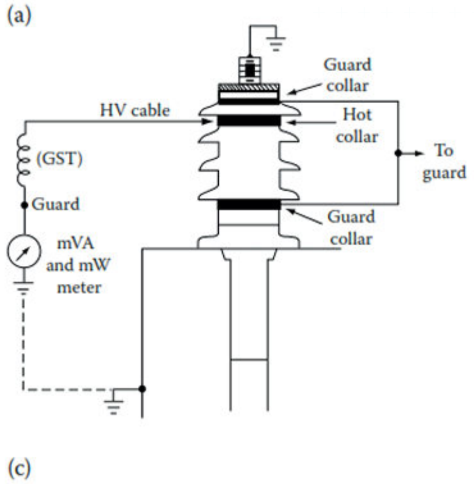
In a given test, when the test voltage is applied, all bushing of that group will be at the same potential with respect to ground due to the short between them. On groups of bushings untested, a second auxiliary connection to ground is necessary, (Figure 6, connection (c)), to avoid floating potentials to be developed on such bushings, which, just as open test taps, can be hazardous for the persons taking the measurements.

In addition to the safety factors involving shorting and grounding groups of bushings during power factor and capacitance measurements, these connections will also be useful when facing situations involving surrounding energized overhead lines and equipment, which can cause unwanted induced voltages. These voltages, in conjunction with the winding inductance of the transformer, and the stray capacitance between the windings and the bushings insulation, can lead to measurement errors.

Hot collar application

A hot collar test generates a localized high-voltage stress by using and energizing a conductive collar around the porcelain, which is useful to determine the dielectric losses (Watts and current, as PF is not analyzed) through various sections of any bushing when troubleshooting high PF results. It is useful to detect cracked porcelain, deteriorated cement joints, gasket leaks, or faults within condenser layers in condenser-type bushings and to check the oil level of oil-filled bushings when normal oil level readings has been stablished or comparing to bushings of the same type. If an abnormal mA or Watts reading is obtained when the test is performed at under the top petticoat, the test should be repeated at under the second petticoat and move further down until finding normal readings.





Hot collar test can be performed with any of the test modes, GST, GST-g, and UST, and using one or multiple collars depending on what is expected to achieve with the troubleshooting, as per the images below, from the book, Electrical Power Equipment Maintenance and Testing by Paul Gill.

The general guidelines to evaluate hot collar data are as follows:

- Watts Loss
    - <100 mW - Acceptable
    - ≥100 mW - Unacceptable, possible contamination
- Current
    - Within 10% of similar bushings - Acceptable
    - <10% of similar bushings - Unacceptable, low level of liquid or compound, possible faults within condenser layers

NBDFR, an Alternative Technique for Results Validation

It is common with PF results that after troubleshooting, the result is still not satisfactory, it is slightly high compared to the reference values or the trend, and the main conclusion is to investigate further. The Narrow Band Dielectric Frequency Response (NBDFR) technique is an alternative method to troubleshoot and investigate inconclusive PF results. It consists of multiple PF tests at different frequencies in a range of 1 to 500 Hz. Incipient or emerging changes of the resistive losses at 60 Hz PF are too small in comparison to the capacitive component, which is proportional to the frequency, of the total current.

The example in Figure 8, illustrates a case of four LV bushings exposed to the same loading/thermal profile and environment. The 60 Hz results are below 0.5% and almost identical, the evaluation of this result will not trigger any investigation or action. The NBDFR result shows that X3 has higher losses, yet unnoticeable at 60 Hz; enabling an individual to decide on proper remedial actions.

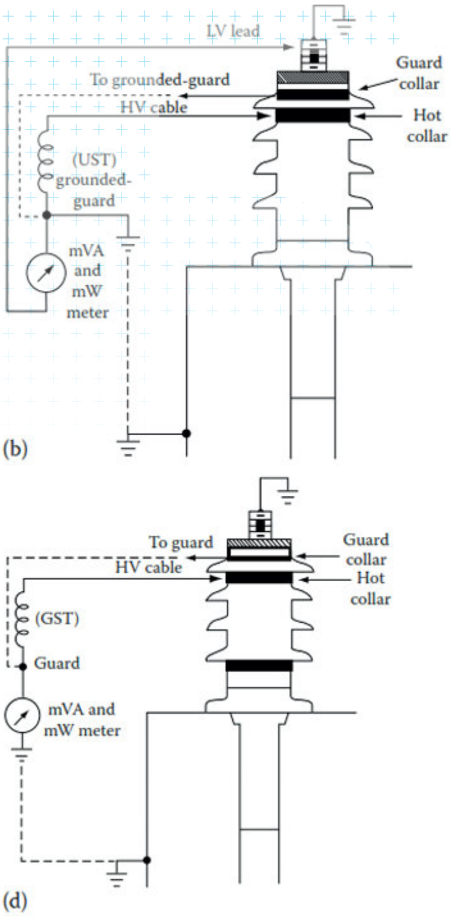


Figure 7. Hot collar test setup in: (a) GST mode; (b) UST mode; (c) guard mode, guard above and below; and (d) guard mode, guard above

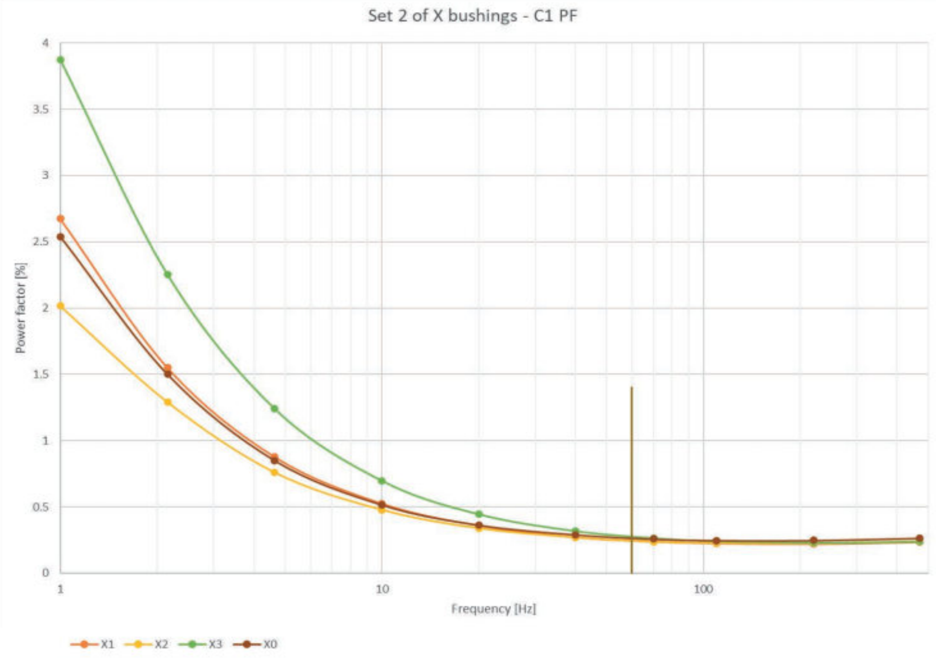


Figure 8. NBDFR on four OIP bushings

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> *Alternative test procedures such as NBDFR measurements, provide extra information about the condition of the insulation system, thus enabling the user to make a deeper and more informed analysis of the results.*

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Conclusion

Field tests of PF and capacitance of bushings are demonstrated to be very valuable to assess the insulation integrity of a bushing, but, as described in this article, are susceptible to measurement errors due to external factors. Following the best practices outlined in the previous paragraphs, will help an individual to either find the cause of an abnormal reading or to ensure those results are an indication of a deteriorated insulation system, or an actual failure. Another important source of measurements error is the temperature dependency of PF, which can be accurately corrected using the ITC method. Additionally, alternative test procedures such as NBDFR measurements, provide extra information about the condition of the insulation system, thus enabling the user to make a deeper and more informed analysis of the results.

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