INSULATION POWER FACTOR TESTING
of
POWER TRANSFORMERS

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RESUME

This paper discusses the dissipation factor measurements that can be carried out on the insulation of power transformers during routine maintenance procedures. This presentation includes a definition of terms, outlines measurements and calculations to be performed and discusses the interpretation of test results.

INTRODUCTION & DEFINITIONS

Capacitance.

Capacitance of a system is defined by the magnitude of charge that it can store at a given voltage. The charge is proportional to the area of the conductive plates, the dielectric constant of the insulating material between the plates and inversely proportional to the distance between them (Figure 1). Vacuum and air have a dielectric constant of 1 and all other insulating materials have a dielectric constant larger than 1.

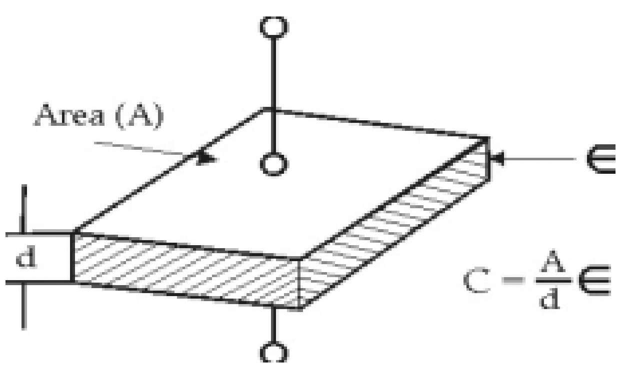
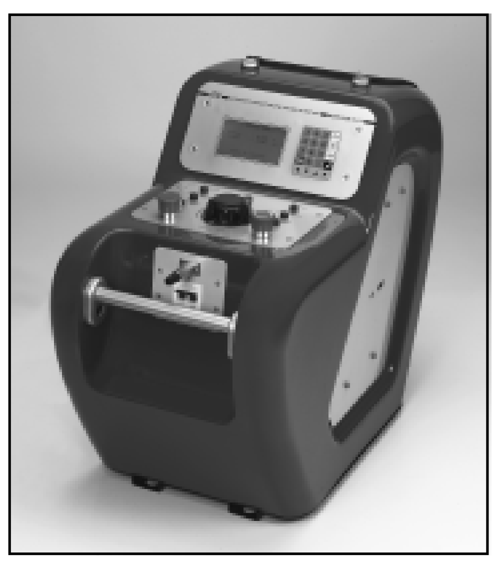


Figure - 1
Capacitance



Power Factor, Dissipation Factor, Tan Delta.

The Power Factor in a circuit is defined as the ratio of power to volt-amperes (W/VA). Power Factor is also defined as the cosine of the angle between the voltage and current in a circuit, with the angle typically referred to as 'theta'. This angle is typically very close to 90 degrees for capacitive (insulation) circuits.

Dissipation Factor is defined as the ratio of power to reactive volt-amperes (W/VAr) in a circuit. The Dissipation Factor is equal to the tangent of 'Delta', where 'Delta' is the angle of 90^{O} minus 'theta' (Figure 2 for clarification).

For practical insulation circuits, where 'theta' is larger than 85^{O}, the Power Factor and the Dissipation Factor are numerically the same.

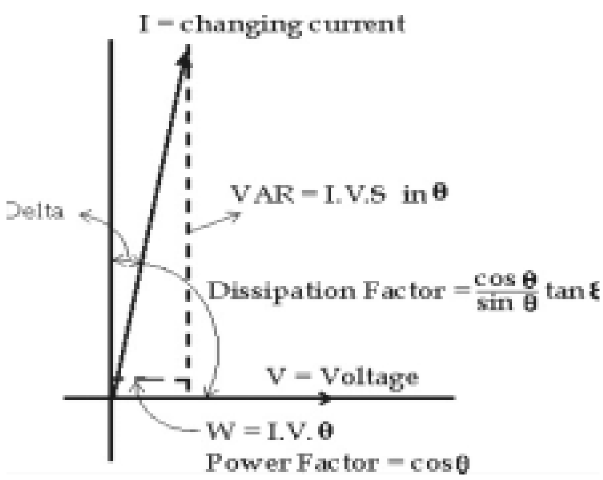


Figure - 2

Power Factor / Dissipation Factor

Grounded Specimen Test.

The Grounded Specimen Test (GST) is referred to as the measurement of an insulation sample that has one of its terminals grounded. To conduct a GST test, the measuring circuit of the instrument used must be ungrounded to make the measurement possible. As most pieces of electric power system equipment is grounded, the grounded specimen test must be used if the equipment is to be tested in the installed condition. GST is therefore the most important and most frequently used test. Most up-to-date test equipment also offer a grounded specimen test with guard-GSTg. This connection allows one to measure one component of a multi-component, grounded, insulation system.

Ungrounded Specimen Test.

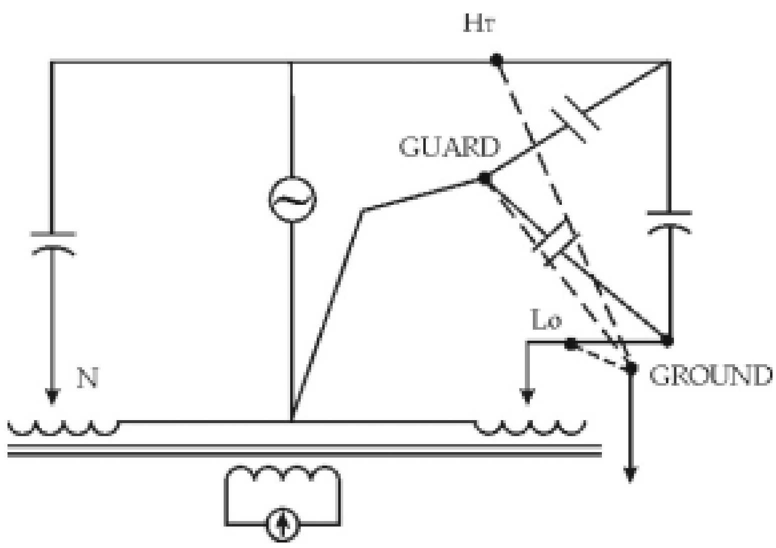
The Ungrounded Specimen Test (UST) is referred to as the test of an insulation sample that is not grounded. This test configuration automatically provides a 'guard' connection that can be used effectively to measure only one component out of a multi-component insulation system. The UST is of great advantage as its 'guard' connection is also 'ground'. This means that anything that is grounded in a UST measurement is automatically excluded from the measurement.

Cold Guard / Hot Guard Measurements.

Cold guard or hot guard connections refer to the potential of the 'guard' terminal or connection. When the guard potential is at or near ground potential, then it is referred to as a 'cold guard'. The UST configuration, providing a guard that is also a ground, is therefore a 'cold guard' connection.

When using the GST connection, the 'guard' potential may be at or near ground potential (cold guard), or at the test potential (hot guard), depending on the configuration of the test equipment. In practice, the 'cold guard' configuration is typically used in test equipment operating at higher voltage, and the 'hot guard' is used in test equipment operating at low voltage. This is so because of safety considerations, where test personnel may inadvertently mistake the 'hot guard' terminal as being at ground potential.

The primary advantage of the 'hot guard' connection is that it is more tolerant of interference that is typically encountered in a field test situation. See Figure 3 for UST, GST, Cold Guard & Hot Guard connections. It must be pointed out that typical measuring instruments will feature either the Hot Guard or the Cold Guard connection, not both.



1. UST = GUARD = GROUND, COLD GUARD
2. GST = LO = GROUND, COLD GUARD
3. GST = HI = GROUND, HOT GUARD

Figure - 3 Transformer Ratio Arm Bridge

Power Loss.

Power loss or watts loss is the colloquial term often used in connection with insulation measurements and refers to the power being dissipated in the insulation. It is the product of the test voltage, the test current and the cosine of 'theta'. It is typically used for test specimen that have small capacitance and as a result the power factor (tan Delta) of the test circuit is rather high. The 'power loss' is also a very convenient number when checking the accuracy of measurements.

Equivalent "10kV value".

Capacitance, Power Factor and Dissipation Factor are terms that are not affected by changes in test voltage. They can be measured without having to set the test voltage precisely. The 'power loss' or 'watts loss' values depends on the test voltage (proportional to the square of the test voltage) and therefore needs to be corrected to a 'reference voltage'. 10 kV has become the preferred 'reference voltage' when testing high voltage electric power equipment. A 'reference voltage' of 2.5 kV is often used when testing equipment rated at distribution or lower voltages.

COMPONENTS REQUIRING TESTING

General Comments.

It must be pointed out that a single measurement on a transformer typically represents several components within the transformer. For this reason it is necessary to perform certain simple calculations that will separate out individual components for comparison purposes. A good example of this is the situation where the measurement of a transformer includes the winding capacitance and the capacitance of the bushing or bushings. If one wishes to examine only the quality of the winding insulation, one must subtract the capacitance and loss of the bushings from the overall measurement.

The winding insulation of three phase transformers is typically measured together for all three phases. The reason for this is that the windings are interconnected and it is impractical to separate them for the test. It is often possible to separately measure the capacitance of each winding in the factory before the bushings are installed and connected.

Bushings.

The measurement of bushings is rather simple, provided that they are equipped with a 'test tap' or a 'Cap-Tap' as it is often referred to. All modern high-voltage bushings are equipped with this feature. If the bushing is not equipped with the 'test tap', then one must resort to other techniques to evaluate the condition of the bushing. Using the 'hot collar' method is one such technique.

The actual measurement of a bushing is typically done using the UST connection, and the 'test tap' may be connected to the test voltage or to the measuring lead. The important measurement is the 'Tap-to-conductor' capacitance. When in service, it has the system voltage applied to it. The 'Tap-to-ground' capacitance is shorted out during normal operation of the equipment and is typically not measured.

Two Winding Transformers.

The simplified schematic diagram of a two winding transformer is shown in Figure 4. It consist of three components, namely:

- ❋ The high voltage winding to ground capacitance (Ch-g),
- ❋ The high voltage to low voltage winding capacitance (Ch-l),
- ❋ The low voltage winding to ground capacitance (Cl-g).

The Ch-g and Cl-g measurements include the capacitance of the appropriate bushings. The Ch-g measurement includes the capacitance of the HV bushing and the Cl-g measurement includes the LV bushing. It is IMPORTANT to note that the Ch-l measurement does not include the bushings as the capacitance of the bushings is connected to ground and is automatically removed from the measurement in the UST connection.

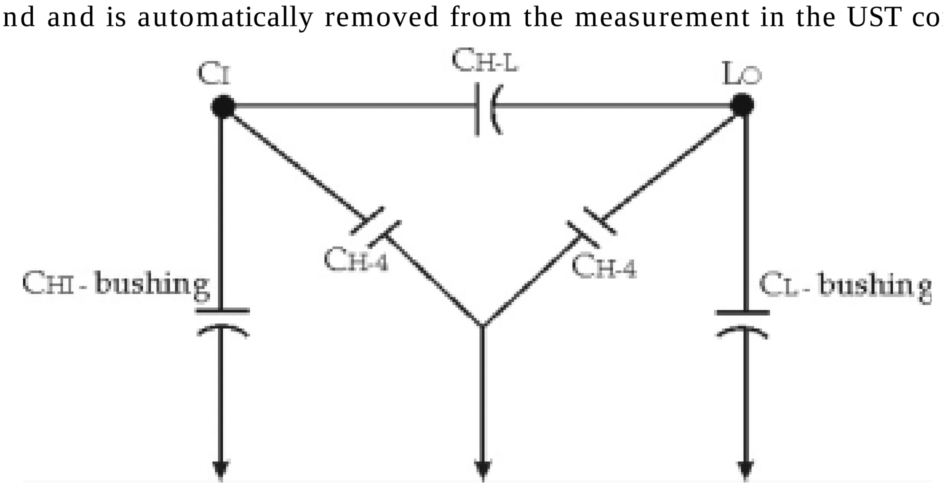
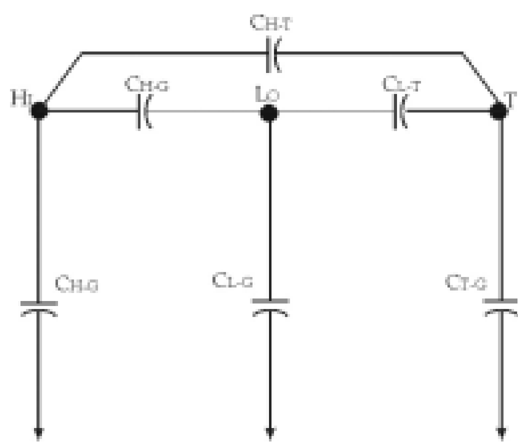


Figure - 4
2 Winding Transformers

Three Winding Transformers.

The simplified schematic diagram of a three winding transformer is shown in Figure 5. Labelling the windings in this transformer as high voltage, low voltage and tertiary, the schematic consists of six components, namely:



Note : C_{H-G}, CL_{-G} and C_{T-G} include capacitances of Associated bushings,

Figure - 5

3 Winding Transformers

- The high voltage to low voltage winding capacitance (Ch-l),
- The high voltage to tertiary winding capacitance (Ch-t),
- The low voltage to tertiary winding capacitance (Cl-t),
- The high voltage winding to ground capacitance (Ch-g),
- The low voltage winding to ground capacitance (Cl-g), and
- The tertiary winding to ground capacitance (Ct-g).

Similar to the two winding example, all the capacitances between the windings and ground (Ch-g, Cl-g, Ct-g) include the capacitances of the appropriate bushings. The capacitance and loss of the bushings need to be subtracted from the measurement if only the losses in the winding are to be examined. Again, it is IMPORTANT to point out again that the interwinding capacitances (Ch-l, Cl-t & Ct-h) do not include the capacitances of the associated bushings.

Insulating Oil.

Testing of insulating oil requires a 'oil test vessel' in addition to the power factor test set. The vessel, or 'oil test cell' is typically a three-electrode system which provides guarding against surface leakage. This is important as the test cell capacitance is small and even small leakage may cause substantial errors in measurement.

Unless the sampled oil is to be subjected to numerous other tests, it is best to directly fill the power factor test cell from the sampling facility provided on the tested power transformer. One must assure that the test cell is clean and it is a wise precaution to bleed the sampling tube to assure a representative sample.

Oil tests in the shop or laboratory would be carried out at room temperature (20^{O} C) as well as at an elevated temperature of 90^{O} or 100^{O} C. Tests at these two temperatures provides much more insight into the characteristics and quality of the oil encountered.

Testing of oil in the field is typically limited to testing at whatever temperature prevails at the test site. As the temperature may vary widely, it must be measured so that temperature correction can be applied to the results.

PREPARATION for TESTING

Isolation.

Before attempting to connect test equipment to a transformer, one must make certain that it is fully isolated and grounded. The best isolation is at the terminals (bushings) of the transformer and not at the end of a length of bus or cable. The reason for this is that every meter of bus attached to the transformer will be instrumental in attracting capacitive interference current from energised equipment in the station. As the accuracy of power factor measurement is inversely proportional to the amount of interference, it is prudent to have as little interference as possible so that the results will be most accurate and reproducible.

Another reason for isolating the test specimen at its terminals is that this avoids measuring the losses associated with the cable or bus (insulators) that may be attached to it.

Cleaning.

It is prudent to clean all insulators on a transformer prior to any measurement. This is important in coastal areas where salt may settle on insulators or in areas of heavy industrial pollution. This is especially important when the transformer bushings are not equipped with 'test taps' and have to be measured using collars.

Recording of Information.

It is very important to record all information that is relevant to the test. Such information, in addition to all test equipment readings, must include:

- The location of the station and the position of the equipment within the station.
- Make, Type and Serial Number of equipment tested.
- Condition of the test transformer regarding its temperature, oil level, tap position and mechanical appearance.
- The prevailing ambient weather conditions including Temperature, Humidity, Wind direction and velocity.

It is desirable to record ALL the information the test equipment provides. Some test equipment provides readings of capacitance, dissipation factor as well as watts loss. Recording all of this information makes calculations and double checking of the readingseasier.

It is a very good practice to standardize on a suitable 'test report' format that will guide the test personnel in providing all of the desired data.

Given in the APPENDIX are several procedures that can be used to test the insulation power factor (dissipation factor) of power transformer insulation.

INTERPRETATION of TEST RESULTS

General discussion.

Interpreting the results of Dissipation / Power Factor test is as demanding as is the measurement process. The interpretation is especially difficult in the beginning when one does not have much history on the equipment - transformer being evaluated. In the end one must admit that the evaluation of test results is as much art as it is science.

The interpretation process involves comparing the results on hand with previous results, or with the results from similar equipment.

Temperature corrections.

It must be recognised that the losses of most electrical insulation are temperature sensitive. The temperature sensitivity depends on the materials used in the insulation system, such as paper, fibreboard, oil etc. Different sources of paper or oil will exhibit different temperature characteristics.

Before any comparison or interpretation can take place, the readings must be corrected to a reference temperature of 20^{O} C. The use of a particular temperature correction table in itself may be an important decision as there are many different temperature correction curves available and used in the industry. There are different tables for different insulating oils, one North American and the other European. There are different tables for different types of insulation systems within the transformer. There are also different types of tables for different types and makes of bushings.

One must assure himself that the temperature correction one is using indeed applies to the equipment being tested. One way of avoiding the reliance on corrections is to test the equipment approximately at the same time of the year, when the ambient temperature and the loadings may be similar.

Comparison with factory tests, precious readings

When comparing to factory readings or to previous readings, one is looking for abrupt changes as well as for rending. Abrupt changes are typically investigated immediately, while the trends are watched for limits that indicate the necessity of corrective action. Dissipation Factor limits for various pieces of equipment have been determined from practice and are used as a guide for corrective action.

Some guidelines.

As a guide for those starting out in the insulation Dissipation Factor test field, one can assemble a table that can be used as a guide. This table is made up of information published by a variety of individuals as well as associations working in the field.

Dissipation Factor at 20^{O} C.

Rating	New Equipment	Used Equipment	Questionable
HV Oil	0.0005	0.005	0.01
LV Oil	0.001	0.01	0.03
<19 kV	0.01	0.03	0.09
20-80 kV	0.007	0.015	0.03
90-200 kV	0.005	0.01	0.02
210-400 kV	0.004	0.007	0.015
>400 kV	0.003	0.006	0.012

The above table must not be used blindly and without considering the occurrence of over voltages and surges on the system as well as the consequences of failure of the equipment while in service. There is no guarantee that Dissipation Factor values lower then those listed will not result in failure of the equipment.

APPENDIX

CONDUCTING THE MEASUREMENTS

Whenever making measurements, it is important to make more measurements than the bare minimum. This allows one to double check all the results on the spot and avoid repeats.

To allow for convenient measurement with the fewest possible connections, many commercial test sets provide two measuring leads and a variety of test configurations. With two measuring leads, labelled as Yellow (Y) and Blue (B), the Ground connection labelled as G, and the high voltage lead as Red (R), the following measurements are possible:

1.	UST	R - (Y+B)
2.	UST	R - B
3.	UST	R - Y
4.	GST	R - (G+Y+B)
5.	GSTg	R - G
6.	GSTg	R - (Y+G)
7.	GSTg	R - (B+G)

The listed measurements offer duplication and therefore allow one to check the results. It is suggested that all of these, plus even additional readings be taken to ascertain good results.

Connecting the Test Equipment.

To promote safety, it is recommended that the transformer to be tested be isolated and grounded by the operating personnel, using the normal utility practices. The power factor test equipment would then be connected to the transformer by the test personnel, including any shorting of windings etc. Now the grounds would be removed and the testing with commence.

As was recommended in the earlier section, it is recommended that all possible readings be taken as cross checking these readings will provide a measure of accuracy and repeatability in the measuring process. All the readings are to be entered on prepared forms or alternatively in work books.

When changing connections, it is recommended to first ground the test transformer, change the connections, then remove the grounds and continue testing.

Two Winding Transformer.

Generally speaking, the test connections listed below are designed to provide all the desired measurements with the fewest test set ups. The actual number of connections will depend on the number and ratings of bushings installed on the transformer.

Example No. 1.

This first example is that for a transformer with one HV bushing and intended for line to neutral installation on the HV side.

Test connection No. 1.

a. Remove the grounding strap from the neutral bushing of the HV winding.

b. Short the HV winding; short the LV winding.

c. Connect the RED lead to the HV bushing.

d. Connect the YELLOW lead to the LV bushing.

e. Connect the BLUE lead to the HV bushing Cap Tap.

f. Remove grounds before proceeding with measurements.

Measure all seven (7) possible combinations on the test set:

1.	(1)	R-Y	Ch-l	HV to LV capacitance.
2.	(2)	R-B	Ch-bushing,	Bushing capacitance only.
3.	(3)	R-(Y+B)	(Ch-l)+(Ch-bushing)	

4.	(4)	R-(Y+B+G)	(Ch-l)+(Ch-bushing)+(Ch-g)	
5.	(5)	R-G	Ch-g	H to Ground capacitance only.
6.	(6)	R-(Y+G)	(Ch-l)+(Ch-g)	
7.	(7)	R-(B+G)	(Ch-bushing)+(Ch-g)	

Note that this sequence measures ALL the capacitances associated with the HV winding, including the bushing. Combinations of readings allow operator to double check individual readings.

Test connection No. 2.

g. Move the RED lead to the LV bushing.
h. Move the YELLOW lead to the HV bushing.
i. Disconnect the BLUE lead.

Measure the following 3 configurations:

8.	(2)	R-Y	Cl-h	HV to LV capacitance.
9.	(5)	R-G	Cl-g	Capacitance LV to Ground.
10.	(6)	R-(Y+G)	(Cl-h)+(Cl-g)	

This example measures the 4 primary values (Ch-l; Ch-g; Ch-bushing; Cl-g) using 10 measurements. Each primary value is measured separately as well as in combination, two or mere times.

Example No. 2.

Two winding transformer with two HV bushings.

Test connection No. 1.

a. Short the HV winding; short the LV winding.
b. Connect the RED lead to the HV winding.
c. Connect the YELLOW lead to the LV winding.
d. Remove grounds before proceeding with measurements.

Measure the following 3 configurations:

1.	(1)	R-Y	Ch-l	HV to LV capacitance.
2.	(5)	R-G	Cl-g	HV to ground capacitance.
3.	(6)	R-(Y+G)	(Ch-l)+(Ch-g)	

Set up No. 2.

e. Move the YELLOW lead to the HV1 bushing tap.
f. Connect the BLUE lead to HV2 bushing tap.

Measure the following 3 configurations:

4.	(1)	R-Y	C1-bushing.
5.	(2)	R-B	C2-bushing.
6.	(3)	R-(Y+B)	C1+C2-bushings.

Additional measurements can be taken using this set up.

Set up No. 3.

g. Move the RED lead to the LV winding.

h. Move the YELLOW lead to the HV winding.

7.	(1)	R-Y	Cl-h	HV to LV capacitance.
8.	(5)	R-G	Cl-g	LV to ground capacitance.
9.	(6)	R-(Y-G)	(Cl-h)+(Cl-g)	

The No. 2 example sequence measures the 5 primary values using 9 measurements. Each capacitance is measured separately as well as in combination.

Additional examples can be cited for three phase, two winding, transformers. The complication here is that there is one or two additional bushings to deal with on the HV side. No additional complications exist if the bushings on the LV side are of low voltage rating. If the LV winding is of high voltage and has bushings with cap taps, then these need to be dealt with in the same fashion as the bushings on the HV side.

Three Winding Transformer.

For those who considered the two winding transformer example to be rather tedious, they will be thrilled by all the readings that are possible and indeed suggested for a three winding single phase transformer.

Assuming that there are bushings to be tested on the HV and Tertiary windings of the transformer, then the procedure below is suggested:

Test connection No. 1.

a. Short the HV winding; short the Tertiary winding; short the LV winding.

b. Connect the RED lead to the HV winding.

c. Connect the YELLOW lead to the LV winding.

d. Connect the BLUE lead to the T winding.

e. Remove grounds before proceeding with measurements.

Measure the following 7 configurations:

1.	(1)	R-Y	Ch-l	HV to LV capacitance.
2.	(2)	R-B	Ch-t	HV to T capacitance.
3.	(3)	R-(Y+B)	(Ch-l)+(Ch-t)	
4.	(4)	R-(Y+B+G)	(Ch-l)+(Ch-t)+(Ch-g)	
5.	(5)	R-G	Ch-g	H to Ground capacitance.
6.	(6)	R-(Y+G)	(Ch-l)+(Ch-g)	
7.	(7)	R-(B+G)	(Ch-t)+(Ch-g)	

Test connection No. 2.

f. Move the YELLOW lead to the HVa bushing tap.

g. Move the BLUE lead to HVb bushing tap.

Measure the following 3 configurations:

8.	(1)	R-Y	HVa-bushing.
9.	(2)	R-B	HVb-bushing.
10.	(3)	R-(Y+B)	HVa+HVb-bushings.

Test connection No. 3.

h. Move the YELLOW lead to the HVc bushing tap.

i Move the BLUE lead to HVn bushing tap (if applicable).

Measure the following 3 configurations:

11.	(1)	R-Y	HVc-bushing.
12.	(2)	R-B	HVn-bushing (if applicable).
13.	(3)	R-(Y+B)	HVc+HVn-bushings (if applicable).

Test connection No. 4.

j. Move the RED lead to the Tertiary winding.
k. Leave the YELLOW lead on the LV winding.
l. Move the BLUE lead to the HV winding.

Measure the following 7 configurations:

14.	(1)	R-Y	Ct-l	Tertiary to LV capacitance.
15.	(2)	R-B	Ct-h	Tertiary to HV capacitance.
16.	(3)	R-(Y+B)	(Ct-l)+(Ct-h)	
17.	(4)	R-(Y+B+G)	(Ct-l)+(Ct-h)+(Ct-g)	
18.	(5)	R-G	Ct-g	Tertiary to Gr. capacitance.
19.	(6)	R-(Y+G)	(Ct-l)+(Ct-g)	
20.	(7)	R-(B+G)	(Ct-h)+(Ct-g)	

Test connection No. 5.

m. Move the YELLOW lead to the Ta bushing tap.
n. Move the BLUE lead to Tb bushing tap.

Measure the following 3 configurations:

21.	(1)	R-Y	Ta-bushing.
22.	(2)	R-B	Tb-bushing.
23.	(3)	R-(Y+B)	Ta+Tb-bushings.

Test connection No. 6.

o. Move the YELLOW lead to the Tc bushing tap.
p. Move the BLUE lead to Tn bushing tap (if applicable).

Measure the following 3 configurations:

24.	(1)	R-Y	Tc-bushing.
25.	(2)	R-B	Tn-bushing (if applicable).
26.	(3)	R-(Y+B)	Tc+Tn-bushings (if applicable).

Test connection No. 7.

q. Move the RED lead to the LV winding.
r. Move the YELLOW lead to the Tertiary winding.
s. Leave the BLUE lead to the HV winding.

Measure the following 7 configurations:

27.	(1)	R-Y	Cl-t	LV to Tertiary capacitance.
28.	(2)	R-B	Cl-h	LV to HV capacitance.
29.	(3)	R-(Y+B)	(Cl-t)+(Cl-h)	
30.	(4)	R-(Y+B+G)	(Cl-t)+(Cl-h)+(Cl-g)	
31.	(5)	R-G	Cl-g	LV to Ground capacitance.
32.	(6)	R-(Y+G)	(Cl-t)+(Cl-g)	
33.	(7)	R-(B+G)	(Cl-h)+(Cl-g)	

The above test sequence is designed to measure the 6 capacitance values associated with a three winding transformer plus up to eight bushings. The sequence uses seven different connections and 33 measurements. Similarly to the previous examples, each value is measured at least twice using different connections or a combination of connections. This procedure allows for complete verification of results before any action is taken.

Checking of Test Results.

As was explained earlier in the text, the suggested procedures measure the various capacitance values two or more times in order to assure that the results are correct and valid. This is accomplished in the following way:

1. A full sequence of 7 tests in a connection allows one to check the following: #1 = #2 + #3; #4 = #1 + #2 +#5; #6 = #2 + #5; and #7 = #3 + #5. A partial sequence allows for partial checking.

2. The winding to winding capacitance values are always measured twice, once from each winding. This allows for easy comparisons, as Ch-l should equal Cl-h. Similarly for other windings.

These calculations are easiest to carry out if the data is presented in ‘capacitance’ and ‘loss’. The picofarads (microfarads) and watts (milliwatts) can be added directly to verify readings.

If the data is presented in ‘capacitance’ and ‘dissipation factor’, then the calculation requires a four function calculator, as the dissipation factor must be weighted according to the capacitance value. The capacitance values can be added directly as before.

Interference considerations.

One of the most difficult situations to contend with is the presence of interference during the measurement process. As was explained earlier, some measurement connections are more sensitive to interference than others. Thus, for example, a UST connection is less bothered by interference than a GST connection. Also, an instrument featuring a HOT GUARD in the GST connection is less sensitive to interference than is an instrument featuring a COLD GUARD.

It must be pointed out that even in the UST connection, which typically can be configured two different ways on a test sample, will perform differently on the two connections. It all depends on how the interference is coupled to the test specimen.

Thus, for example, when measuring a bushing using the cap-tap, it is usually desirable to apply the test voltage to the HV terminal and connect the cap-tap to the measuring lead. This is because interference is typically coupled to the HV terminal and not to the cap-tap connection.

Most test equipment provides some means of rejecting or cancelling the encountered interference. This is typically done by injecting a current that is equal to the interfering current, but of opposite polarity, into the test circuit. This configuration is not perfect as the encountered interference varies with variations in the system voltage. If the system voltage goes up, so does the amount of interference. Typical interference cancellation schemes are not capable of following line voltage swings so there always is a residual quantity of interference that cannot be eliminated.

The result of residual interference vary. At times the readings fluctuate and the instrument is difficult to balance. At times it will result in readings that are low in dissipation factor, or even exhibit a negative value.