OMICRON

Application Guide

A Transformer Testing Toolbox: Troubleshooting Checklists, Test Plans, and Analysis Tips

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Introduction

This "Toolbox" is a collection of notes that provides troubleshooting checklists, test plans, and analysis tips for many of the industry accepted transformer tests. The intention of this document is not to have someone learn every piece of information within it, but to provide a document that can be revisited as questions and issues arise when testing transformers. The most practical way to use this document is to (1) search the Table of Contents for specific topics and to (2) search the document using keywords (e.g. via Ctrl+F).

For example, try searching for *troubleshooting Power Factor*, or *electrostatic shield ground,* or *voltage regulator*, or *limits for natural ester*, or *troubleshooting DC Winding Resistance*.

We hope that this information can be helpful to you in some way, when testing and managing the condition of your transformers.

-Brandon Dupuis

Content

1 Overall Power Factor

1.1 Troubleshooting Power Factor/The Power Factor Checklist

Please review the Power Factor Checklist prior to any Power Factor measurement. Typically, an abnormal Power Factor measurement is caused by not adhering to all the steps provided within the Power Factor Checklist.

> Are the transformer tank and the test-equipment solidly grounded to an earth-ground reference potential?

> Are you using a generator to power the test set?

- For transformer testing in general, it is always recommended to use a true power supply/receptacle versus a generator or inverter. We must be aware that using certain generators or inverters can increase the safety risk when operating the equipment, they can result in open-loop errors which prevent the user from executing a test (typically during TD measurements), and they can result in abnormal results (typically during TD measurements). However, some generators or inverters are adequate for safely powering OMICRON test equipment.

> Are the groups of bushing terminals short-circuited together? All primary-side (H) bushing terminals must be shorted together. Separately, all secondary-side (X) bushing terminals must be shorted together.

- Since Power Factor is typically a high-voltage, low-current test, the cross-sectional size of the shorting-jumpers is not typically too important. We recommend using the flexible copper shorting-jumpers (braided wire).
- Connect the shorting jumpers as tightly as possible from bushing-terminal to bushing-terminal (and do not let the shorting jumpers sag and/or touch any surface other than the terminal being energized).
- Always use NON-insulated shorting jumpers to short-circuit the bushing terminals together when performing a Power Factor measurement. Do NOT use insulated shorting jumpers. If insulated shorting jumpers are used, then the jumper's insulation can become part of the Power Factor insulation measurement.

> Are the bushing terminals of the transformer completely disconnected and isolated from all cable, bus, support insulators, surge arresters, etc.?

- When applying a test-voltage of 10kV, a minimum clearance of 3in. should be established (between the terminal(s) that is energized and all other surfaces). We recommend avoiding using a rubber blankets, insulated gloves, etc. to isolate the bushing terminals from external surfaces. The best insulator for Power Factor testing is air.
- If you must use an insulator, then make sure it's clean and dry. If you obtain an abnormal power factor measurement, then investigate the insulator that's being applied.

- Are the surfaces of the bushings dry (and reasonably clean)? Be aware that the test-environment can significantly influence a Power Factor measurement.
    - Do not Power Factor test in the rain
    - Moisture on the surfaces of the bushings can significantly influence a Power Factor measurement. In most cases, using a clean, dry rag to dry the surfaces of the bushings is sufficient. In cases where excessive surface contamination on the bushing surfaces is present (e.g. in an unusually polluted or dirty environment), using Windex or Collinite may help to clean the surfaces of the bushings.
    - Avoid testing in high-humidity situations (where excessive moisture is present). Power Factor test after lunch, if possible, which is typically when the least amount of moisture/humidity is present.
- Ensure that the exterior surface of the test-equipment's high-voltage cable is not touching any surface of the transformer, the bushings, etc. at the "far-end" where the test-terminal is being energized. The last two feet of the "far-end" of the high-voltage cable should be surrounded by air. If the bushings are tall enough, you can hang the HV cable off the shorting jumpers in the middle between two bushings
- Remove all in-service grounds from any neutral bushing terminals
    - For example, remove the in-service ground-connection from the X0 bushing terminal, if applicable
- Place the LTC in any off-neutral tap-position
    - Some transformer Load-Tap-Changers (LTCs) utilize a "tie-in resistor", which has been known to negatively influence the Power Factor measurement when the transformer is tested in the Neutral tap-position. Federal Pioneer Electric and Federal Pacific Electric transformers with LTCs have been known to utilize tie-in resistors and typically exhibit this behavior.
- Additional, less-common items to consider:
    - Test a different test-specimen if possible, which can help confirm that the test-equipment is functioning properly.
    - Is the test-equipment potentially defective? Can you use a different test set to confirm the results?
    - Do the bushing terminals have test links? Are they being guarded properly?
    - Do the bushings have resistive grading? This causes excessive leakage current to flow across the surface which results in abnormal PF values
        - You may be able to guard (i.e., remove) the influence of a given bushing's surface tracking from the Overall PF measurement by applying a hot-collar band on the bushing while the Overall PF measurement is performed. The Blue B lead can be connected to the hot-collar band and utilized as the guard lead.
    - Are all the bushing taps solidly grounded via a tap-cap or ground wire?
    - If a high resistive path to ground is suspected, then you could try:
        - Manually ground the bushing flanges with a jumper wire

        - Remove all the bushing tap-caps from the bushings and manually ground the bushing taps with a jumper wire – *you need to ensure a solid ground to the tap when doing this!*
    - Oil Temperature
        - For Power Factor testing we recommend avoiding testing when the temperature of the transformer oil is below 0°C, because it can sometimes result in unusual test-results; however, this isn't a hard and fast rule, and we've seen many examples where the oil temperature was close to or slightly below 0°C and the results were fine.
        - If you must test with the oil temperature close to or below 0°C then just use your best judgment when analyzing the results. If the results look normal then they're probably fine, but if they're unusual then it may be due to the cool oil temperature.

1.2 Using Generators/Inverters as a Power Supply

For testing in general, it is always recommended to use a true power supply/receptacle versus a generator or inverter. We must be aware that using certain generators or inverters can increase the safety risk when operating the equipment, they can result in ground-loop-check errors which prevent the user from executing a test (typically during TD measurements), and they can result in abnormal results (typically during TD measurements). Some generators or inverters are adequate for safely powering OMICRON test equipment. It's very difficult to make blanket statements about which alternative power supply options work well for testing.

The following list includes generators that have been reported by our customers to work well with our equipment,

- Honda EB Series
- Westinghouse WH Series
- Hobart Champion Elite Series

The following list includes generators that have been reported by our customers to NOT work well with our equipment. HOWEVER, different generator models, power ratings, and manufacturing years can vary the functionality of a given generator relative to our equipment, so you may find a generator that works fine for you in the list below.

- Honda EU inverter series
- Honda EZ series
- Honda EM
- Honda EG 6500 CL

Generators that tend to work better as a supply for OMICRON test equipment often state one of the following key-terms (on either the front plate of the generator, in the manual of the generator, or in the specifications of the generator),

- "Neutral Bonded to Frame"
- "Bonded Neutral"

The ground-loop-check feature of the equipment is provided for safety and should NEVER be disabled. The test set has an internal relay to ensure that the proper ground connection has been made. If the ground check message still appears, then you should not begin testing until the message is cleared. If an appropriate generator is used, there should never be a reason to defeat/bypass the safety check.

Note, the grounding and power supply issues are not specific to the OMICRON test set, but influence competitor's transformer test equipment as well. All power factor test sets check to see if the mains ground is properly connected to the test specimen ground.

1.3 Negative Power Factor/Low Capacitance Specimen/Low Current Specimen

A negative Power Factor is typically caused by a high resistive path to ground, which is often caused by,

- Not adhering to the rules outlined in the Power Factor Checklist
- In some special cases, abnormally low, and negative Power Factor measurements are common. These special cases typically occur when the test specimen has an unusually low capacitance (pF) value. For example, below approximately 80-100pF. When the test specimen has an unusually low capacitance (and low test-current), the power factor percent can be unreliable and misleading. When the measured current is low, a small change with the measured current may result in a disproportionally large change with the power factor percent value. Abnormally low, and negative Power Factor measurements may be observed when testing,
    - A transformer with an electrostatic shield ground – See electrostatic shield ground/ESG section
        - If the power factor measurement is performed on a transformer that has an electrostatic ground shield between two (or more) windings, the measured current and capacitance is typically abnormally low for the inter-winding insulation (UST) measurements, due to the presence of the electrostatic shield ground. The shield acts as a guard and blocks the current flowing from the injection winding to the measurement winding.
    - A three-winding transformer
        - An unusually low capacitance value (pF) is often measured when testing a three-winding transformer. It's usually the CHT measurement that has the unusually low capacitance value (pF), but it can be either (or any combination) of the three UST measurements. Often the center winding (typically the secondary X winding) guards the current flowing from the primary to the tertiary winding during the CHT measurement. However, any of the windings can act as a guard and block the current flowing from the injection winding to the measurement winding.
    - Power Factor measurements on SF6 and Vacuum breakers
    - Any test specimen that has a small Capacitance AND a small Watt Loss

1.4 Limits for Power Transformers – Mineral Oil

The limits provided within the IEEE C57.152-2013 Guide for power factor testing are reasonable aiming points for assessing the condition of the insulation of a power transformer filled with mineral oil. According to the IEEE C57.152-2013 limits for power factor testing, a measured power factor value below 0.5% (0.4% for transformers rated at and above 230kV) typically is indicative of healthy insulation, assuming the transformer is filled with mineral-oil and has a power rating larger than *approximately* 5MVA. A power factor value in the range of 0.5%-1% typically represents deteriorated and questionable insulation. A power factor value above 1% is typically unacceptable and may be cause for immediate investigation.

Assuming the transformer is filled with mineral-oil and has a power rating larger than *approximately* 5MVA,

> Once the Overall Power Factor value(s) exceeds 0.5%, the unit should be monitored closely in the future. The best way to monitor an "at risk" transformer is to test it more frequently. For example, if the typical routine maintenance interval for a fleet is 8 years, then you may want to test an "at risk" transformer every 1-2 years, to gauge/monitor the severity of the situation, and to begin trending the potential issue.

> Overall Power Factor values that exceed 1% indicate that the main-tank winding-insulation-system of the transformer is compromised and is at some risk of failing if the unit remains in service. Transformers in this category should be investigated immediately and monitored very closely in the future.

		Power factor		
Assessment against	Limit	Silicone	Mineral oil	Natural ester
Absolute limits for measurements	Low limit (fail)	0.000 %	0.000 %	0.000 %
	Low limit (warn.)	0.100 %	0.100 %	0.100 %
	High limit (warn.)@ <230kV	0.500 %	0.500 %	1.000 %
	High limit (warn.)@ >=230kV	0.500 %	0.400 %	1.000 %
	High limit (fail)	1.000 %	1.000 %	2.000 %
Absolute limits for cross check	Multiplier (high warn. limit)	1.10	1.10	1.10
	Multiplier (high fail limit)/Divider (low fail limit)	1.20	1.20	1.20

Figure 1: Typical Limits for Overall Power Factor

1.5 Limits for Transformers Rated Approximately < 3-5MVA – Mineral Oil

Due to the relatively low power/voltage rating of these units, there could be some unique challenges when assessing the Overall PF measurement. Transformers with relatively low power ratings (e.g. approximately < 3-5MVA) tend to test with "higher than normal" Power Factor values (sometimes up to and exceeding 1%). For an oil-filled transformer of this size, I would expect that the range of Overall PF values could be wider than we typically see (i.e. relative to a larger "power transformer"); therefore, Overall PF values exceeding 0.5% can be expected and allowed on a case-by-case basis.

In general, the higher the voltage/power rating of the transformer, the stricter we tend to be with the Power Factor assessment. The lower the voltage/power rating of the transformer, the more lenient we tend to be with the Power Factor assessment.

The best method for performing the analysis on these transformers is to document and trend the measured power factor over time, to look for any increases in power factor. Another analysis strategy is to compare the results to a sister unit transformer(s).

1.6 Limits for Natural Ester/FR3/Less-Biodegradable Fluid Transformers

It is not uncommon that a power factor measurement on a power transformer *(i.e. rated for approximately > 5MVA)* filled with a "Less-Flammable Biodegradable Fluid" (e.g. natural ester) has higher power factor value relative to a transformer filled with mineral oil. Therefore, higher power factor values are expected and are allowed within reason. Typically, for a power transformer filled with natural ester, we typically recommend that the measured power factor is below 1%.

For a transformer filled with natural ester, a measured power factor value higher than 1% is a bit unusual and may warrant further investigation, *unless it's a relatively low power/voltage rated unit (e.g. approximately < 3-5MVA)*. Transformers rated for approximately < 3-5MVA that are filled with a "Less-Flammable Biodegradable Fluid" have been known to test in the 1-2% range (or even higher). In general, the higher the voltage/power rating of the transformer, the narrower the range of PF values we tend to see, and therefore we tend to be stricter with the Power Factor assessment. The lower the voltage/power rating of the transformer, the wider the range of PF values we tend to see, and therefore we tend to be more lenient with the Power Factor assessment.

The best method for performing the analysis on transformers filled with a "Less-Flammable Biodegradable Fluid" would be to document and trend the measured power factor over time, to look for any increases in power factor. Another analysis strategy is to compare the results to a sister unit transformer(s).

		Power factor		
Assessment against	Limit	Silicone	Mineral oil	Natural ester
Absolute limits for measurements	Low limit (fail)	0.000 %	0.000 %	0.000 %
	Low limit (warn.)	0.100 %	0.100 %	0.100 %
	High limit (warn.)@ <230kV	0.500 %	0.500 %	1.000 %
	High limit (warn.)@ >=230kV	0.500 %	0.400 %	1.000 %
	High limit (fail)	1.000 %	1.000 %	2.000 %
Absolute limits for cross check	Multiplier (high warn. limit)	1.10	1.10	1.10
	Multiplier (high fail limit)/Divider (low fail limit)	1.20	1.20	1.20

Figure 2: PTM Overall PF Limits for Different Insulating Fluids

1.7 Limits for Dry Type Transformers

In general, performing and analyzing Power Factor measurements on dry-type transformers is often challenging, due to,

- The Power Factor measurements performed on dry-type transformers are often significantly higher relative to transformers filled with oil – in other words, the range of Power Factor values obtained from testing dry-type transformers is very wide. Often the Overall Power Factor measurement can yield values in the 0.25%-10% range, which may be normal/typical for a given dry-type transformer.
- Often, one or more of the Overall Power Factor/Capacitance measurements on a dry-type transformer yields a relatively small Capacitance (pF) value (e.g. < 500pF), which indicates that there is a minimal amount of insulation being tested for that measurement.
    - In general, measurements with relatively small Capacitances (pF) values are more sensitive (and thus, are more prone to measurement error), than measurements with relatively sizeable Capacitances (pF)
    - In general, the measurements with low Capacitances (pF) values usually produce the highest power factor values (i.e. sometimes in the 4-10% range).
    - Measurements with relatively small Capacitances (pF) values (e.g. the CH measurement on a dry-type transformer) typically test the integrity of,
        - The bushings associated with the winding being energized
        - The support insulators that are supporting the winding structure
- The test-environment – The test-environment can heavily impact any Power Factor measurement, but even more so for Power Factor measurements performed on a dry-type transformer. For example, moisture/contamination on the surfaces of the bushings and/or the windings can significantly influence the Overall Power Factor test results.

The best method for analyzing the Overall Power Factor on a dry-type transformer is to document and trend the measured power factor over time, to look for any increases in Power Factor. Another analysis strategy is to compare the results to a sister unit transformer(s). The frequency sweep test on dry type transformers has to be taken with a grain of salt, as the rules we typically use for this test only apply to fluid filled insulation systems. I would focus more on the 60Hz Power Factor for dry type transformers.

1.8 Temperature Correction Factors

Based on experience there isn't a good umbrella, one-fits-all solution for temperature correcting Power Factor measurements. The good news is that nearly all the measurements our customers perform have an oil temperature between 0 degrees C and 35 degrees C, which is a range where we don't feel the power factor changes much versus temperature.

For Overall Power Factor, Bushing C1, and Bushing C2, we typically recommend enabling the temperature correction in the software (to unlock the assessment), and then applying a correction factor of 1. However, please document the ambient temperature, humidity, oil temperature, and winding temperature during the time of the test (to the best of your abilities). Sometimes unusually high or unusually low temperatures can justify unusual measurements.

You may notice that the “correction factor” field cannot be changed after an assessment has been applied to a measurement; therefore, to change the “correction factor” field, you must click the “clear all assessments” button in the “Assessment” section of the Overall Power Factor measurement. Once the “correction factor” field has been changed, you can re-apply the assessment by clicking “assess measurements”.

1.9 Variable Frequency Power Factor/Frequency Sweep

The Variable Frequency Power Factor test involves performing Power Factor measurements at a series of different test frequencies (e.g. 15Hz, 30Hz, 45Hz, 60Hz, 150Hz, 200Hz, 300Hz, and 400Hz). This test has proven to be invaluable for helping to identify invalid Power Factor measurements and for helping to assess the condition of the insulation system under test.

The analysis of the frequency sweep test is performed by visual inspection of the plot produced by the frequency sweep. The rule of thumb is to analyze the slope (from left to right) of the trace. An insulation system that is in good condition will generally have a positive slope (i.e. increasing trace from left to right) through most of the sweep. As the insulation system begins to deteriorate, the slope of the trace becomes less positive, and eventually becomes negative through most or all the sweep. Typically, the more negative the slope of the trace, the more deteriorated the insulation system.

Variable Frequency Power Factor traces that are erratic and jagged are typically indicative of invalid Power Factor measurements. The Variable Frequency Power Factor curves should always be smooth regardless of the health of the insulation. Often, a “jagged” Power Factor Frequency Sweep trace is caused by not short-circuiting the bushing terminals of the transformer under test when the Power Factor measurement is performed.
Note, the oil temperature can influence the shape of the frequency sweep trace. The hotter the oil temperature, the more likely the frequency sweep trace will have some negative slope to it in the lower frequencies (and look like slightly deteriorated/“bad” insulation).

The general guidelines used to assess the Variable Frequency Power Factor test (along with several case studies) are provided in the OMICRON paper titled, “The Value of Performing Power Factor Sweep Measurements on Bushings.”

1.10 Voltage Sweep/Voltage Tip Up Test

The Voltage Sweep test involves performing Power Factor measurements at different test voltages (e.g. 2kV, 4kV, 6kV, 8kV, and 10kV). This test has proven to be invaluable for helping to identify invalid Power Factor measurements and for helping to assess the condition of the insulation system under test.

In most cases, the measured power factor of a fluid-filled insulation system should not change as the applied voltage changes. Therefore, as the applied voltage changes, a healthy insulation system will typically provide a relatively constant power factor versus voltage. Note, in many cases, voltage sensitive Power Factor measurements are indicative of invalid Power Factor measurements, so the test can help users quickly and easily identify invalid Power Factor measurements.

For fluid-filled bushings, the PF measurements should be reasonably similar when comparing measurements performed at different voltages. In general, a Power Factor measurement performed on an oil-and-paper insulation system should not be voltage sensitive. Note, however, as a bushing begins to age, deteriorate, fail, etc. the C1 Power Factor measurement for that bushing often becomes voltage sensitive.

1.11 The Bushing's Influence on the CH Test

We must keep in mind that the CH measurement is often heavily influenced by the primary-side (H) bushings. The amount of influence that the primary-side (H) bushings have on the CH measurement is largely determined by the capacitance value of the CH insulation, relative to the sum of the C1 capacitance values of the primary-side (H) bushings.

For example, if the CH capacitance value is 2,000pF, whereas the sum of the C1 capacitances for the primary-side (H) bushings is 1000pF. Therefore, the primary-side (H) bushings account for approximately 50% of the CH Power Factor measurement.

If the primary-side (H) bushings do not have test-taps, it is challenging to determine to what extent the primary-side (H) bushings are influencing the CH measurement. It could simply be that the primary-side (H) bushings are influencing the CH measurement.

Note, there is a feature called "Bushings compensation" in the "Settings and Conditions" section of the Overall Power Factor Test (see the screenshot below), which allows the user to subtract the contribution of the bushings from the Overall Power Factor measurements. To unlock the "Bushings compensation" field, the "use reference voltage @10kV" must be checked off for both the Overall Power Factor and Bushing C1 Power Factor tests.

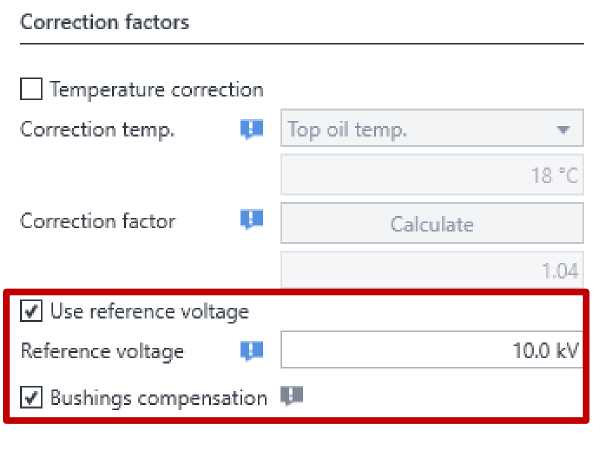


Figure 3: Selecting Bushings Compensation in PTM

If the bushings do not have test taps, then the only practical way to remove the contribution of the bushings from the Overall measurement is to remove the bushings from the main tank. If this is done, then you could either test the bushings as "spare bushings" and subtract the individual bushing measurements from the Overall measurement.

Also, the Overall Power Factor measurements could be performed with the bushings removed, which may help us determine whether the unusually high measurements are due to the bushings or due to an issue within the main tank of the transformer.

Bushing compensation calculation and example:
To remove the effects of the H bushings from the ICH measurement, perform the following calculation,

	Current (mA)	Watts (mW)
H1	1.19	102
H2	1.21	111
H3	1.2	70.73
Total	3.6	283.73
ICH	8.77	474
ICH' (ICH – Total)	5.17	190.27
CH' PF	0.367504836	

Table 1: Bushing Compensation Calculation

Where the CH' PF represents the power factor value of the ICH insulation without the contribution from the H bushings. The CH' PF was calculated as follows,

CH' Power Factor = (Watt Loss/(mA*kV)) * 100% = (190mW/(5.17mA * 10kV)) * 100% = 0.367%

1.12 The Bushing's Influence on the CL Test

We must keep in mind that the CL measurement is influenced by the secondary-side (X) bushings. The amount of influence that the secondary-side (X) bushings have on the CL measurement is largely determined by the capacitance value of the CL insulation, relative to the sum of the C1 capacitance values of the secondary-side (X) bushings. For example, if the CL capacitance value is 10,000pF, whereas the sum of the C1 capacitances for the secondary-side (X) bushings is 1,000pF. Therefore, the secondary-side (X) bushings account for approximately 10% of the CL Power Factor measurement.

Note, there is a feature called "Bushings compensation" in the "Settings and Conditions" section of the Overall Power Factor Test (see the screenshot below), which allows the user to subtract the contribution of the bushings from the Overall Power Factor measurements. To unlock the

“Bushings compensation” field, the “use reference voltage @10kV” must be checked off for both the Overall Power Factor and Bushing C1 Power Factor tests.

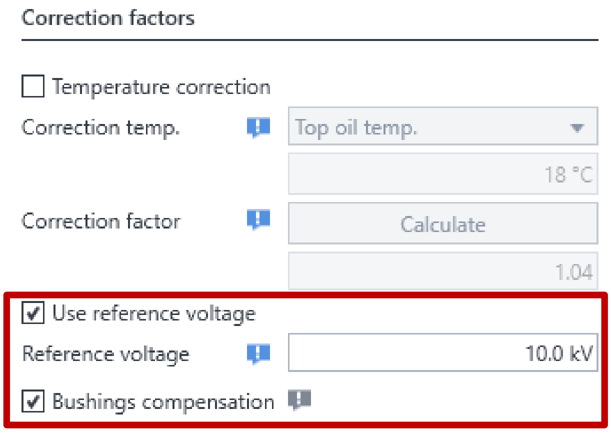


Figure 4: Selecting Bushings Compensation in PTM

If the bushings do not have test taps, then the only practical way to remove the contribution of the bushings from the Overall measurement is to remove the bushings from the main tank. If this is done, then you could either test the bushings as “spare bushings” and subtract the individual bushing measurements from the Overall measurement.

Also, the Overall Power Factor measurements could be performed with the bushings removed, which may help us determine whether the unusually high measurements are due to the bushings or due to an issue within the main-tank of the transformer.

1.13 Capacitance Change (pF)

In general, if the measured Capacitance value of an Overall Power Factor measurement changes over-time, then it typically suggests that the insulation system under test has physically/mechanically changed over-time. Typically, the measured capacitance should not change by more than ±1-2% between test dates when performing the Overall PF test. A change in the measured capacitance value could be an indication of,

- Not adhering to the rules outlined in the Power Factor Checklist and/or defective test-equipment
  - E.g., leaving the busbar connected/disconnected when comparing the two test dates
- Changing or adding/removing the bushings can change the capacitance of the insulation system (high-voltage bushings affect CH only and the low-voltage bushings affect CL only)
- Changing or adding/removing the insulating fluid
- Loss of core ground
  - The intentional ground connection to the core can become disconnected from the core. Losing the intentional core ground may cause the core to float to undesired potentials, which could lead to overheating and/or an insulation failure. It is possible to detect a “Loss of Core Ground” with the

Overall Power Factor and Capacitance test; however, a baseline (previous) Overall Power Factor and Capacitance measurement is required to identify this type of failure. For example, the measurement must have been performed before the “Loss of Core Ground” and after the “Loss of Core Ground” to identify the failure.

  - It is well documented that when a transformer “loses” its core ground connection, the CL capacitance decreases; conversely, when the core ground connection is made, I would expect that the CL capacitance should increase.

- The insulation system under test has physically changed (e.g. winding movement within the transformer or a loss of a core ground).

If the capacitance measured during the power factor test changes between test dates by more than 1-2%, then a leakage reactance and/or SFRA tests could be performed, to determine if there has been winding movement or deformation within the transformer.

1.14 Three Winding Transformers: Unusual UST Power Factor (CHT or CLT or CHL)

An unusually low capacitance value (pF) is often measured when testing a three-winding transformer. It’s usually the CHT measurement that has the unusually low capacitance value (pF), but it can be either (or any combination) of the three UST measurements. Often the center winding (typically the secondary X winding) guards the current flowing from the primary to the tertiary winding during the CHT measurement. However, any of the windings can act as a guard and block the current flowing from the injection winding to the measurement winding.

When the test specimen has an unusually low capacitance/current (approximately below 100pF), the power factor percent can be unreliable and misleading. When the measured current is low, a small change with the measured current may result in a disproportionally large change in power factor.

The UST measurement(s) with an unusually low capacitance/current (approximately below 100pF) should be disregarded and not considered when analyzing the results.

Block 1: injection at H

Start all ☑ Use global corr. factor (K) 1.2

No.	Measurement	Test mode	Sweep	V test	Freq.	V out	I out	Watt losses	PF meas	PF corr	Cap. meas	Assessment
1	ICH+ICHL+ICHT	GST	None	10.00 kV	60.00 Hz	10.00 kV	38.49 mA	777.17 mW	0.2019 %	0.2423 %	10207.0 pF	Pass
2a	ICH (V)	GSTg-A+B	Voltage	10.00 kV	60.00 Hz	10.00 kV	14.70 mA	353.75 mW	0.2407 %	0.2888 %	3894.3 pF	Pass
2b	ICH (f)	GSTg-A+B	Frequency	2.00 kV	60.00 Hz	2.00 kV	2.94 mA	12.78 mW	0.2174 %	0.2609 %	3895.3 pF	Pass
3a	ICHL (V)	UST-A	Voltage	10.00 kV	60.00 Hz	10.00 kV	23.55 mA	415.31 mW	0.1764 %	0.2116 %	6248.4 pF	Pass
3b	ICHL (f)	UST-A	Frequency	2.00 kV	60.00 Hz	2.00 kV	4.71 mA	16.42 mW	0.1742 %	0.2091 %	6250.0 pF	Pass
4a	ICHT (V)	UST-B	Voltage	10.00 kV	60.00 Hz	10.00 kV	0.24 mA	3.30 mW	0.1381 %	0.1657 %	63.3 pF	Investigate
4b	ICHT (f)	UST-B	Frequency	2.00 kV	60.00 Hz	2.00 kV	0.05 mA	0.13 mW	0.1333 %	0.1599 %	63.4 pF	Investigate

Block 2: injection at X

Start all ☑ Use global corr. factor (K) 1.2

No.	Measurement	Test mode	Sweep	V test	Freq.	V out	I out	Watt losses	PF meas	PF corr	Cap. meas	Assessment
5	ICL+ICLT+ICLH	GST	None	10.00 kV	60.00 Hz	10.00 kV	49.27 mA	1055.30 mW	0.2141 %	0.2570 %	13064.5 pF	Pass
6a	ICL (V)	GSTg-A+B	Voltage	10.00 kV	60.00 Hz	10.00 kV	8.52 mA	276.46 mW	0.3245 %	0.3894 %	2258.1 pF	Pass
6b	ICL (f)	GSTg-A+B	Frequency	2.00 kV	60.00 Hz	2.00 kV	1.70 mA	10.81 mW	0.3171 %	0.3805 %	2258.1 pF	Pass
7a	ICLT (V)	UST-B	Voltage	10.00 kV	60.00 Hz	10.01 kV	17.19 mA	367.87 mW	0.2138 %	0.2566 %	4556.9 pF	Pass
7b	ICLT (f)	UST-B	Frequency	2.00 kV	60.00 Hz	2.00 kV	3.44 mA	14.58 mW	0.2124 %	0.2548 %	4557.7 pF	Pass
8a	ICLH (V)	UST-A	Voltage	10.00 kV	60.00 Hz	10.00 kV	23.55 mA	414.15 mW	0.1759 %	0.2110 %	6249.0 pF	Pass
8b	ICLH (f)	UST-A	Frequency	2.00 kV	60.00 Hz	2.00 kV	4.71 mA	16.40 mW	0.1740 %	0.2088 %	6249.8 pF	Pass

Block 3: injection at Y

Start all ☑ Use global corr. factor (K) 1.2

No.	Measurement	Test mode	Sweep	V test	Freq.	V out	I out	Watt losses	PF meas	PF corr	Cap. meas	Assessment
9	ICT+ICTH+ICTL	GST	None	7.00 kV	60.00 Hz	7.00 kV	56.33 mA	1238.24 mW	0.3140 %	0.3768 %	21338.4 pF	Pass
10a	ICT (V)	GSTg-A+B	Voltage	7.00 kV	60.00 Hz	7.00 kV	44.12 mA	1057.51 mW	0.3424 %	0.4109 %	16717.9 pF	Pass
10b	ICT (f)	GSTg-A+B	Frequency	2.00 kV	60.00 Hz	2.00 kV	12.61 mA	85.81 mW	0.3403 %	0.4084 %	16717.0 pF	Pass
11a	ICTH (V)	UST-B	Voltage	7.00 kV	60.00 Hz	7.00 kV	0.17 mA	1.73 mW	0.1478 %	0.1774 %	63.4 pF	Investigate
11b	ICTH (f)	UST-B	Frequency	2.00 kV	60.00 Hz	2.00 kV	0.05 mA	0.14 mW	0.1469 %	0.1763 %	63.4 pF	Investigate
12a	ICTL (V)	UST-A	Voltage	7.00 kV	60.00 Hz	7.00 kV	12.02 mA	179.72 mW	0.2136 %	0.2563 %	4556.8 pF	Pass
12b	ICTL (f)	UST-A	Frequency	2.00 kV	60.00 Hz	2.00 kV	3.44 mA	14.56 mW	0.2119 %	0.2543 %	4557.4 pF	Pass

Figure 5: Example Showing the Guarding Effect of the Center Winding for CHT

1.15 Transformers with an Electrostatic Shield Ground

An electrostatic shield ground typically only influences the Overall Power Factor measurement, so the other measurements should produce normal/typical results. If the power factor measurement is performed on a transformer that has an electrostatic ground shield between two (or more) windings, the measured current and capacitance is typically abnormally low for the inter-winding insulation (UST) measurements, due to the presence of the electrostatic shield ground. The shield acts as a guard and blocks the current flowing from the injection winding to the measurement winding.

When a transformer has an electrostatic shield ground located between two (or more) windings, typically, we recommend only analyzing the percent power factor for the Grounded Specimen Test (GST – e.g. CH and CL) measurements. The UST measurement(s) with an unusually low capacitance/current (approximately below 100pF) should be disregarded and not considered when analyzing the results.

When the test specimen has an unusually low capacitance/current (approximately below 100pF), the power factor percent can be unreliable and misleading. When the measured current is low, a small change with the measured current may result in a disproportionally large change in power factor.

Note, although the measured percent power factor for the UST measurement(s) are typically disregarded, the measured current and capacitance could be documented for future reference. A defect involving the electrostatic shield ground (e.g. a loss of a ground connection) may be detected if the current and capacitance of the UST measurement(s) changes over time.

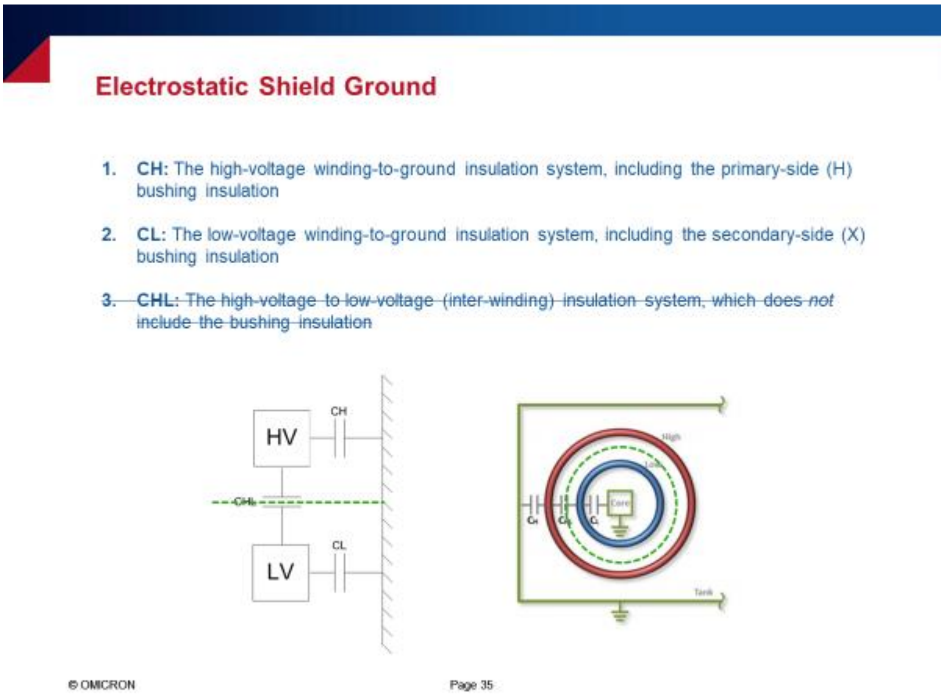


Figure 6: Diagrams Showing Presence of Electrostatic Shield Ground

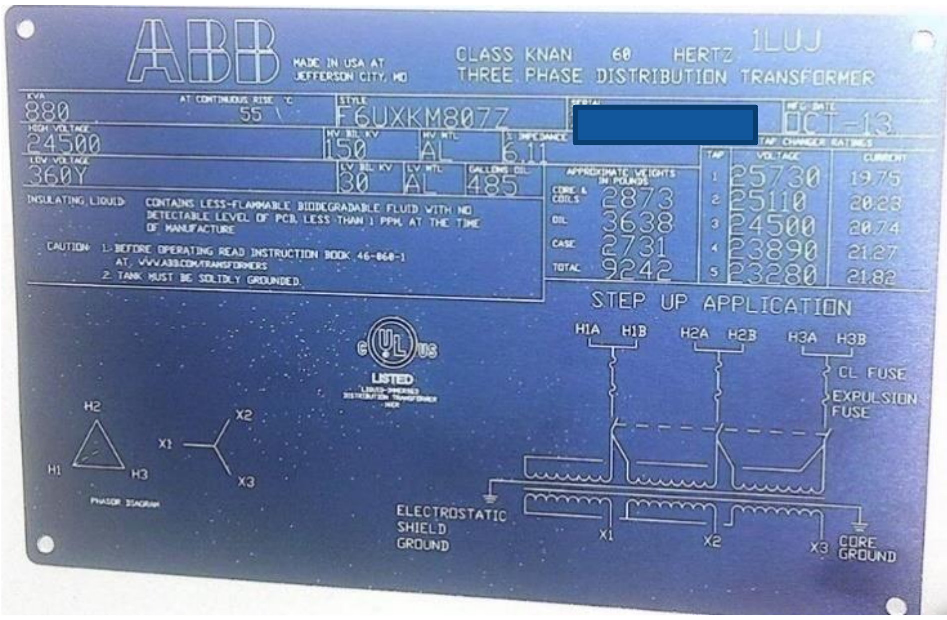


Figure 7: Nameplate Example Showing Presence of Electrostatic Shield Ground

1.16 Federal Pacific Electric/Federal Pioneer Electric Transformers

Some transformer Load-Tap-Changers (LTCs) utilize a “tie-in resistor”, which has been known to influence the Overall Power Factor measurement when the transformer is tested in the Neutral tap-position. Specifically, Federal Pioneer Electric and Federal Pacific Electric transformers with LTCs have been known to exhibit this behavior. If these transformers are tested in the Neutral tap-position, then it can compromise the Power Factor measurement; therefore, always ensure that the LTC is NOT in the Neutral tap-position when the Overall Power Factor measurement is performed (for any transformer).

Note, all the Federal Pioneer Electric and Federal Pacific Electric transformers I’ve ever seen have a tie-in resistor. The tie-in resistor seems to create an abnormally large amount of leakage current flowing to ground, which usually results in an abnormally high or negative Power Factor value.

An example of a tie-in resistor is shown in the screenshot below. From my understanding, when the LTC is placed in the Neutral position, the tie-in resistor is connected to the regulating winding, so that when the reversing switch changes position, the regulating winding does not float to an undesired potential.

Figure 8: Nameplate Example Showing Presence of Tie-In Resistor

1.17 Overall Power Factor Cross-Checks

There are three cross-checks that can be performed automatically within the software if the “Use reference voltage” option is selected in the “settings and conditions” section. By analyzing these cross-checks, typically, the validity of the measurement can be verified.

Cross-Checks #1 and #2: The software subtracts the measured current, watts, and capacitance of measurement 2 from measurement 1, and produces the result (“CHL calculated”) below measurement 3 (CHL). The “calculated CHL” and the “measured CHL” current, watts, capacitance, and power factor should be approximately equal, if the measurement was performed properly.

In addition, the software subtracts the measured current, watts, and capacitance of measurement 5 from measurement 4, and produces the result (“calculated CLH”) below measurement 6 (CLH). The “calculated CLH” and the “measured CLH” current, watts, capacitance, and power factor should be approximately equal, if the measurement was performed properly.

Cross-Check #3 (CHL/CLH): The measured current, watts, capacitance, and power factor for the CHL and CLH (measurements 3 and 6) measurements should be approximately equal since they are the same insulation.

2 Bushing Power Factor

2.1 Bushings by Type – Tips, Tricks, and Challenges

2.1.1 Bushings that Require Bushing Adapters/Tap Adapters

We offer bushing C1 and C2 tap adapters for the following bushing types,

- Westinghouse Type O
    - The Westinghouse Type O bushing typically requires the “hockey stick” adapter. It is critical that this tap adapter is fully isolated when in place, especially for the C2 measurement. If any part of the tap adapter is touching ground, you could experience unusual results.
- ASEA GO Types
- Westinghouse Type OS/S bushings

These adapters are part of the Bushing Adapters and Accessories Set. Note, this Bushing Adapters and Accessories Set is also part of the American Transformer Accessory Set which includes the following TD accessories,

- Bushing Adapters and accessories set
- Test Hook
- Short-Circuit Cable Set
- HV-Cable Adapter (for C2 measurements)
- 3-Position Remote Safety Switch
- SAA2 Warning Lamp Set – Basic Package

> MCA1 – HV TTR Measurement Capacitance

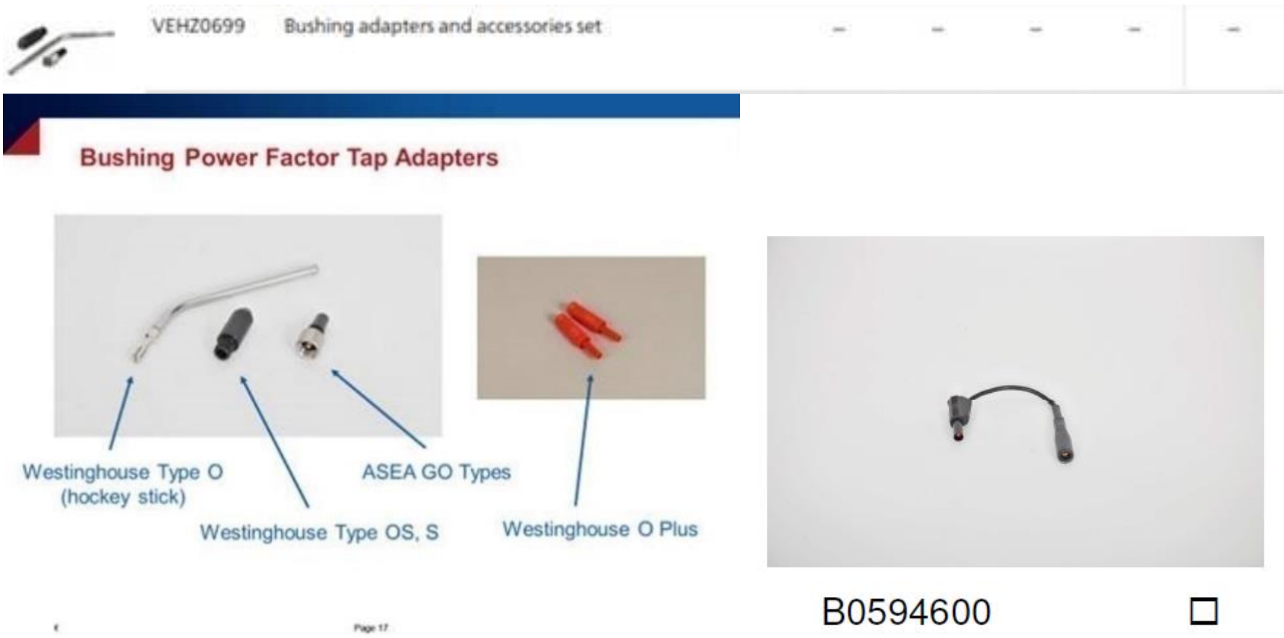


Figure 9: Images Showing Various Bushing Adapters

2.1.2 Lapp PRC bushings – Old vs. New

Lapp PRC bushings have been known to produce higher C2 power factor measurements than most other bushing types – often in the 2-10% range.

- This is especially common for Lapp PRC bushings manufactured prior to 2000
- This is especially common for Lapp PRC bushings that don't have a C2 power factor value stamped on the nameplate
- For analyzing the results, the keys are,
    - To ensure the sister unit bushings are testing similarly – if they are then there probably isn't an issue
    - To document the baseline C2 PF values and trend them over time to make a reliable condition assessment.

Note, there exists a manufacturer's note about the differences between "older" and "newer" Lapp PRC bushings, so please feel free to ask your contact at OMICRON for this document.

2.1.3 GE Type U Bushings

These bushings often exhibit a higher power factor value along with other undesirable traits such as negative slope in the 60Hz region of the frequency sweep trace, and voltage sensitivity. This is because the GE Type U bushing is constructed with a herringbone ink design. This design is common with GE Type U bushings rated between 15kV and 345kV. This type of bushing is notorious in the industry for failing, especially once the insulation is compromised.

GE's recommendations and "Criteria for Concern" for the Type U bushings in 1979 were:

- If the capacitance change is below 5%, there is little risk of failure
- If the capacitance has increased by 10% or more, remove the bushing from service.
- If the P.F. is below 1.5%, there is no cause for concern.
- If the P.F. exceeds 1.5%, but is less than 3%, the bushing is in the region for concern
- If the P.F. exceeds 3%, remove the bushing from service.

HOWEVER, if the bushings are Type U, then replacement should be considered regardless of how they test, and regardless if they have been involved in a fault or not. Before 2000, most Utilities used the 1.0 % PF criteria for removal. After 2000, many utilities instituted a GE Type U removal program.

An ideal approach is, if you have the resources, then replace all GE Type U bushings as soon as you can to mitigate the risk of failure. If you can't replace all GE Type U bushings immediately, then we recommend testing the GE Type U bushings frequently going forward.

2.1.4 Composite Bushings

It's been observed that composite bushings test with different C2 Power Factor and capacitance values compared to the factory nameplate tests. This is quite common and usually not a cause for concern, provided that all the sister unit bushings are behaving the same way.

2.2 C1 Power Factor

2.2.1 Troubleshooting C1 Power Factor

Please review the Power Factor Checklist prior to any C1 Power Factor measurement. Typically, an abnormal C1 Power Factor measurement is caused by not adhering to all the steps provided within the Power Factor Checklist.

- Are the transformer tank and the test-equipment solidly grounded to an earth-ground reference potential?
- Are you using a generator to power the test set?
    - For transformer testing in general, it is always recommended to use a true power supply/receptacle versus a generator or inverter. We must be aware that using certain generators or inverters can increase the safety risk when operating the equipment, they can result in open-loop errors which prevent the user from executing a test (typically during TD measurements), and they can result in abnormal results (typically during TD measurements). However, some generators or inverters are adequate for safely powering OMICRON test equipment.
- Are the groups of bushing terminals short-circuited together? All primary-side (H) bushing terminals must be shorted together. Separately, all secondary-side (X) bushing terminals must be shorted together.
    - Since Power Factor is typically a high-voltage, low-current test, the cross-sectional size of the shorting-jumpers is not typically too important. We recommend using the flexible copper shorting-jumpers (braided wire).

- Connect the shorting jumpers as tightly as possible from bushing-terminal to bushing-terminal (and do not let the shorting jumpers sag and/or touch any surface other than the terminal being energized).
- Always use NON-insulated shorting jumpers to short-circuit the bushing terminals together when performing a Power Factor measurement. Do NOT use insulated shorting jumpers. If insulated shorting jumpers are used, then the jumper's insulation can become part of the Power Factor insulation measurement.

> Are the bushing terminals of the transformer completely disconnected and isolated from all cable, bus, support insulators, surge arresters, etc.?

- When applying a test-voltage of 10kV, a minimum clearance of 3in. should be established (between the terminal(s) that is energized and all other surfaces). We recommend avoiding using a rubber blankets, insulated gloves, etc. to isolate the bushing terminals from external surfaces. The best insulator for Power Factor testing is air.
- If you must use an insulator, then make sure it's clean and dry. If you obtain an abnormal power factor measurement, then investigate the insulator that's being applied.

> Are the surfaces of the bushings dry (and reasonably clean)? Be aware that the test-environment can significantly influence a Power Factor measurement.

- Do not Power Factor test in the rain
- Moisture on the surfaces of the bushings can significantly influence a Power Factor measurement. In most cases, using a clean, dry rag to dry the surfaces of the bushings is sufficient. In cases where excessive surface contamination on the bushing surfaces is present (e.g. in an unusually polluted or dirty environment), using Windex or Collinite may help to clean the surfaces of the bushings.
- Avoid testing in high-humidity situations (where excessive moisture is present). Power Factor test after lunch, if possible, which is typically when the least amount of moisture/humidity is present.

> Ensure that the exterior surface of the test-equipment's high-voltage cable is not touching any surface of the transformer, the bushings, etc. at the "far-end" where the test-terminal is being energized. The last two feet of the "far-end" of the high-voltage cable should be surrounded by air. If the bushings are tall enough, you can hang the HV cable off the shorting jumpers in the middle between two bushings

> Remove all in-service grounds from any neutral bushing terminals

- For example, remove the in-service ground-connection from the X0 bushing terminal, if applicable

> Place the LTC in any off-neutral tap-position

- Some transformer Load-Tap-Changers (LTCs) utilize a "tie-in resistor", which has been known to negatively influence the Power Factor measurement when the transformer is tested in the Neutral tap-position. Federal Pioneer Electric and Federal Pacific Electric transformers with LTCs have been known to utilize tie-in resistors and typically exhibit this behavior.

- It is recommended to inspect the oil in all sight glasses for anything unusual such as oil level, color, signs of contaminated oil, signs of overheating, and X-wax. Anything unusual should be investigated. Also look for any obvious physical defects on the exterior surface of the bushing. Any external damage or darkening of the sight glass should be a cause for concern.
- Additional, less-common items to consider:
    - Test a different test-specimen if possible, which can help confirm that the test-equipment is functioning properly.
    - Is the test-equipment potentially defective? Can you use a different test set to confirm the results?
    - Do the bushing terminals have test links? Are they being guarded properly?
    - Do the bushings have resistive grading? This causes excessive leakage current to flow across the surface which results in abnormal PF values
        - You may be able to guard (i.e., remove) the influence of a given bushing's surface tracking from the Overall PF measurement by applying a hot-collar band on the bushing while the Overall PF measurement is performed. The Blue B lead can be connected to the hot-collar band and utilized as the guard lead.
    - If a high resistive path to ground is suspected, then you could try:
        - Manually ground the bushing flanges with a jumper wire
        - Remove all the bushing tap-caps from the bushings and manually ground the bushing taps with a jumper wire – *you need to ensure a solid ground to the tap when doing this!*
    - Oil Temperature
        - For Power Factor testing we recommend avoiding testing when the temperature of the transformer oil is below 0°C, because it can sometimes result in unusual test-results; however, this isn't a hard and fast rule, and we've seen many examples where the oil temperature was close to or slightly below 0°C and the results were fine.
        - If you must test with the oil temperature close to or below 0°C then just use your best judgment when analyzing the results. If the results look normal then they're probably fine, but if they're unusual then it may be due to the cool oil temperature.

2.2.2 Analysis Guidelines/Limits for C1

The condition assessment for a bushing depends on several factors, including,

- The bushing's manufacturer and type
- The bushing's age
- How the C1 Power Factor measurement compares to the nameplate value
- How the C1 Power Factor measurement compares to the C1 Power Factor measurements performed on the sister unit bushings
- How the C1 Power Factor measurement compares to the previous field results
- How voltage sensitive the Power Factor measurements are for a bushing
- How the Power Factor Frequency Sweep trace looks for a given bushing

If the C1 power factor results are more than 1.5 times the nameplate value, then the bushing should be investigated. A change in capacitance relative to the nameplate value (or to a previous test value) of more than 5-10% is typically considered unacceptable and may warrant further investigation.

Guidelines if no nameplate value is available:

- Typically, a bushing filled with mineral-oil is considered acceptable if the measured C1 power factor is below 0.5%
- If the bushing filled with mineral-oil tests with a C1 power factor value between 0.5%-1%, then typically, the bushing insulation is deteriorated, and should be investigated.
- If the bushing filled with mineral-oil tests with a C1 power factor value above 1%, then typically, the bushing is considered questionable, and should be investigated immediately.

2.3 C2 Power Factor

2.3.1 Troubleshooting C2 Power Factor

The list below highlights the most likely causes of an abnormal C2 Power Factor measurement,

- Was the transformer tank and test equipment solidly connected to earth ground potential when the C2 Power Factor measurements were performed?
- Are you using a generator to power the test set?
    - For transformer testing in general, it is always recommended to use a true power supply/receptacle versus a generator or inverter. We must be aware that using certain generators or inverters can increase the safety risk when operating the equipment, they can result in open-loop errors which prevent the user from executing a test (typically during TD measurements), and they can result in abnormal results (typically during TD measurements). However, some generators or inverters are adequate for safely powering OMICRON test equipment.
- Was the tap area of each bushing clean and dry when the C2 Power Factor measurements were performed? The bushing tap area can be dried by *applying heat to the outside* (i.e. the enclosure) of the tap area. Note, applying heat directly to the tap area significantly increases the temperature, and can result in abnormal PF values.
- Was the end of the high-voltage cable (i.e. the end of the cable that is connected to the bushing tap) “in the clear” when the measurement was performed? The end of the CP TD1 high-voltage cable is unshielded and must be “in the clear” (i.e. surrounded by a minimum of three inches of air), when any Power Factor measurement is performed. The transition from the non-shielded to the shielded part of the cable begins when the high-voltage cable visibly becomes “thicker”.
- Were rubber blankets or insulator gloves used to keep the high-voltage cable off the transformer tank, when the C2 Power Factor measurements were performed? From my experience, rubber blankets and/or other insulators used to isolate the high-voltage cable from the grounded transformer tank may result in “bad” Power Factor measurements. The best insulator for the high-voltage cable is air.

- Did you use any special adapter to connect to the tap of the bushing and was it applied properly?
- Was the HV C2 cable adapter locked into place?
- One option to troubleshoot the C2 Power Factor measurement, is to apply a jumper from the bushing flange to the grounded transformer tank, while repeating the C2 measurement
- One option to troubleshoot the C2 Power Factor measurement, is to connect the test equipment ground directly to bushing flange
- From time to time, the C2 insulation could be damaged if the tester leaves the bushing tap open-circuited on one bushing while C1 testing the other bushings. This voltage could damage the bushing tap area, and, in most cases, it will not affect the C1 test results. Check to see whether there is visual damage to the tap area.

2.3.2 Analysis Tips for C2 Power Factor

- We typically see a much wider range of Power Factor values for the C2 test than with C1 and Overall Power Factor. It's not uncommon that a bushing tests with a C2 value that exceeds 1.5 or 2 times the nameplate value. Good judgement must be used, but for oil-filled bushings, a C2 value below 1% is typically fine.
- Resin impregnated bushings/PRC bushings often test with relatively high C2 Power Factor values (often above 1% and sometimes even in the 1-10% range, depending on the make and model).
- Bushings that don't have C2 Power Factor values stamped on the nameplate often test with relatively high C2 Power Factor values (often above 1%)
- A change in capacitance relative to the nameplate value (or to a previous test value) of more than 5-10% is typically considered unacceptable and may warrant further investigation.

2.4 Hot Collar Test/Energized Collar Test

2.4.1 SAFETY HAZARD WARNING

The hot collar band is "partly conductive" which means the resistivity of the band is several ohms. If the band is energized via the HV cable, and some part of the band (e.g. the tail) touches a point at a different potential (e.g. ground), it forms a resistor between the HV injection and that other potential. The dissipated power within the band can destroy the band, and in some cases may result in the band heating excessively, smoking, and/or melting. **Note, this is true for any test equipment manufacturer's hot collar band.**

The solution is to keep a good eye on the setup and avoid having the band contact a point at a different potential (e.g. ground). There is technically nothing wrong with the band and it is not possible to design a band which can withstand this, since we must consider flexible bands within a reasonable price range.

2.4.2 Hot collar overview/assessment

The energized collar measurement should be utilized and assessed with a grain of salt. Just because a bushing Passes a hot collar test, it doesn't necessarily mean that the bushing is in good condition.

Most bushings test with a measured Watt Loss value less than 100mW, which is a typical industry accepted limit for the hot-collar test. In addition, many transformers have sister bushings, which can be compared, and are expected to test with a similar measured Watt Loss value.

The energized collar test is a very sensitive measurement (due to the low Capacitance of the test specimen); therefore, even small differences with the test specimen can produce measurements that appear very different. Also, it does not take much moisture, foreign contaminants, etc. on the surfaces of the bushings to create unusual results.

For the hot collar test, we typically we recommend using the UST mode. The benefit of the UST mode is that it helps guard leakage current due to moisture or contamination on the surface of the bushing. However, to investigate a suspect bushing, it may be worthwhile to perform the test in both the UST and GST modes. Also, I would recommend cleaning and drying the bushing surface before performing any hot collar test on it.

In special cases, it may help to guard a bushing’s surface leakage current via hot-collars during the overall power factor measurement.

Note, when the measured Capacitance is relatively small, we recommend NOT using the “Use reference voltage-10kV correction” feature, because it often exaggerates a difference when comparing similar measurements.

2.4.3 Hot Collar Setup Pictures

Figure 10: Images Demonstrating How to Set Up a Hot Collar Measurement

2.5 Testing a Spare Bushing

The BUSHING POWER FACTOR TESTING (IN-DEPTH) ppt posted to the Bulletin webpage outlines the procedure for testing a spare bushing (on slides 147-148 – see below). Also, PTM allows you to create a Spare Bushing Asset, which then outlines the comprehensive test list for a spare bushing.

At a minimum, a customer should perform the Overall, C1, and C2 tests on a Spare Bushing Asset. The two key items for testing a spare bushing successfully are,

> Establishing a metal stand to hold the bushing in place vertically for testing – Some customers use a large metal drum or the two prongs on a forklift to accomplish this

> Establishing a solid earth ground reference connection, for the metal stand, the bushing flange, and the test-equipment – A ground grid, ground rod, or the ground node of a true power supply should work fine.

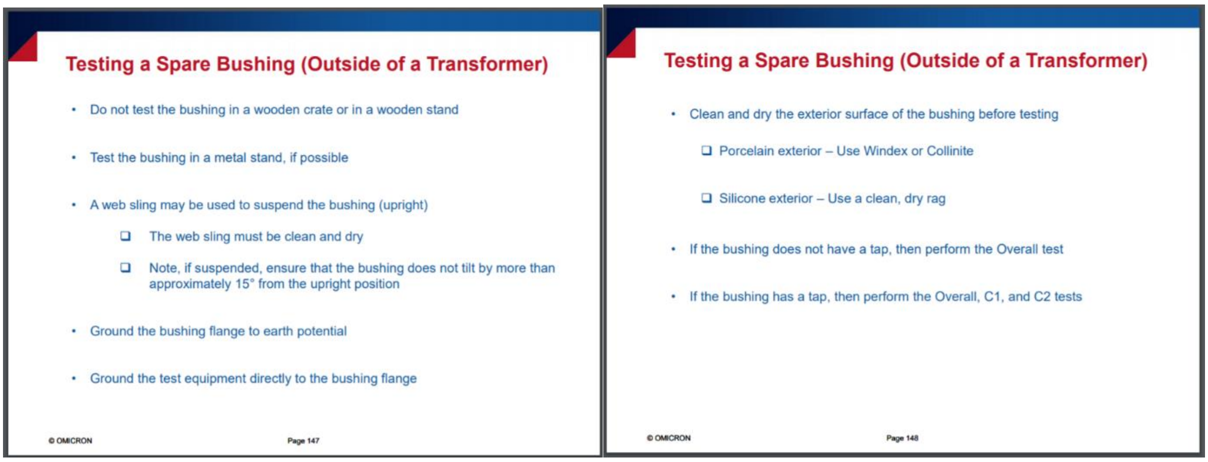


Figure 11: Technical Slides Outlining How to Test a Spare Bushing

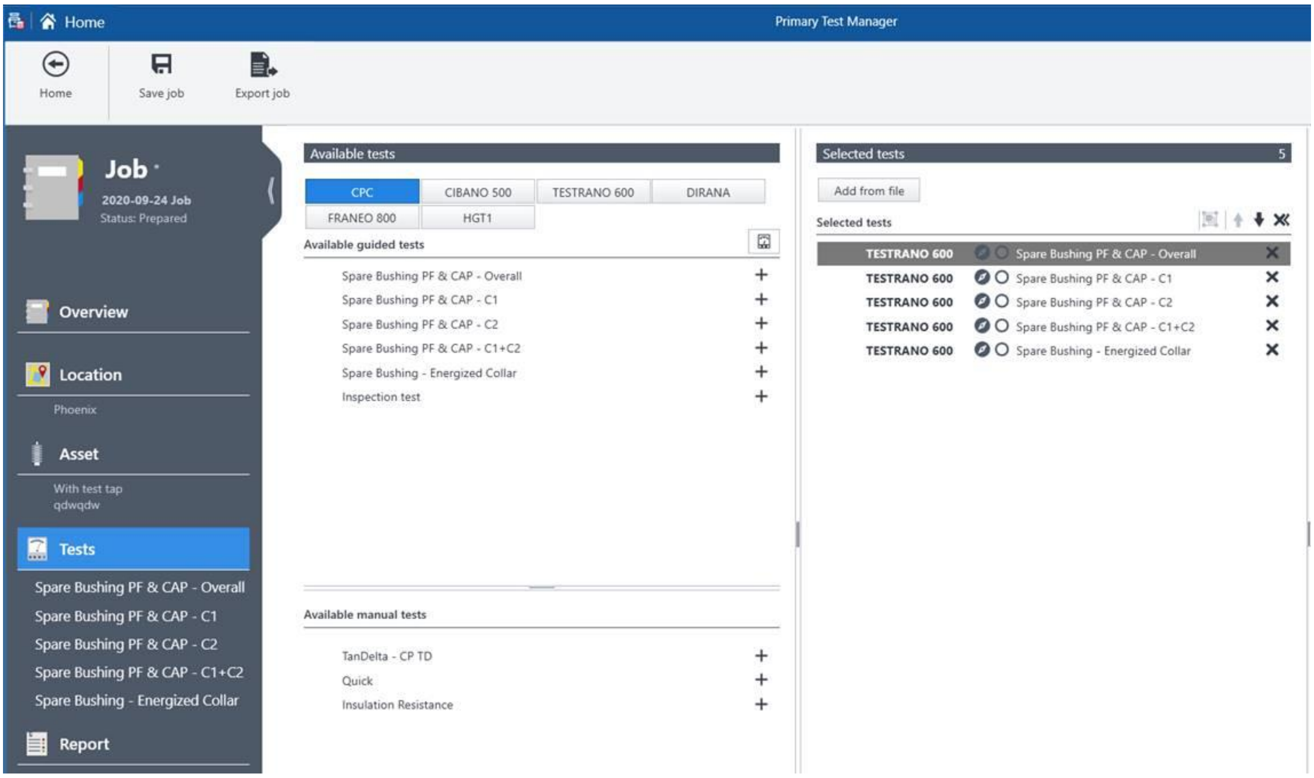


Figure 12: Typical Test Plan in PTM for Testing a Spare Bushing

2.6 Inverted C1 Test and C1+C2 Test on a Bushing

Note, for these two measurements, do not exceed the voltage rating of the test tap.

> Inverted C1 Test (UST-A): High-voltage lead on the bushing test tap, and the return (red-A) lead on the bushing terminal (same test connection as the C2 measurement).

> C1+C2 Test (GST): High-voltage lead on the bushing test tap, and the return (red-A) lead on the bushing terminal (same test connection as the C2 measurement).

3 Surge Arrester Power Factor

3.1 Troubleshooting Surge Arrester Power Factor

> Ensure there's a quality earth-ground connection to the base of the arrester and to the test-equipment

> Was a generator used as a power supply? It is always recommended to use a true power supply/receptacle versus a generator or inverter. We must be aware that using certain generators or inverters can increase the safety risk when operating the equipment, they can result in open-loop errors which prevent the user from executing a test (typically during TD measurements), and they can result in abnormal results (typically during TD measurements). Some generators or inverters are adequate for safely powering OMICRON test equipment.

> Ensure the arrester's exterior surfaces are clean and dry

> The test voltage shouldn't exceed 20% of the line-to-ground voltage rating of the arrester under test

- Ensure that the exterior surface of the test-equipment's high-voltage cable is not touching any surface of the arrester, at the "far-end" where the test-terminal is being energized
- Do not use the "Use reference voltage" function (for 10kV correction) for surge arrester measurements
    - When the measured Capacitance is relatively small like it is for surge arrester PF measurements, we recommend NOT using the "Use reference voltage-10kV correction" feature, because it often exaggerates a difference when comparing similar measurements.
- Confirm that the arresters being compared are true sister units
- One option to troubleshoot an arrester measurement with an unusual GST or GSTg-A test is to apply a jumper from the arrester's base to the substation ground grid node. Does this improve the measurement or not?
- Another option to troubleshoot an unusual GST or GSTg-A test is to connect the test equipment ground directly to the base of the arrester stack
- For a two-stack arrester, it could help to ground the top of the arrester stack, energize the middle point, and perform a GST measurement to ensure the GST measurement is equating to the typical, separate UST-A and GST-gA measurements summed together.
- For a two-stack arrester, it could help to ground the middle point, energize the top of the stack, and perform a GST measurement to ensure the GST measurement is equating to the typical, separate UST-A measurement.

3.2 Surge Arrester Analysis

For surge arrester analysis, we want to assess the measured current and watt loss, as opposed to the power factor. If similar (aka sister unit) surge arresters are available, then the analysis of the test is performed by comparison (i.e. comparing the measured current and watts loss across sister unit arresters).

4 Exciting Current

4.1 Troubleshooting Exciting Current

The following checklist can help you troubleshoot an unusual exciting current measurement,

- Is it user-error?
- Residual magnetism within the core may cause unexpected Exciting Current Test results. The best practice would be to demagnetize the core, and repeat the Exciting Current Test, to remove the influence of the core and see if the results improve. One common cause of residual magnetism is performing the DC Winding Resistance Test before the Exciting Current Test.
    - *Can the transformer be magnetized if it was just de-energized but the winding resistance test wasn't performed yet?*
        - Yes, the core of the transformer will always be magnetized in some way when the unit is removed from service. Usually it's not

magnetized to the extent that causes unusual results, but it can happen.

- *Should we always be de-magnetizing the transformer before any testing?*
  - Typically no, this would probably be overkill for most cases. Usually it's not magnetized to the extent that causes unusual results, but it can happen.

> Did you receive an overcurrent/overload error?

- The test voltage should be carefully considered when performing the exciting current test. The test voltage should be as high as possible without exceeding the line-to-ground voltage rating of the primary winding. In general, the higher the test voltage, the more the insulation system is stressed, which will provide the best opportunity to detect a failure within the transformer.
- It is not uncommon that the maximum allowed test voltage cannot be applied when performing the exciting current test. The test set can "trip" because of exceeding the output volt-amps (VA) power limitation of the test instrument.
- In most cases, if the test set produces an overcurrent/overload when attempting to test all three phases, then it is probably not due to a problem with the transformer, and the test voltage needs to be lowered (I'd just keep cutting it in half) until you can test all three phases and all tap positions at the same voltage; however, if there is a reason to suspect that there is a problem with a given transformer, then I would be more hesitant to apply this general statement.
- Relatively high exciting current measurements are often observed in the following situations,
  - Dry-type transformers have been known to produce higher exciting currents, and often lead to an overcurrent error when energizing at the maximum allowed test voltage
  - Voltage regulators have been known to produce higher exciting currents, and often lead to an overcurrent error when energizing at the maximum allowed test voltage
  - Transformers with a power rating *approximately* less than 5MVA have been known to produce higher exciting currents, and often lead to an overcurrent error when energizing at the maximum allowed test voltage
  - Power transformers with reactive-type load tap-changers have been known to produce higher than normal exciting currents when tested in a "bridging position", and often lead to an overcurrent error when energizing at the maximum allowed test voltage
- Delta primary winding
  - If you're testing a Dyn1 transformer, always start the Exciting Current Test on Phase-C (H3-H2) – this measurement requires the most output power from the test set, so if you can test Phase-C on

all LTC taps without an overcurrent error, then you should be able to test the other phases on all LTC taps without an overcurrent error.

- If the transformer under test has a Delta primary winding and the test instrument “trips” when all three phase-measurements are performed, then it is unlikely (although still possible) that a fault within the transformer is the culprit (assuming the recommended test connections have been made).
- If the transformer under test has a Delta primary winding and only one measurement “trips”, then it is unlikely (although still possible) that a fault within the transformer is the culprit (assuming the recommended test connections have been made).
- If the transformer under test has a Delta primary winding and two of the three phase-measurements “trip”, then a fault within the transformer is possible (assuming the recommended test connections have been made). In this case, the transformer should be investigated immediately.

- If the transformer under test has a Wye primary winding and any combination of the three phase-measurements “trip”, then the user must troubleshoot to determine whether the cause of the “tripping” is due to a failure, user error, or due to the construction of the transformer.

> Keep in mind that when the Exciting Current Test is performed on a Dyn1 transformer, one terminal of the delta winding must be grounded when each phase-measurement is performed. Adding/removing this ground connection will change your relative Exciting Current (mA) values.

> When using the CPC 100, an alternative test could be to perform TTR at 2kV (without the CP SB1) and assess the TTR Exciting Current@2kV. This isn’t a perfect replacement but for diagnostic purposes, but sometimes it’s a reasonable replacement/cross-check (especially on transformers with primary ratings <10kV).

4.2 Why Do Phase Patterns Occur?

Most transformers are constructed with a 3-limbed magnetic core. Typically, the Phase B winding stack is positioned on the center-limb of the magnetic core, while Phases A and C are positioned on the two outer limbs of the transformer core.

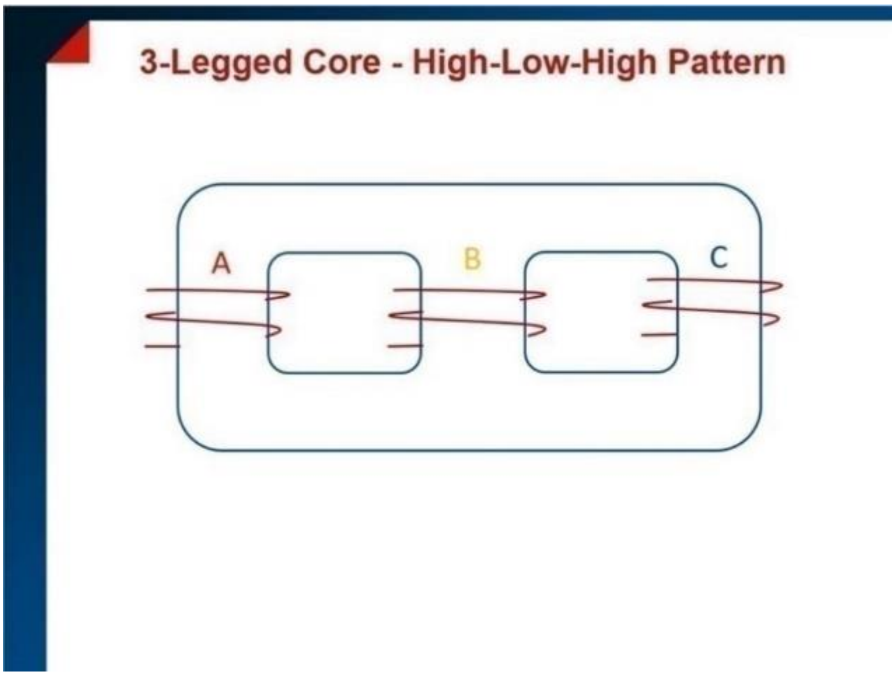


Figure 13: Image Demonstrating a Typical 3-limb Core Construction

When we excite a phase during the exciting current measurement, the applied voltage will result in current flow through the primary winding. Then, this primary current flow will induce flux (which is essentially “magnetic current”) through the transformer core.

- Phase A: When Phase A is “excited”, there are two different flux paths flowing through the transformer core (i.e. one path through the center limb and one path through the opposing outer limb)
- Phase B: When Phase B is “excited”, there are two similar flux paths flowing through the transformer core (i.e. two similar paths from the center limb to the outer limb of the transformer core)
- Phase C: When Phase C is “excited”, there are two different flux paths flowing through the transformer core (i.e. one path through the center limb and one path through the opposing outer limb)

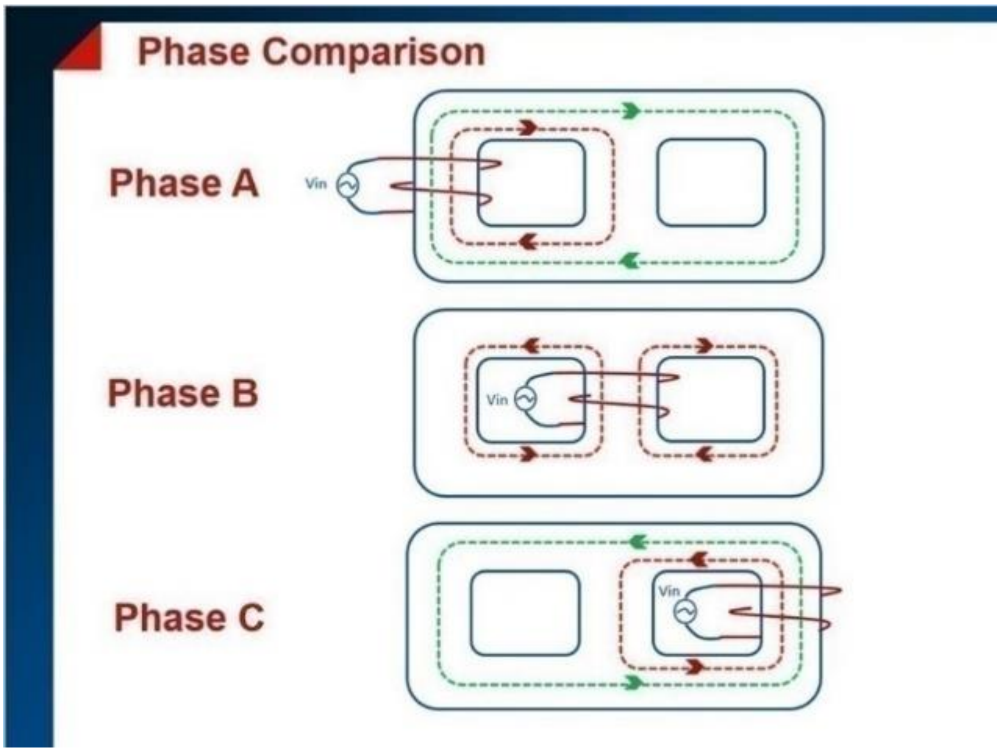


Figure 14: Image Demonstrating the Typical Core Flux Distribution for Exciting Current

By comparing the flux distribution (i.e. the flux paths) of the three phases, there are two key observations,

> The flux distribution through the transformer core is approximately equal for Phases A and C, due to the symmetry of the 3-limbed core. This will result in the exciting current for Phases A and C to be approximately equal.

> If you were to sum the length of the two flux paths for each phase, the length of the two flux paths for Phases A and C is larger than the length of the two flux paths for Phase B. The measured exciting current (mA) is proportional to the length of the flux paths through the transformer core. Therefore, if Phase B is positioned on the center limb of the transformer core, it will typically produce a lower exciting current relative to the other two phases.

This same “High-Low-High” pattern exists within a sweep frequency response analysis (SFRA) trace. An exciting current test and an SFRA open-circuit test parallel each other well and can be used in conjunction to confirm/deny a fault within the transformer core (or to detect residual flux within the transformer core).

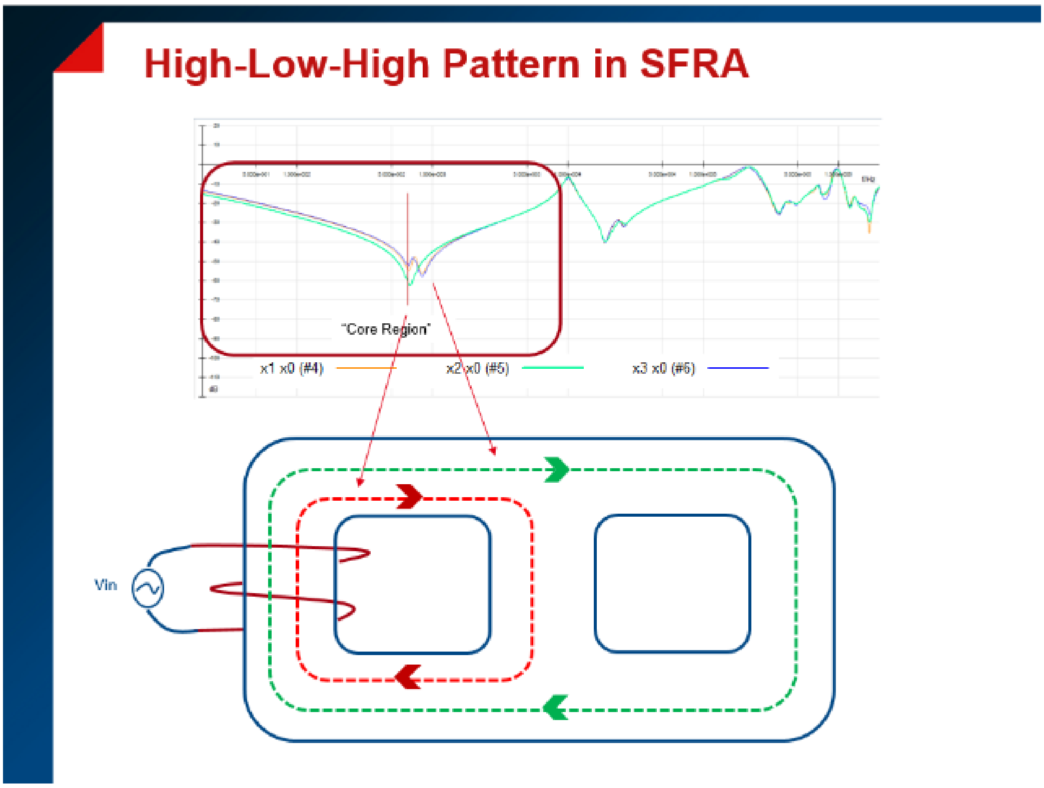


Figure 15: Image Demonstrating the High-Low-High Pattern in SFRA

4.3 High Low High Phase Pattern

It is expected that for a 3-limb core-form transformer with a primary Delta or Wye (with an accessible neutral bushing terminal) winding, the measured exciting current produces a High-Low-High phase pattern. For example, the measured current and Watt Losses of Phase B (the middle phase) should be lower than that of Phases A and C, and Phases A and C should compare reasonably well.

Is there an "expected" value that the two "high" measurements should be within when completing the excitation tests?

There's no hard and fast rule because it depends on the magnitude of current you're measuring, but Phases A and C often compare to within approximately 15-20%. The percentage depends on the magnitude of current however, so sometimes they differ by more than 15-20%.

Keep in mind that when the Exciting Current Test is performed on a transformer with a primary Delta winding, one terminal of the delta winding must be grounded when each phase-measurement is performed. Adding/removing this ground connection will change your relative Exciting Current (mA) values.

4.4 High Low Low Phase Pattern

It is expected that for a 3-limb core-form transformer with a primary Wye winding without an accessible neutral bushing terminal, the measured exciting current produces a High-Low-Low phase pattern. Since there is no neutral accessible on the high-voltage Wye connected winding, we cannot isolate and test each individual phase at a time. Unfortunately, due to the inaccessible neutral, we must excite and measure two phases simultaneously, which results in a "High-Low-Low" phase pattern.

For each measurement, you test/excite two phase-windings in series; therefore, for each measurement, you must sum the relative magnitudes of current for the two phase-windings in series, to obtain the total Exciting Current.

For example, for a Yd1 transformer,

> For the H1-H3 measurement, Phase A and C are tested in series, and they each produce a relatively "High" magnitude of current.

> For the H2-H1 measurement, Phase B and A are tested in series - Phase B produces a relatively "Low" magnitude of current and Phase A produces a relatively "High" magnitude of current. So, the total summed current for the H2-H1 measurement is less than the total summed current for the H1-H3 measurement.

> The H3-H2 measurement involves Phase C and B, so the total summed current is approximately equal to the H2-H1 measurement

4.5 Low High Low Phase Pattern

This pattern is when the Phase B current is higher than A and C. This pattern typically only occurs when testing relatively small transformers with a power rating *approximately* less than 2-3MVA.

Example #1:

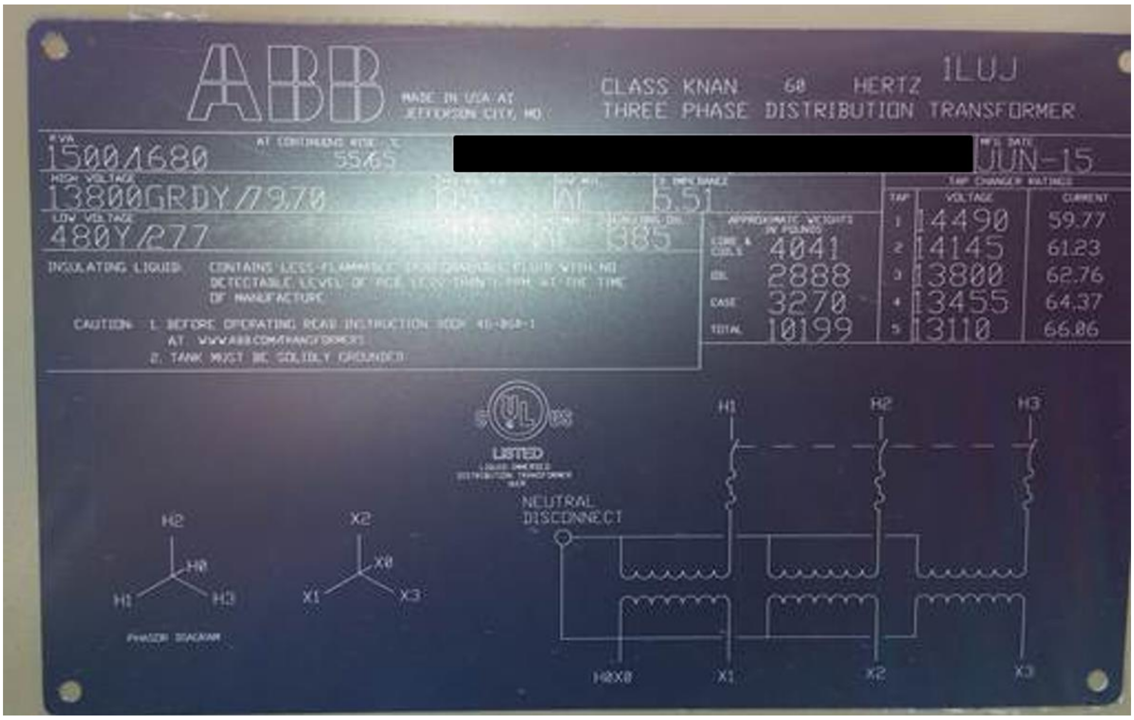


Figure 16: Nameplate Example where Low High Low Phase Pattern was Measured

	Phase A	Phase B	Phase C
Measured Current	113mA	127mA	110mA

Table 2: Measurement Example where Low High Low Phase Pattern was Measured

Example #2:

ABB, Ynyn0, 24.9kV-0.480kV, 1.5MVA, Oil Filled Transformer			
	Phase A	Phase B	Phase C
Measured Current	35.1mA	37.6mA	35.5mA

Table 3: Measurement Example where Low High Low Phase Pattern was Measured

4.6 Exciting Current Automatic Assessment

Unfortunately, it’s difficult to apply an automatic assessment for exciting current. This is because it's difficult to create one umbrella algorithm that can assess the exciting current measurement correctly. The measurement can vary quite a lot based on the construction of the transformer and LTC, so it's just tough to put defined rules in place. We don’t want to create a failed assessment when there isn’t an issue.

Most Exciting Current results are typically NOT compared to previous results (unless there is a reason to suspect that there is a problem with the transformer). The Exciting Current Test is one of the measurements where previous results are not typically needed to reasonably assess the measurement.

Keep in mind, the measured Exciting Current typically fluctuates over time, because the core is not typically magnetized the same way each time the Exciting Current Test is performed; however, regardless of how the core is magnetized, the Exciting Current phase-pattern should not change over time.

4.7 Capacitive Exciting Current Measurements

Most power transformers produce Exciting Current Test measurements that are inductive, as opposed to being capacitive. Most inductive Exciting Current measurements obtained from testing a power transformer, result in the expected “high-low-high” phase-pattern, where the Phase-B current (mA) value is lower in magnitude relative to the Phase-A and Phase-C current (mA) value.

However, occasionally we encounter a power transformer that produces a capacitive Exciting Current measurement. Based on our experience, a capacitive Exciting Current measurement often does not produce the “typical” high-low-high phase-pattern, where the Phase-B current is lower in magnitude relative to the Phase-A and Phase-C current; however, for these cases, we find that, although the measured Current (mA) does not produce the “typical” high-low-high phase-pattern, the measured Watt Loss (W) values do. This is because the watt loss calculation is not dictated by either an inductive or capacitive component, because it involves the measurement of the "real" current.

Therefore, as a rule-of-thumb, if the Exciting Current measurement is capacitive AND the measured Watt Losses produce the expected phase-pattern, then the Exciting Current Test results are typically deemed acceptable (provided that all other diagnostic tests are acceptable and if there is no reason to suspect that the transformer has a problem).

- Inductive Exciting Current measurements produce a positive-signed (+) reactance value, and a negative-signed (-) current phase angle
- Capacitive Exciting Current measurements produce a negative-signed (-) reactance value, and a positive-signed (+) current phase angle

4.8 Testing with a Primary-Side Delta Winding - Test Connection Explanation

For a primary-side delta winding, although we are only measuring the exciting current of one phase at a time, we are actually “exciting” two phases simultaneously. Therefore, the current that the test set (i.e. the CP TD unit) must supply to excite the transformer is always more than what is visible (or shown in the measurement).

For example, on a Dyn1 transformer:

- When performing the exciting current test on Phase A, although you only measure the current for Phase A, the test set must supply the current for both Phases A and B
- When performing the exciting current test on Phase B, although you only measure the current for Phase B, the test set must supply the current for both Phases B and C
- When performing the exciting current test on Phase C, although you only measure the current for Phase C, the test set must supply the current for both Phases C and A

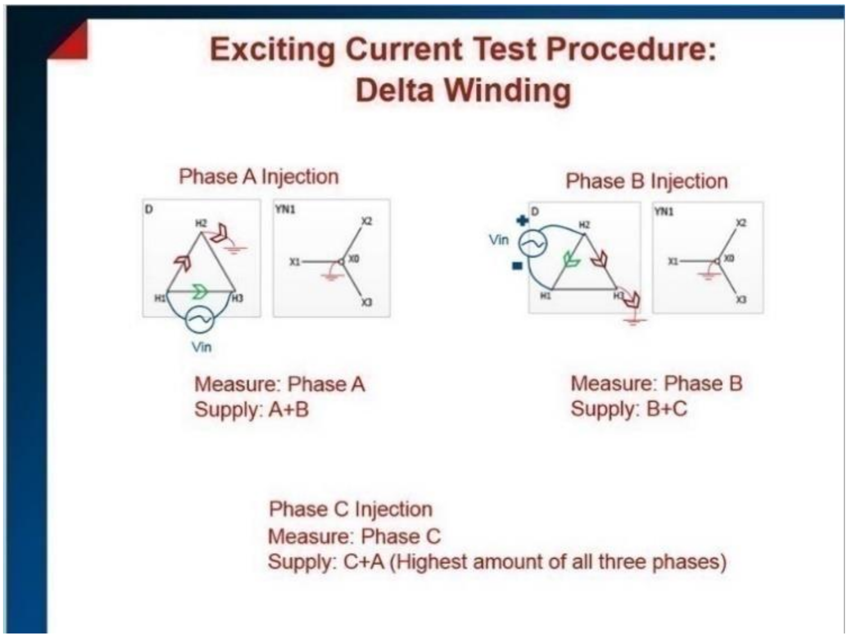


Figure 17: Images Demonstrating Excitation for Delta Primary Winding

For a three-limbed core-form transformer, the exciting current phase-pattern typically follows the "high-low-high" pattern (i.e. Phases A and C are approximately equal, and higher than Phase B). So, by applying the concept described above, the test set must supply the highest amount of current to the transformer during the Phase C exciting current measurement. Therefore, it is not uncommon that the Phase A and B measurements can be completed successfully, while the Phase C measurement returns an "overcurrent error". Therefore for a Dyn1 transformer, always start the Exciting Current Test on Phase-C (H3-H2).

At 10kV the maximum output current of the CP TD unit is approximately 250mA-300mA.

4.9 Differentiating between resistive and reactive LTCs

A user can distinguish between a reactive-type and resistive-type LTC by identifying the number of stationary contacts that the regulating winding has.

A resistive-type LTC can be identified by reviewing the nameplate information (specifically, the wiring diagram) of the transformer. Emphasis should be placed on the regulating winding and tap-changer components shown in the wiring diagram. A resistive-type LTC will typically have a regulating winding that has approximately sixteen stationary contacts (seventeen including the neutral contact).

A reactive-type LTC can be identified by reviewing the number of stationary contacts that the regulating winding of the transformer possesses. A reactive-type LTC will typically have a regulating winding that has approximately eight stationary contacts (nine including the neutral contact), which is approximately half the number of stationary contacts that a resistive-type regulating winding will possess.

4.10 True 3 phase injection, low-voltage exciting current (e.g. TESTRANO 600 exciting current)

The single phase exciting current and a true 3-phase injection exciting current don't provide the same phase patterns, so they can't really be compared in many cases. The 3-phase exciting current is a bit convoluted since it is influenced by more than one phase at a time.

I can't provide any general rules for reliably analyzing the 3-phase low-voltage exciting current measurement, so I must recommend that you not put much effort/weight into analyzing it. I recommend focusing on the measured VTR/TTR and separately, the 10kV single-phase exciting current measurement.

5 TTR

5.1 Assessment Criteria

According to industry guidelines, it is often recommended that the measured turns-ratio compares to the nominal value within ±0.5% for all phases and tap-positions. However, what is also important for the analysis of the turns-ratio measurement is that the ratio deviation percentage for all three phases compares reasonably well. Even if the ratio deviation percentage exceeds the 0.5% recommendation, if all three phases compare reasonably well, then typically, the turns-ratio measurement can be passed. The phase-comparison analysis strategy supersedes the nameplate-comparison analysis strategy.

When performing the TTR test on transformers with LTCs, it is common that the percent deviation exceeds 0.5% when comparing the measured TTR and the nominal TTR. This is especially common when testing the tap-positions farthest from the neutral (e.g. the extreme raise and lower tap positions), but it can occur on any of the tap positions. If all three phases compare reasonably well, then typically, the turns-ratio measurement can be passed.

For example, as can be seen in the following plot, even though some of the tap-positions exceed 0.5%, the ratio deviation for all three phases overlaps well for all tap positions, and therefore, the turns-ratio results can be passed.

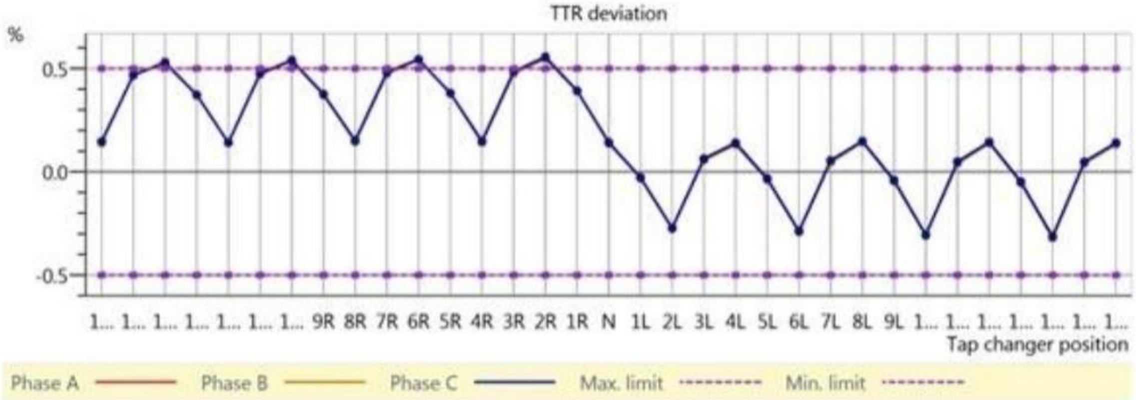


Figure 18: Example of TTR Exceeding 0.5% but Still Passing

Note, a component of the TESTRANO 600's TTR assessment is comparing the phase shift of the Asset's vector group to the measured phase shift (Vphase). If there is a mismatch, it creates the Investigate assessment.

5.2 High voltage (HV) TTR Test

When investigating a questionable transformer, the applied voltage for the turns-ratio measurement should be as high as possible, which provides the best chance to see a fault. An instrument that can only apply 150V-300V may not detect a voltage sensitive insulation failure (e.g. a turn-to-turn short-circuit).

For investigative purposes (e.g. post-fault or when a transformer is gassing), we recommend using either,

- The MCA1 capacitor to perform a high-voltage turns-ratio measurement via the CP TD1/CP TD12.
    - The maximum applied voltage will be dependent on the primary voltage rating of the transformer and the turns-ratio of the transformer, but often 10kV can be applied when using the MCA1.
    - We can also use the MCA1 as a test-specimen for troubleshooting the CP TD1/CP TD12.
- The CPC 100's 2kV source to perform a high-voltage turns-ratio measurement. Please keep in mind that the measured secondary voltage cannot exceed 300V when using the CPC 100's 2kV source to perform a high-voltage turns-ratio measurement.

Note there are some special cases where a high-voltage turns-ratio measurement is needed to measure the correct ratio.

6 DC Winding Resistance

6.1 Troubleshooting DC Winding Resistance with the CPC 100

- Verify the correct test-connections
- Select the appropriate test current
    - When performing the DC Winding Resistance test on a transformer, we recommend that you do not inject a current that is more than 10-15% of the current rating of the winding. For example, if the current rating of the winding is 200A, then please do not inject more than 20A into the transformer winding.
    - In general, the lower the resistance of the winding under test, the higher the test current you should use
    - For some general rules, I recommend the following ranges,

        - If the Resistance < 100mΩ, we often recommend using the 400A DC Source with at least 25A-30A of current
        - If the Resistance > 100mΩ, we often recommend using the 6A DC Source
        - If the Resistance > 10Ω, we recommend using the VDC (2 wire method)
    - We do not recommend using the CP SB1 for resistance measurements lower than 100mΩ (e.g. for winding resistance X measurements on a transformer), due to the 6A DC limitation of the CP SB1.
    - When using the 400A DC source, the measured voltage during the test should not exceed 6.5V DC (once the resistance measurement has stabilized), which is the rated "compliance voltage" of the 400A DC current source. Note, exceeding a measured voltage of 6.5V DC will not typically damage the CPC 100; however, if the measurement is recorded when the measured voltage is > 6.5V DC, then the accuracy of the measurement can be compromised. The maximum test current for the test can be calculated using the following equation,
        - Itest_max = 6.5V / Resistance

- Decrease the "Tolerance R dev" in the settings and conditions section to 0.05% and re-test
    - Note, the "Tolerance R dev" can be set to a lower value with the TESTRANO 600 than the CPC 100, because the ripple of the TESTRANO 600's DC current source is lower than the CPC 100's current source
    - If the "Automatic Result" feature (which can be found in the "Settings and conditions" section) is used when performing the DC Winding Resistance test, we strongly recommend that the "Tolerance R dev" field in PTM is set to 0.05%. Experience has shown that a deviation percentage of 0.1% does not always guarantee that the transformer core will achieve complete saturation and that the measurement is stable (especially when testing lower resistance values)
    - The R dev % that you see on the winding resistance measurement results is not a calculation of the resistance percent difference between the three phases. The R dev % number doesn't relate to the assessment of the measurement. R dev % is related to the Automatic Result function. It is the deviation of the measurement in question over the last recorded Settling Time. Once the measured R dev falls below the value set in the Settings and Conditions section (Tolerance R dev) and remains below that value for the duration of the Settling time (also in the Settings and Conditions section), the Winding Resistance value is said to be stable, and is captured automatically.
    - Note, decreasing the Tolerance R dev % will typically increase the test time (assuming the same injected current), so to counter this, we recommend increasing the magnitude of the test current

- Fail assessment using 2% tolerance when testing low resistances
    - When performing a DC Winding Resistance measurement on a winding that has a resistance below *approximately* 50mΩ, we sometimes must allow a

    - percentage difference between the three phases that is higher than 2% (typically up to 5% maximum). Increasing the assessment tolerance above 2% is done on a case-by-case basis, and good judgement must be used when doing this.
    - In general, the lower the resistance of the winding under test, the higher the percentage difference we typically allow between the three phases.
    - When measuring resistances in the μΩ range, often, a tolerance of more than 2% must be allowed, when comparing the resistance values for the three phases.
- If I find that I am struggling to obtain an accurate measurement when performing the DC Winding Resistance test, one trick is to turn the Automatic Result off and capture the measurements manually after a relatively long wait time (e.g. 5-10 minutes) for each measurement
    - This will require the user to manually select the "Keep Results" button to record the resistance measurement. This can sometimes prevent the test set from recording the measurement before the resistance has stabilized.
    - After turning the "Automatic Result" feature off, I will allow the resistance measurement to run continuously for *approximately* 5-10 minutes, and then I will manually select the "Keep Result" button, to record the measurement and stop the test.
    - This is especially helpful if there's no LTC and only one tap position needs to be tested
- Investigate Assessment due to incorrect measurement range. In most cases, the measurement can still be accurate enough to reasonably assess the test, even if the recommended range is not used. However, overriding the Investigate Assessment is done on a case-by-case basis, and good judgement must be used when doing this.
    - For assessing the condition of the transformer based on the DC winding resistance measurement, the assessment in PTM technically only has either a pass or fail criteria. The pass or fail assessment is provided based on whether the DC winding resistance measurements compare to within 2% amongst the three phases.
    - *However, an investigate assessment is triggered (and supersedes the condition assessment) if the current source selected for the resistance under test, does not fall within the recommended ranges provided in the "general" section of the DC winding resistance measurement (see below).*

8. Recommended measurement ranges for:
    a. DC 6A: 10 mΩ to 10 Ω
    b. DC 400 A: 1 μΩ to 10 mΩ
    c. V DC (2-wire): 10 Ω to 20 kΩ

- Investigate Assessment due to V DC exceeding 10V DC.
    - An investigate assessment can be triggered (and supersedes the condition assessment) if the measured voltage (V DC) exceeds 10V DC, which is the specification limit for the CPC's V DC voltmeter. This software flag was put into place before we allowed the use of the 300V AC voltmeter (in parallel to

the 10V DC voltmeter) to allow a higher measured voltage than 10V. Therefore, this investigates flag no longer applies but still exists in PTM.
    - In most cases, the measurement can still be reasonably assessed, even if the measured voltage exceeds 10VDC. However, overriding the Investigate Assessment is done on a case-by-case basis, and good judgement must be used when doing this.
- CP SB1 6A Source Vs. 400A DC Source
    - For winding resistance tests on lower resistances, although it may sound like using the 400A DC source (as opposed to the CP SB1) for the DC winding resistance would add a significant amount of test time, the test time should be approximately the same (and could even be faster) relative to using the CP SB1. Using the high-current source typically saturates the transformer core much faster (and thus, stabilizes the resistance measurement faster) relative to the CP SB1, so you may find that the measurement is faster with the 400A source.

6.2 Troubleshooting DC Winding Resistance with the TESTRANO 600

- Verify the correct test-connections
- Select the appropriate test current
    - When performing the DC Winding Resistance test on a transformer, we recommend that you do not inject a current that is more than 10-15% of the current rating of the winding. For example, if the current rating of the winding is 200A, then please do not inject more than 20A into the transformer winding.
    - The lower the resistance of the winding under test, the higher the test-current should be
    - Typically, when testing winding resistances greater than 100mΩ, a test-current in the range of 5-10A is enough - most resistance measurements performed on the primary-side (H) winding of a transformer have resistance values greater than 100mΩ
    - Typically, when testing winding resistances less than 100mΩ, a test-current in the range of 20-30A is ideal - most resistance measurements performed on the secondary-side (X) winding of a transformer have resistance values less than 100mΩ
    - The test-current multiplied by the resistance (of the winding under test) should not exceed the maximum compliance voltage rating of the test-instrument's DC current source - In general, the more power (VA) the test-instrument's DC current source is rated for, the higher the test-current that can be injected into a given winding, the faster the DC Winding Resistance Test can be performed.
- Decrease/Keep the "Tolerance R dev" in the settings and conditions section to 0.01%
    - Note, the "Tolerance R dev" can be set to a lower value with the TESTRANO 600 than the CPC 100, because the ripple of the TESTRANO 600's DC current source is lower than the CPC 100's DC current source

- If the "Automatic Result" feature (which can be found in the "Settings and conditions" section) is used when performing the DC Winding Resistance test, we strongly recommend that the "Tolerance R dev" field in PTM is set to 0.01%. Experience has shown that a deviation percentage higher than 0.01% does not guarantee that the transformer core has achieved complete saturation and the measurement is stable, especially when testing lower resistance values.
- The R dev % that you see on the winding resistance measurement results is not a calculation of the resistance percent difference between the three phases. The R dev % number doesn't relate to the assessment of the measurement. R dev % is related to the Automatic Result function. It is the deviation of the measurement in question over the last recorded Settling Time. Once the measured R dev falls below the value set in the Settings and Conditions section (Tolerance R dev) and remains below that value for the duration of the Settling time (also in the Settings and Conditions section), the Winding Resistance value is said to be stable, and is captured automatically.
- Note, decreasing the Tolerance R dev % will typically increase the test time (assuming the same injected current), so to counter this, we recommend increasing the magnitude of the test current

> Fail assessment using 2% tolerance when testing low resistances

- When performing a DC Winding Resistance measurement on a winding that has a resistance below *approximately* 50mΩ, we sometimes must allow a percentage difference between the three phases that is higher than 2% (typically up to 5% maximum). Increasing the assessment tolerance above 2% is done on a case-by-case basis, and good judgement must be used when doing this.
- In general, the lower the resistance of the winding under test, the higher the percentage difference we typically allow between the three phases.
- When measuring resistances in the µΩ range, often, a tolerance of more than 2% must be allowed, when comparing the resistance values for the three phases.

> If I find that I am struggling to obtain an accurate measurement when performing the DC Winding Resistance test, one trick is to turn the Automatic Result off and capture the measurements manually after a relatively long wait time (e.g. 5-10 minutes) for each measurement

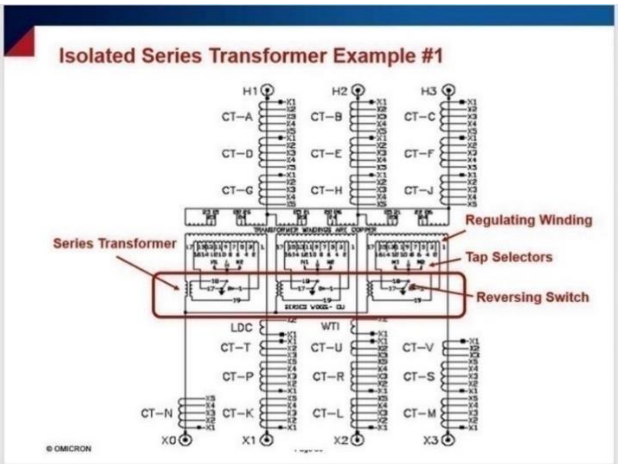
- This will require the user to manually select the "Keep Results" button to record the resistance measurement. This can sometimes prevent the test set from recording the measurement before the resistance has stabilized.
- After turning the "Automatic Result" feature off, I will allow the resistance measurement to run continuously for *approximately* 5-10 minutes, and then I will manually select the "Keep Result" button, to record the measurement and stop the test.
- This is especially helpful if there's no LTC and only one tap position needs to be tested

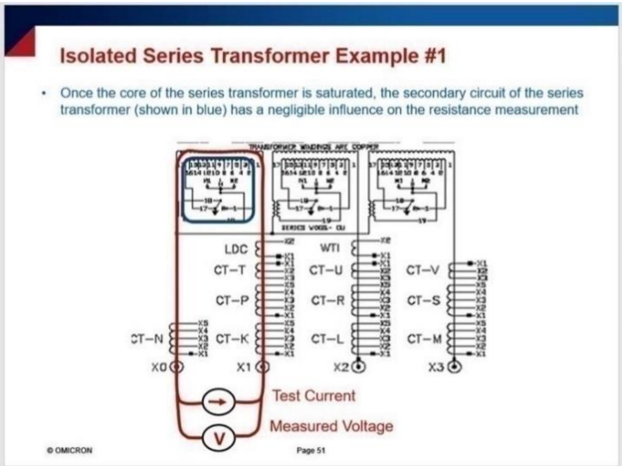
6.3 Series Transformers and its Effect on DC Winding Resistance

Isolating Series Transformers:
Some transformers have a “series transformer” (aka “Series WDG”, aka “booster winding”), which is associated with the LTC. In some cases, a series transformer prevents us from checking the continuity of the components associated with the LTC (i.e. the regulating winding, tap selectors, stationary contacts, barrier board connections, etc.). In such cases, usually you cannot identify a bad connection associated with the LTC’s components, even if one exists; therefore, the diagnostic reach of the static DC Winding Resistance test will be limited in these cases.

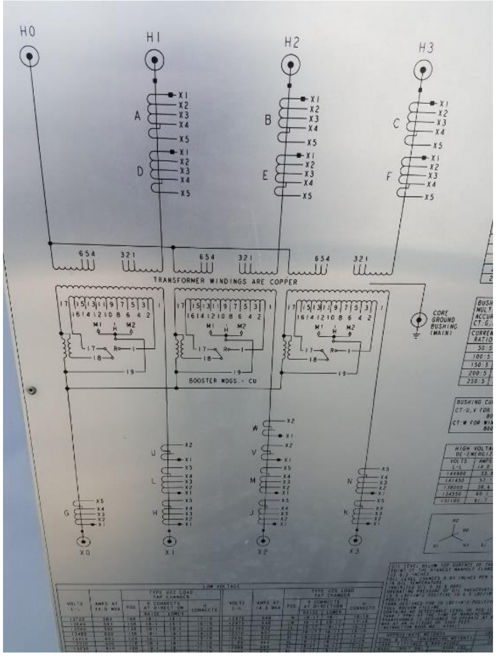
When an isolating series transformer exists, you often only must perform the static DC Winding Resistance measurement on one LTC tap-position (any LTC tap-position of your choosing), because regardless of the LTC position, you will measure the same resistance for each tap. If you notice you’re measuring the same resistance for each tap, then it’s reasonable to stop the test. The diagrams below may help you understand this concept better.

Caution: This concept only applies to isolating series transformers that have a primary winding that is electrically isolated from the regulating winding.





Non Isolating Series Transformers:
Some transformers have a “series transformer” (aka “Series WDG”, aka “booster winding”), which has a primary winding that is NOT electrically isolated from the regulating winding. In such cases, usually you CAN identify a bad connection associated with the LTC’s components, so testing on the different tap-positions is appropriate and necessary. In such cases, usually the primary winding of the series transformer is in parallel to the regulating winding. The nameplate below shows an example of a non-isolating series transformer.



7 Core Demagnetization/Demag

7.1 General Information

It is a good practice to demagnetize the core of the transformer after you have completed your electrical tests (especially after the winding resistance test). Residual magnetism in the transformer core (e.g. leaving the core saturated after a winding resistance test) can lead to undesirable outcomes, including:

> Nuisance trips
> Large system voltage sags
> Large harmonic distortion that has caused tripping of sensitive customer equipment
> Tripping of transformer differential relaying
> Supersaturation of transformers
> Inrush between transformers supplied from a common bus
> High inrush currents that place unnecessary stress on the transformer when it is placed back into service

In addition, residual magnetism within the transformer core may contaminate the test results of electrical diagnostic measurements involving the transformer core (e.g. Exciting Current and SFRA). Therefore, from a diagnostic perspective, it is useful to have an instrument that can demagnetize the transformer core, to rule out the influence of residual magnetism.

7.2 Troubleshooting Demagnetization

The demag test shouldn't take more than approximately 5-10 minutes to complete. To troubleshoot a demag test that isn't working as expected, you can,

- Verify the test-connections
- Adjust the test-current (try lower and higher currents)
    - When performing the Demag test on a transformer, we recommend that you do not inject a current that is more than 10-15% of the current rating of the primary winding. For example, if the primary current rating of the winding is 200A, then please do not inject more than 20A into the transformer winding.
- It's been observed that a demag test can be more challenging to complete on a low voltage/low power rated transformer (e.g. less than approximately 3-5MVA) than a power transformer
- It's been observed that demagnetizing via a Delta winding can be more challenging than demagnetizing via a Wye winding with an accessible neutral terminal
- Occasionally there are instances when performing the Demag test via the primary winding is not successful. In such cases, you can attempt to perform the Demag test by injecting on the secondary winding. HOWEVER, please note that some care must be taken when creating the test plan.
    - The demagnetization feature is slightly different when comparing Delta and Wye windings, so the vector diagram in the Asset section may need to be adjusted if the winding configuration of the secondary is not the same as the primary.
    - A new Asset may need to be created in the PTM software, and the Winding Configuration for this asset should be the opposite of the actual Winding Configuration (e.g. Dyn1 becomes Ynd1). Please do not bother to spend time filling out the other nameplate information, since it is not relevant to the test (i.e. only the serial number, asset/asset type, and winding configuration are necessary).
    - Proceed to the "Demagnetization" test card. Although the test connection in the PTM software will show a wiring diagram, please connect the primary test set leads to the secondary bushing terminals of the transformer, while leaving the transformer's primary bushing terminals open-circuited. For example, for a true Dyn1 transformer with a reversed vector group of Ynd1, connect the H1, H2, H3, and H0 test leads to the secondary bushing terminals of the transformer (to X1, X2, X3, and X0) while leaving the transformer's primary bushing terminals open-circuited.
- To double-check and verify a successful demag test, we recommend that you first perform a Demag test; then, perform the Demag test a second time, to see if the Initial Remanence (for the second test) is reasonably low. If the Initial Remanence for the second test is reasonably low AND the Demag test looks like it is functioning properly, then the Demag test should be working as intended.

8 Leakage Reactance

8.1 Troubleshooting Leakage Reactance

A questionable Leakage Reactance measurement may be caused by one of the following,

- User-error
  - For the CPC 100
    - The user did not short-circuit (with a jumper wire) the 6A current source to the 10A (I AC) ammeter
  - A bad connection somewhere along the test circuit. It is possible that the leads were not connected properly to the test-instrument, the measurement clamps, and/or the bushing terminals
- Is the correct Asset information populated? To “unlock” the Leakage Reactance Automatic Assessment, the following fields must be populated in the “Asset” section of PTM,
    - Leakage Reactance Z (%)
    - Base power
    - Base voltage
    - DETC and/or LTC positions that the factory test was performed on (when applicable)
  - Note, although the nameplate of the transformer provides both a primary and secondary base voltage rating, you should always use the primary voltage rating since the leakage reactance 3-phase equivalent test is performed by injecting a signal on the primary winding of the transformer.
  - In addition, to unlock the leakage reactance assessment, the “temperature correction” box should be selected, and we recommend that the “correction factor” is set to 1 (which is the default value).

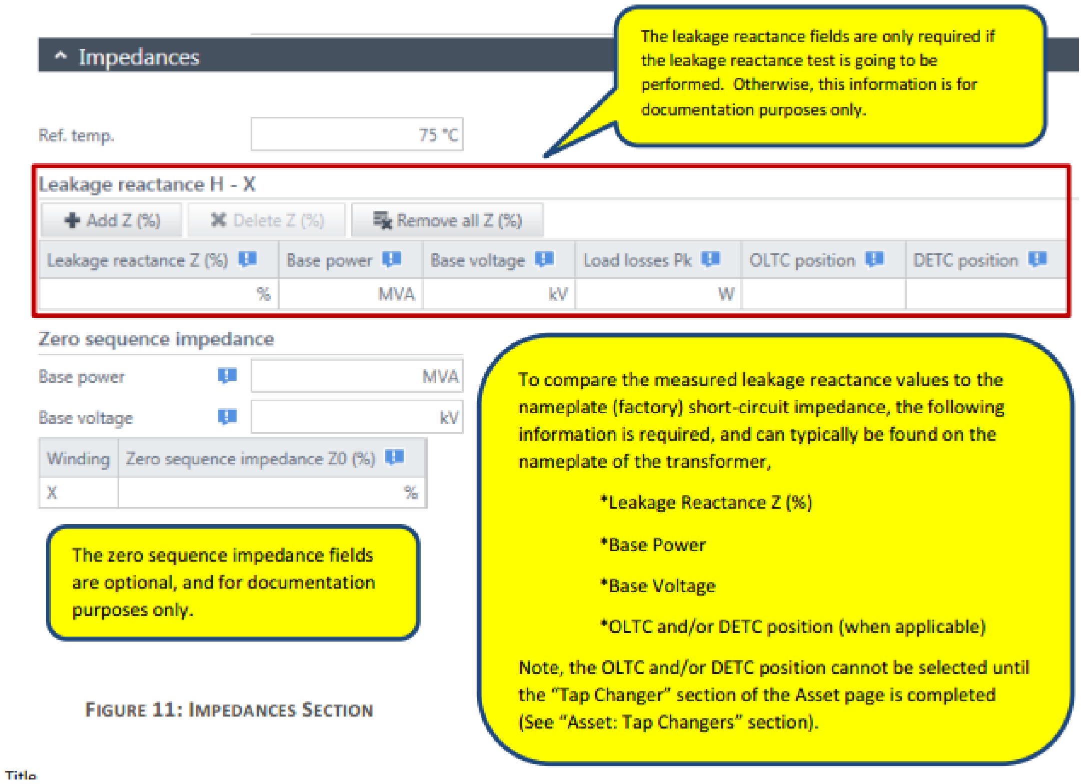


Figure 19: PTM Asset Information Needed for 3-Phase Leakage Reactance Assessment

> Wrong Tap Position
  - To properly compare the field leakage reactance measurement (i.e. the 3-phase equivalent test value) to the factory short-circuit impedance test, the transformer must be tested in the same DETC and OLTC tap-positions as the factory test.
  - In nearly all cases, the factory short-circuit impedance test is performed on the nominal DETC (e.g. position 3 or C) and OLTC (e.g. N or 17) positions.
  - If the transformer wasn't tested on the "nominal" position, then the nameplate impedance percent value and the field impedance percent value should not be compared to each other.
  - If the measured tap-position and the tap position entered in the Asset/Leakage Reactance section match, then it will trigger the comparison between the nameplate impedance percent value and the field impedance percent value.

> Shorting Jumpers
  - The user did not properly short-circuit the secondary of the transformer during the leakage reactance measurement and/or the shorting jumpers used to short-circuit the secondary of the transformer were not appropriately sized. For the leakage reactance measurement, the shorting jumpers that are applied to the secondary-side of the transformer can significantly influence the measurement. This phenomenon is most common when the turns-ratio of the transformer is relatively large. For the

shorting jumpers used during the leakage reactance test, we recommend the following,

    - The shorting jumpers are ideally at least size #4
    - The shorting jumpers should be as short as possible from bushing terminal to bushing terminal
    - The shorting jumpers must make a solid connection to the bushing terminals of the transformer to avoid added contact resistance from influencing the impedance measurement
    - In some special cases it's necessary to short-circuit the X1 and X3 bushing terminals directly, and separately from short-circuiting X1-X2 and X2-X3

- For low power rating/low voltage rating transformers (below *approximately* 5MVA)
  - If the transformer is a small sized transformer (i.e. has a power rating below *approximately* 5MVA), it is not uncommon that the 3-phase equivalent impedance percentage (Zk meas %) deviates from the nameplate impedance value by more than the recommended 3% tolerance.
  - In general, the lower the power rating of the transformer under test, the more the measured 3-Phase Equivalent percentage value tends to deviate from the nameplate value. Deviations of 10-15% in these cases is not uncommon.
  - Sometimes it is difficult to assess the 3-Phase equivalent leakage reactance results for a small transformer, which is why we highly recommend that the Per-Phase leakage reactance measurement is performed on a small transformer. The Per-Phase measurement is typically more valuable to the analysis because the test isolates and tests each individual phase.
- Defective test-instrument
  - For the CPC 100
    - It is possible that the 6A AC source and/or the 10A meter is defective
    - It is possible that one of the fuses which is used to protect the 6A AC current source and/or the 10A AC meter is blown. The fuses are located directly to the right of the 6A AC current source and to the right of the 10A AC meter, on the front panel of the CPC 100
    - To confirm that the source, meter, and fuses are working properly, you can use the quick card to feed the 6A AC current source into the 10A AC ammeter (I AC) of the CPC 100. Please use a test current of 3A when performing this diagnostic check and confirm that the current requested from the source is close to the current measured by the 10A (I AC) ammeter.
- Instrumentation differences between the field leakage reactance test and the factory short circuit impedance test, which may cause discrepancies between the measured 3-Phase equivalent and nameplate value. These instrumentation differences include,
  - The factory impedance test is performed with a 3-Phase injection test set, whereas the field leakage reactance test is performed with a single-phase injection test set

    - The factory impedance test is performed at rated current (i.e. higher power), whereas the field leakage reactance test is performed with a low-current (i.e. lower power) injection
- Significant resistance deviation across phases
    - A significant resistance deviation across phases can be caused by the shorting jumpers and connection technique used to short circuit the secondary side of the transformer. It is important that the shorting jumpers used to test each phase are of similar length and size (especially for transformers with a relatively large ratio). Also, a solid connection to the bushing terminals is important.
    - If the integrity of the shorting jumpers has been confirmed, then a resistance deviation among phases may be due to one of the following,
        - Eddy Current Losses
        - Proximity Losses
        - It is possible that the stray flux within the transformer is cutting through some component of the transformer, which may increase the loss component of the measurement. However, if the reactance (Xk) values compare well across phases, then the leakage channels among the phases are similar, and probably no significant winding movement has occurred within the transformer.
- A physical change (e.g. winding movement) within the transformer

8.2 3 Phase Test

The purpose of the 3-phase equivalent test is to reproduce the factory short-circuit impedance percentage value (which can typically be found on the transformer nameplate). For the 3-Phase equivalent measurement, it is recommended to compare the measured 3-Phase equivalent percentage value (Zk meas %) to the nameplate short-circuit impedance percentage value (Zk ref %). For the 3-phase measurement, we typically recommend that the measured 3-phase impedance percentage value (Zk meas %) compares to the nameplate impedance percentage value (Zk ref %) to within 3%, to “pass” the 3-phase equivalent measurement.

Note, to compare the field measured short-circuit impedance percentage (Zk meas %) to the nameplate value (Zk ref %), the transformer must be tested on the same tap changer position(s) as the factory test (which are typically the nominal positions). A discrepancy between the field and factory tap position(s) will typically cause the measured impedance percentage to deviate from the nameplate value by more than the acceptable tolerance (i.e. 3%). When the transformer is not tested in the same tap position(s) as the factory test, we recommend analyzing the 3-phase equivalent results by using a phase comparison of the measured impedance (Zk) values. We recommend that the measured impedance (Zk) values compare reasonably well, and typically within 2-3%.

For this test, you will short-circuit the secondary windings of the power transformer and perform three impedance measurements while injecting on the primary. You will be injecting AC current

(1-2A is typically sufficient) through a particular phase winding and measuring the AC voltage across that same phase winding. For this test, you will perform one measurement for all three phases (A, B, and C) on the primary side of the transformer, and so, the result of the test is three impedance values. So, the three measured impedance values measured will be,

- Za
- Zb
- Zc

These three impedance values are used in conjunction with the transformer nameplate base power and base voltage to calculate a 3-Phase, per-unit impedance percentage value (%Z). Then, the measured %Z can be compared to the nameplate short-circuit impedance and should compare to within 3% to “Pass” the 3-Phase test.

The impedance percentage value is calculated using the following formula and nameplate information.

$$\%Z = \frac{1}{60}\left[(Z_{AC} + Z_{BA} + Z_{CB})\left(\frac{BasekVA_3}{kV_{ll}^2}\right)\right]$$

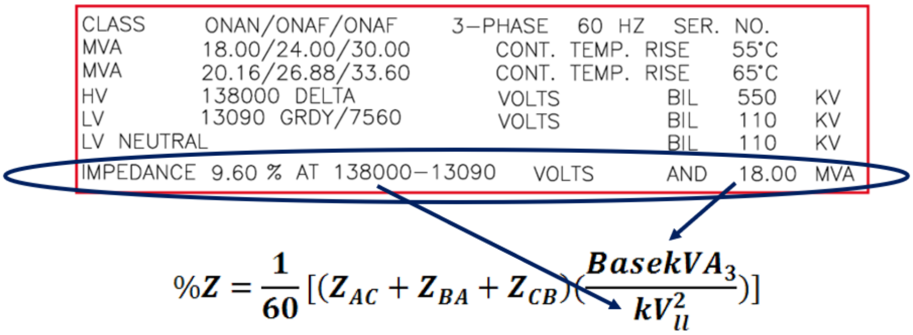


Figure 20: Equations and Nameplate Information Needed for 3-Phase Leakage Reactance Assessment

8.3 Per Phase Test

The purpose of the per-phase test is to detect winding movement within a specific phase of the transformer. The Per-Phase measurement is typically more valuable to the analysis because the test isolates and tests each individual phase of the transformer. Therefore, if an issue exists within a phase of the transformer, it will typically be more obvious with the Per-Phase test, as opposed to the 3-Phase equivalent test (which is a line-to-line impedance measurement consisting of two or more phases).

For the Per-Phase leakage reactance test, we recommend that the measured impedance (Zk) values compare to within 2-3% across the three phases to “Pass” the test. If the transformer “Passes” the Per-Phase leakage reactance test, then typically, there has been no significant winding movement/deformation within the transformer. Finally, even if the measured 3-Phase equivalent value does not compare well to the nameplate value, then the transformer can still “Pass” the overall leakage reactance test, if the Per-Phase test results are acceptable (i.e. the Per-Phase equivalent results typically supersede the 3-Phase equivalent results).

Note, the measured impedances of the per-phase test are not expected to compare well to the nameplate impedance percentage value.
For this test, you will again be performing three impedance measurements by injecting AC current (typically 1-2A) and measuring voltage on the primary of the transformer. However, for this test, you will only short-circuit one phase on the secondary of the transformer at a time (i.e. you will short-circuit the secondary phase of the transformer that corresponds to the primary phase you are injecting on). So, you will perform one measurement for all three phases on the primary of the transformer, and again, the result will be three measured impedance values, which includes

- Za (Per-Phase)
- Zb (Per-Phase)
- Zc (Per-Phase)

9 SFRA

9.1 Troubleshooting SFRA

The following is a list of factors that can influence an SFRA trace, and that can cause two SFRA traces to be dissimilar when comparing over time.

- User error (e.g. a "bad" test connection)
    - When an SFRA trace becomes lower in magnitude, it usually means that there is something impeding the test signal path. Often, this is the result of poor contact resistance on the test lead, clamp, and/or grounding path. This issue is most often seen at the higher frequencies.
- Test instrument failure
    - Perform the "zero check" test to verify that the test equipment is functioning properly
- Residual magnetism – The SFRA trace may change depending on how the core is magnetized at the time of the test
    - The transformer's core will rarely be magnetized the exact same way when comparing SFRA test-dates, so deviations in the frequency range below *approximately* 10kHz of an open circuit test are common. A discrepancy in this frequency range is typically caused by a magnetized core and can often be ignored.
    - Residual magnetism typically only influences the open-circuit tests, but not the short-circuit tests
- Tap-positions – The transformer must be tested on the same DETC and/or LTC tap-position(s) each time the SFRA measurement is performed, to "overlay" and compare similar SFRA traces
- At frequencies of *approximately* 500kHz and above, we expect that the same measurements may not compare well over time.
    - This discrepancy is typically caused by the different test leads used and/or the test lead grounding technique used that may be slightly different when comparing test dates. In many cases, a discrepancy in this frequency range can be ignored.

- An SFRA trace is largely not influenced by the transformer in this higher frequency range. It's typically influenced by the test-lead ground connection/ground loop circuit which is established near the bushing terminals.

- Test voltage – The magnitude of the test voltage typically only influences the "core region" of an open-circuit SFRA trace (i.e. frequencies less than *approximately* 10kHz)
- The bus connection
  - Was the SFRA measurement performed with the bushing terminals completely isolated, or was the bus (surge arresters, support insulators, etc.) connected during the time of the test? Is this different than the previous test?
- Were the SFRA measurements performed using the same "head-to-tail" convention as the previous SFRA measurements (e.g. X1-X0 vs. X0-X1)? We recommend using the "head-to-tail" method, when performing the SFRA test
- The bushing(s) state – Was the SFRA test performed with the bushings installed, with the bushings not installed, or were temporary bushings used during the time of the test? Is this different than the previous test?
- The insulating fluid state – Was the transformer tank filled with oil or not, when the SFRA measurement was performed? Is this different than the previous test?
- The tertiary winding state (if applicable) – Is there is a "broken delta" tertiary, and was it open or closed, and/or grounded when the SFRA measurement was performed? Is this different than the previous test?
- Core ground connection – Is there an external core ground connection, and was it connected or disconnected when the SFRA measurement was performed? Is this different than the previous test?
- Current transformer state – Are there any bushing Current Transformers associated with the power transformer, and was the secondary-side of the CTs shorted, open, grounded, etc.? Is this different than the previous test?
- For a Dyn1 transformer
  - HV Open-Circuit Measurements
    - The Phase-B trace is typically dissimilar from the Phase-A and Phase-C traces, which is expected
  - LV Open-Circuit Measurements
    - The SFRA traces for all three phases typically compare well at frequencies greater than *approximately* 10kHz, which is expected for the LV Open-Circuit Traces of a Dyn1 transformer. Note, a discrepancy between the Phase-B (X2-X0) trace and the other two traces from *approximately* 5kHz-10kHz is expected and is very common for a Dyn1 transformer.
  - HV Short-Circuit Measurements
    - The traces for the three phases typically compare to within 0.2dB (worst-case) at 60Hz, which is acceptable.
- For a Wye winding without an accessible neutral bushing neutral
  - For transformer windings that are wye connected without an accessible neutral bushing terminal, it is common that the Phase-A+Phase-C series

open-circuit measurement deviates from the other two, similar measurements. The other two, similar measurements both involve Phase-B (and either Phase-A or Phase-C), whereas the Phase-A+Phase-C measurement does not involve Phase-B.

> A physical change within the main tank of the transformer

9.2 Recommended Tap Positions for Performing SFRA

Please test the transformer on the DETC that the transformer is going to be in-service on. If you move the DETC position in the future, then please perform the SFRA test on this new DETC position before placing the transformer back into service. Test the transformer with the LTC in either extreme position (e.g. either 16R or 16L). The transformer only needs to be tested in one DETC and LTC position if you use these rules.

9.3 Recommended shorting jumpers for SFRA

For the short-circuit SFRA tests, the shorting jumpers should be solidly connected to the secondary bushing terminals of the transformer, but do not need to be the same cross-sectional area as those used for the leakage reactance test. Typically, using the bare braided copper ("power factor") shorting jumpers supplied with the test set work well for the SFRA test.

10 Different Transformer Types and Configurations

10.1 Voltage Regulators

10.1.1 Overview and Asset Creation in PTM

The key tests for a voltage regulator are outlined below. I also included some useful tips for testing voltage regulators below.

> Overall Power Factor
> Bushing C1 Power Factor (if the bushings have test taps but they probably won't)
> Bushing C2 Power Factor (if the bushings have test taps but they probably won't)
> Exciting Current Test (only if time allows)
> TTR
> DC Winding Resistance

The Voltage Regulator Asset type is in PTM under Transformer. PTM provides guided testing for this asset. VRs are very similar to autotransformers, but the bushing terminal markings are S, L, and S0L0…NOT H, X, and H0X0).

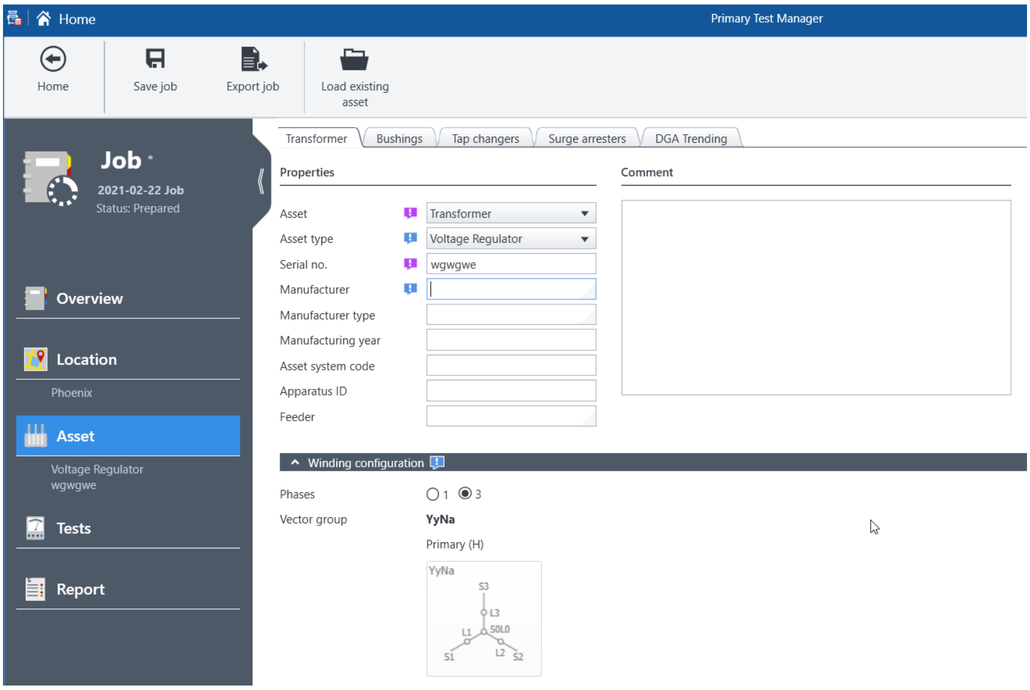


Figure 21: Asset Creation for Voltage Regulator

Voltage Regulators can be either Type A or Type B, where Type B is more popular in NA. You need to place the OLTC on the correct winding (i.e. L vs. S winding) to properly represent Type A or Type B. Also, the Tap Scheme should be set to match the nameplate order.

A Type A Voltage Regulator will typically be set up so that the OLTC is assigned to the L winding. A Type B Voltage Regulator will typically be set up so that the OLTC is assigned to the S winding.

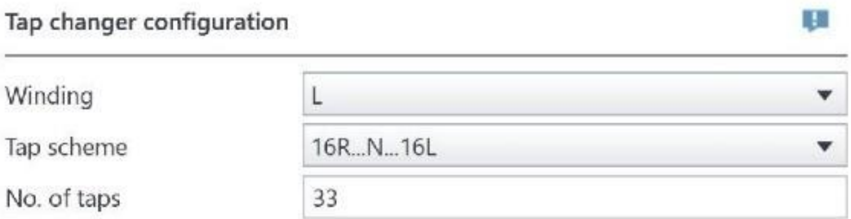


Figure 22: OLTC Creation for Type A

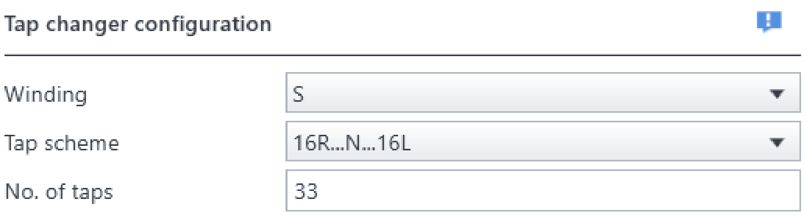


Figure 23: OLTC Creation for Type B

10.1.2 Overall Power Factor measurement tips for a voltage regulator

> Ensure that both the regulator and the test-equipment are solidly grounded to earth-ground

- Short-circuit all the bushing terminals of the regulator using non-insulated leads. Note, the shorting-jumpers should be connected as tightly as possible from bushing terminal-to-bushing terminal.
- Disconnect the “bus” from all the bushing terminals of the regulator
- Remove the in-service ground from any neutral bushing terminal (e.g. S0L0)
- Place the LTC in any off-neutral tap-position
- Ensure that the HV cable is “in the clear”, and that the last two feet of the HV cable is not touching any surface of the transformer (e.g. the transformer tank, the bushings, etc.)
- Perform a GST test
    - Energize the bushing terminals with the HV cable and measure the insulation to ground
    - The red current measurement lead is not used for this measurement - please disconnect it

10.1.3 TTR on voltage regulators

The following two scenarios are common when testing voltage regulators,

1. When performing the TTR test on a voltage regulator, the voltages for each tap-position may not be explicitly defined on the nameplate. In other words, on the nameplate, the user may only see the nominal voltage rating (e.g. 12.470kV) and the percent difference between each tap, or between the Neutral-tap and extreme tap-positions. In these cases, even if the user calculates the difference between each tap (or between the Neutral and extreme tap-positions) correctly, the measured TTR for each tap will probably be slightly different than the calculated TTR; in these cases, the measured TTR and the calculated TTR often differ by more than 0.5%.
2. When performing the TTR test on voltage regulators, it is common that the percent deviation exceeds 0.5% when comparing the measured TTR and the nominal TTR, especially when testing the tap-positions farthest from the neutral (e.g. the extreme raise and lower tap positions).

If the voltage regulator has a 3-Phase configuration, then what is most important for the TTR test analysis, is that the measured ratio is reasonably similar when comparing the three phases to each other. In nearly all cases, when testing a 3-Phase regulator or transformer, if the measured TTR is reasonably similar when comparing the three phases to each other, then the TTR “passes”. The phase-comparison analysis strategy supersedes the nameplate-comparison analysis strategy.

For single-phase voltage regulators, the TTR analysis is more challenging because you cannot directly compare the measured ratio for one phase to the other two phases on the same unit (like you can for a 3-Phase regulator). If you are testing a single-phase voltage regulator, then comparing the TTR measurement to TTR measurements performed on its sister units can be helpful. Comparing to a previous/historical TTR measurement on the same regulator can also be helpful.

I recommend using your best judgement when analyzing the TTR test on a voltage regulator. Keep in mind that, in most cases, the TTR test should “pass”. If there is reason to suspect that a given voltage regulator has a problem, then I would tend to be stricter with the analysis. If not, then I would tend to be more lenient with the analysis.

10.1.4 Voltage regulator without an accessible neutral terminal – workaround:

You can test this voltage regulator by treating it as a two-winding transformer with a Yy0 vector group configuration (see the screenshot below). The two-winding transformer with a Yy0 vector group configuration workaround is a nice solution for all the tests except for Overall Power Factor (see below). For the connection diagrams (for the tests other than Overall Power Factor), just swap the H terminals with S's and the X terminals with L's.

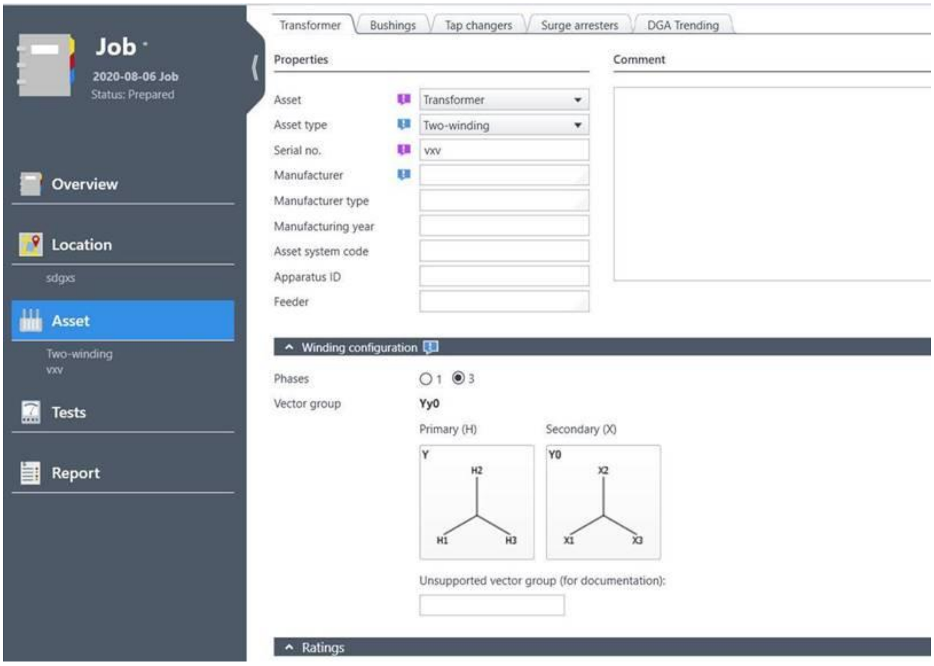


Figure 24: Asset Creation for Workaround

For the Overall Power Factor measurement on a regulator *without* an accessible neutral:

> Ensure that both the regulator and the test-equipment are solidly grounded to earth-ground
> Short-circuit all the bushing terminals of the regulator using non-insulated leads. Note, the shorting-jumpers should be connected as tightly as possible from bushing terminal-to-bushing terminal.
> Disconnect the "bus" from all the bushing terminals of the regulator
> Place the LTC in any off-neutral tap-position
> The high-voltage lead will be placed on either of the six bushing terminals
  - Ensure that the HV cable is "in the clear", and that the last two feet of the HV cable is not touching any surface of the transformer (e.g. the transformer tank, the bushings, etc.)
> **Perform a GST test**
  - **Energize the bushing terminals with the HV cable and measure the insulation to ground**
  - **The red current measurement lead is not used for this measurement – please disconnect it**
  - **The test voltage will be dictated by the rating of the secondary winding and the secondary bushings**
  - **Execute line 4 only in the two-winding Overall PF test plan**

10.2 Wye Wye Two-Winding with Bonded Neutral and H0X0 Bushing

10.2.1 Asset Creation in PTM

I recommend using the following Winding Configuration/Vector Group in PTM for this transformer type. For the connection diagrams in PTM (for the tests other than Overall Power Factor), you can use them without any issue.

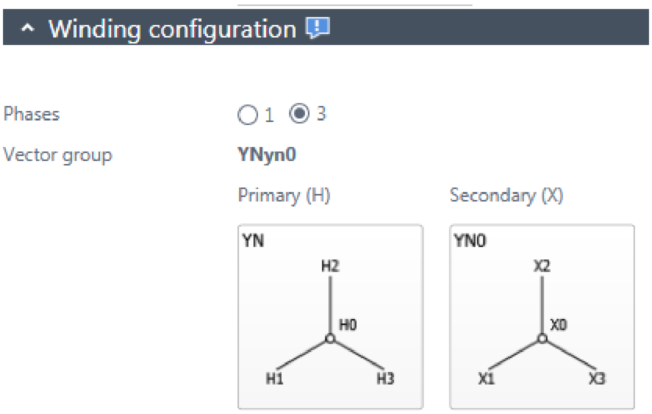


Figure 25: Recommended Vector Group

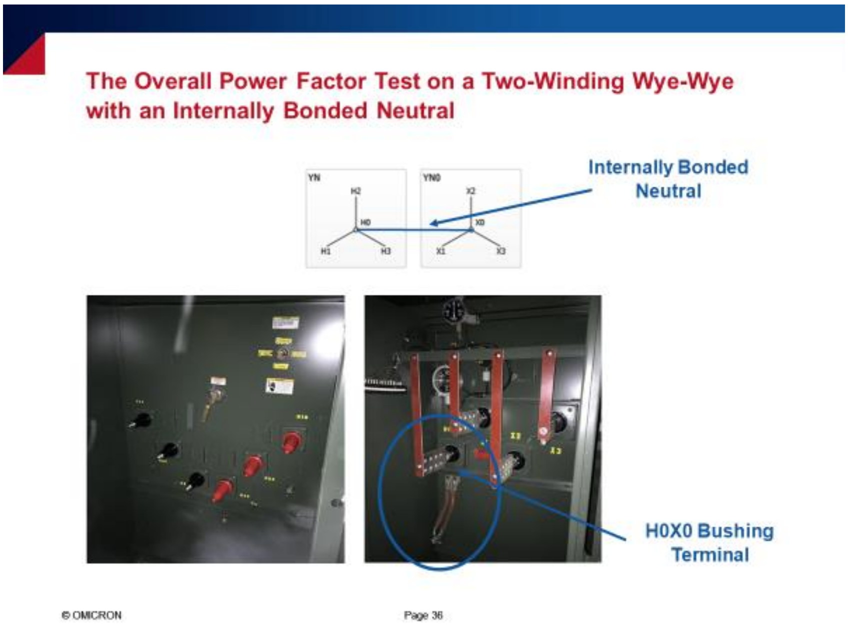


Figure 26: Example of this Transformer Type

10.2.2 Overall Power Factor Test

To perform a Power Factor measurement on this type of transformer, first confirm that the neutrals are internally short-circuited together and that only one neutral bushing is accessible (most likely labeled H0X0). Then,

- > Ensure that both the transformer and the test-equipment are solidly grounded to earth-ground
- > Short-circuit all the bushing terminals of the transformer using non-insulated leads. Note, the shorting-jumpers should be connected as tightly as possible from bushing terminal-to-bushing terminal.
- > Disconnect the "bus" from all the bushing terminals of the autotransformer
- > The high-voltage lead will be placed on either of the seven bushing terminals
- > Ensure that the HV cable is "in the clear", and that the last two feet of the HV cable is not touching any surface of the transformer (e.g. the transformer tank, the bushings, etc.)
- > **Perform a GST test**
    - o **Energize the bushing terminals with the HV cable and measure the insulation to ground**
    - o **The red current measurement lead is not used for this measurement - please disconnect it**
    - o **The test voltage will be dictated by the rating of the secondary winding and the secondary bushings**
    - o **Execute line 4 only in the two-winding Overall PF test plan**

10.2.3 Exciting Current Test

- > Remove the in-service ground from the bonded neutral H0X0
- > Perform the measurement for each phase as expected for a Wye primary with a neutral
    - o Connect the high voltage injection lead to H1 bushing terminal & the measurement lead to the bonded neutral H0X0
    - o Perform a UST-A measurement
    - o Repeat for each phase (H2-H0X0 & H3-H0X0)

10.3 Autotransformers

10.3.1 Overall Power Factor measurement tips for an Autotransformer without a tertiary

- > Ensure that both the autotransformer and the test-equipment are solidly grounded to earth-ground
- > Short-circuit all the bushing terminals of the autotransformer using non-insulated leads. Note, the shorting-jumpers should be connected as tightly as possible from bushing terminal-to-bushing terminal.
- > Disconnect the "bus" from all the bushing terminals of the autotransformer
- > Remove the in-service ground from any neutral bushing terminal (e.g. H0X0)
- > Place the LTC in any off-neutral tap-position
- > Ensure that the HV cable is "in the clear", and that the last two feet of the HV cable is not touching any surface of the transformer (e.g. the transformer tank, the bushings, etc.)
- > Perform a GST test
    - o Energize the bushing terminals with the HV cable and measure the insulation to ground

- The red current measurement lead is not used for this measurement – please disconnect it

10.3.2 Autotransformer without an accessible neutral H0X0 terminal – workaround:

You can test this autotransformer by treating it as a two-winding transformer with a Yy0 vector group configuration (see the screenshot below). The two-winding transformer with a Yy0 vector group configuration workaround is a nice solution for all the tests except for Overall Power Factor (see below). For the connection diagrams in PTM (for the tests other than Overall Power Factor), you can use them without any issue.

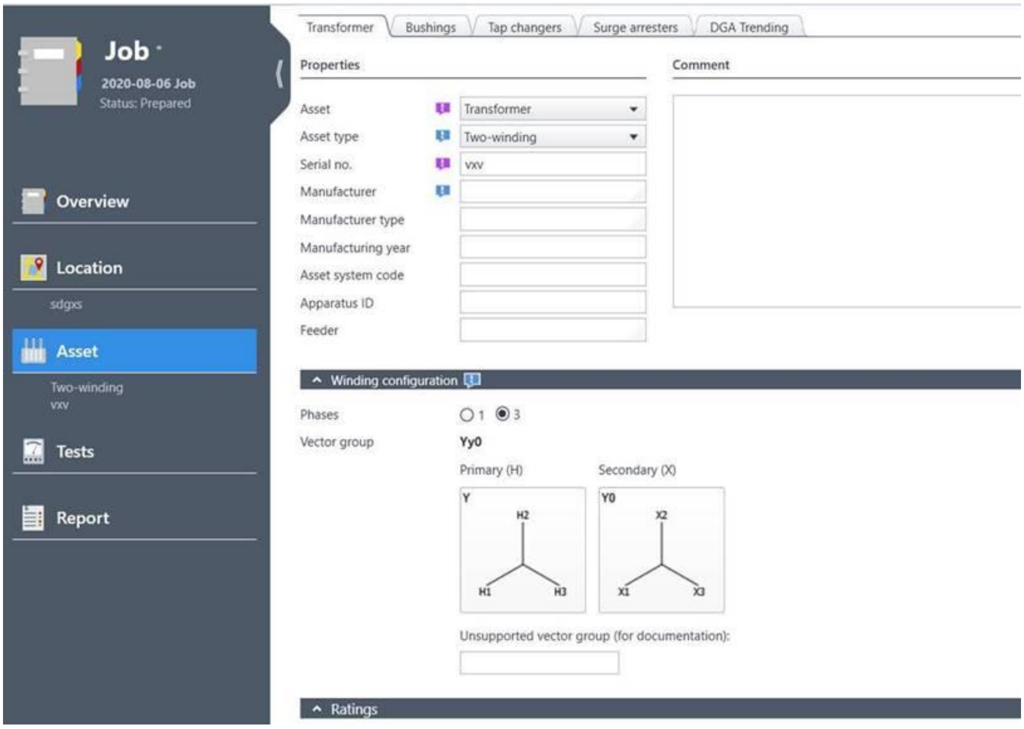


Figure 27: Asset Creation for Workaround

For the Overall Power Factor measurement on an autotransformer *without* an accessible neutral:

> Ensure that both the autotransformer and the test-equipment are solidly grounded to earth-ground

> Short-circuit all the bushing terminals of the autotransformer using non-insulated leads. Note, the shorting-jumpers should be connected as tightly as possible from bushing terminal-to-bushing terminal.

> Disconnect the “bus” from all the bushing terminals of the autotransformer

> Place the LTC in any off-neutral tap-position

> The high-voltage lead will be placed on either of the six bushing terminals

- Ensure that the HV cable is “in the clear”, and that the last two feet of the HV cable is not touching any surface of the transformer (e.g. the transformer tank, the bushings, etc.)

> **Perform a GST test**

- **Energize the bushing terminals with the HV cable and measure the insulation to ground**

- The red current measurement lead is not used for this measurement – please disconnect it
- The test voltage will be dictated by the rating of the secondary winding and the secondary bushings
- Execute line 4 only in the two-winding Overall PF test plan

10.4 Zig zag grounding transformers

10.4.1 Asset Creation in PTM

We don't have this specific Transformer Asset Type in PTM, but my recommended workaround is to use the following Asset Type in PTM; however, you'll need to ignore all the X terminals, X test leads, and X windings in the connection diagrams.

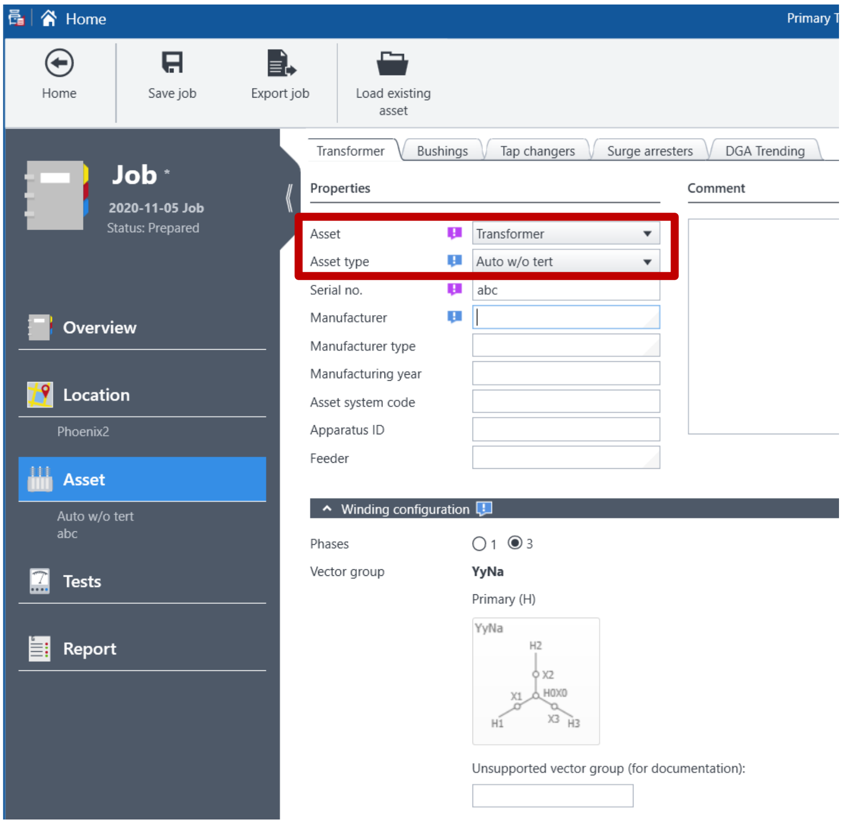


Figure 28: Asset Creation for Workaround

10.4.2 Recommended test list

If it's an oil filled one-winding zig-zag grounding transformer, you can perform,

> Overall PF

- Ensure that both the transformer and the test-equipment are solidly grounded to earth-ground
- Short-circuit all the bushing terminals of the transformer using non-insulated leads. Note, the shorting-jumpers should be connected as tightly as possible from bushing terminal-to-bushing terminal.

    - Disconnect the “bus” from all the bushing terminals of the autotransformer
    - The high-voltage lead will be placed on either of the bushing terminals
    - Ensure that the HV cable is “in the clear”, and that the last two feet of the HV cable is not touching any surface of the transformer (e.g. the transformer tank, the bushings, etc.)
    - Perform a GST test
        - Energize the bushing terminals with the HV cable and measure the insulation to ground
        - The red current measurement lead is not used for this measurement – please disconnect it

- Exciting Current
    - Test H1-H0, H2-H0, and H3-H0
    - A “one high and two lows” phase pattern is typically expected – the measurement involving Phase A and C in series should be the “high” measurement
- DC Winding Resistance H
    - Test H1-H0, H2-H0, and H3-H0
    - With the TESTRANO 600 use the Single-Phase mode only
- SFRA (optional) – Test H1-H0, H2-H0, and H3-H0 (open circuit tests only)

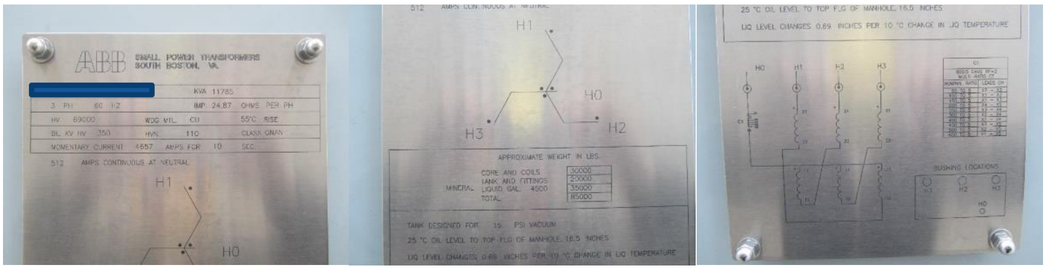


Figure 29: Nameplate Example

10.5 Phase shift transformers/phase shifting

Can we test phase shift transformers with the TESTRANO 600? Does the unit show the phase angle, or does it give a phase deviation from another phase?

Yes, phase shift transformers are a good application for the TESTRANO 600. The TESTRANO 600 shows the phase angle for all three phases. This is all due to its true 3-phase injection.

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