FIELD ELECTRICAL TESTING

Minneapolis, MN RTS

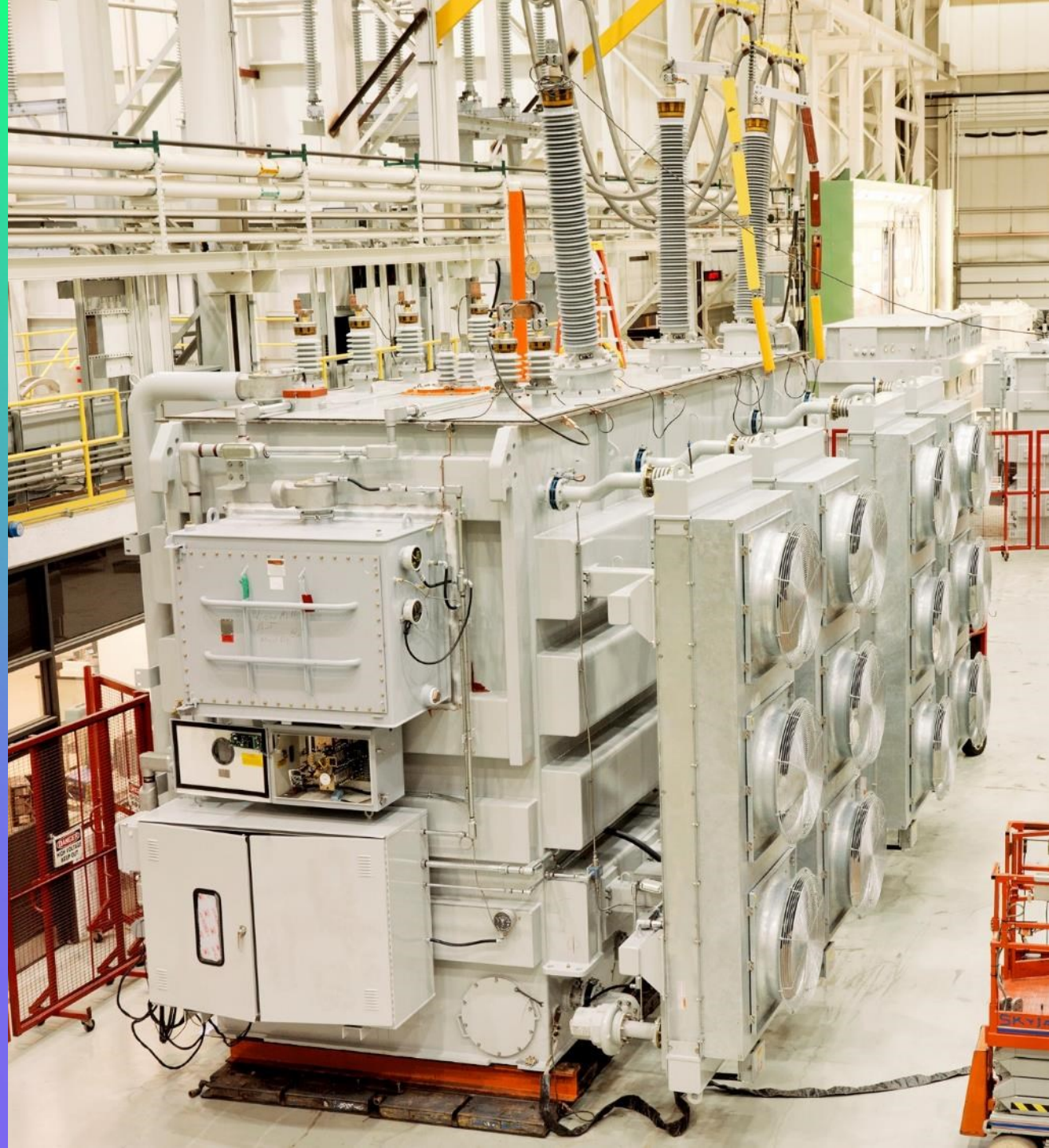
August, 2024

waukesha

a prolec ge company

waukesha
a prolec ge company

Field Electrical Testing



Field Electrical Testing Applications

Key Purposes of Field Electrical Testing:

- Acceptance testing/commissioning of new equipment
- Routine maintenance programs
- Diagnostics/troubleshooting

Field Acceptance Testing – Transformer Assembly

Prior to Assembly

- Dew Point (initial)
- Core Ground Test (initial)

After Assembly, Prior to Filling

- Transformer Turns Ratio (AC)
- Current Transformer Testing (AC)

Post Vacuum Oil Processing/Filling

- Power Factor Testing (AC)
- Excitation Testing (AC)
- Frequency Response Analysis (AC)
- Insulation Resistance (DC)
- Winding Resistance Testing (DC)
- Core ground test (final)
- Controls and Alarm checks
- Oil Sample/DGA

Core Resistance (Megger)

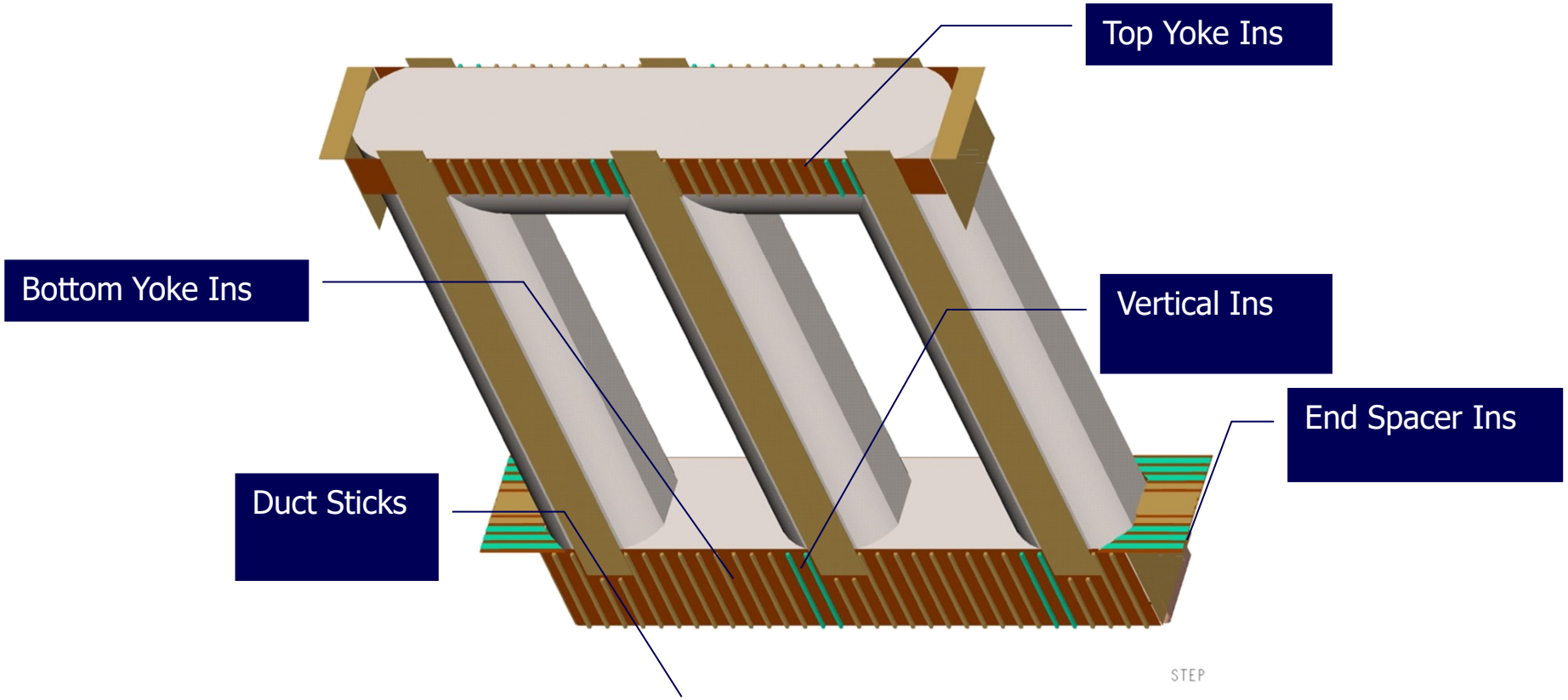
- **Purpose**
  - Prove insulation integrity of core from ground potential and test for inadvertent core grounds
- **Method**
  - Using megger instrument, 1000V is applied for one minute to core ground strap
  - Some transformers may have multiple core grounds and/or a separate clamp/end-frame ground; each should be tested independently
    - Preventative autotransformer
    - Series transformer
    - Clamp
  - Some transformers may be constructed such that core ground strap is not accessible

Core Resistance (Megger)

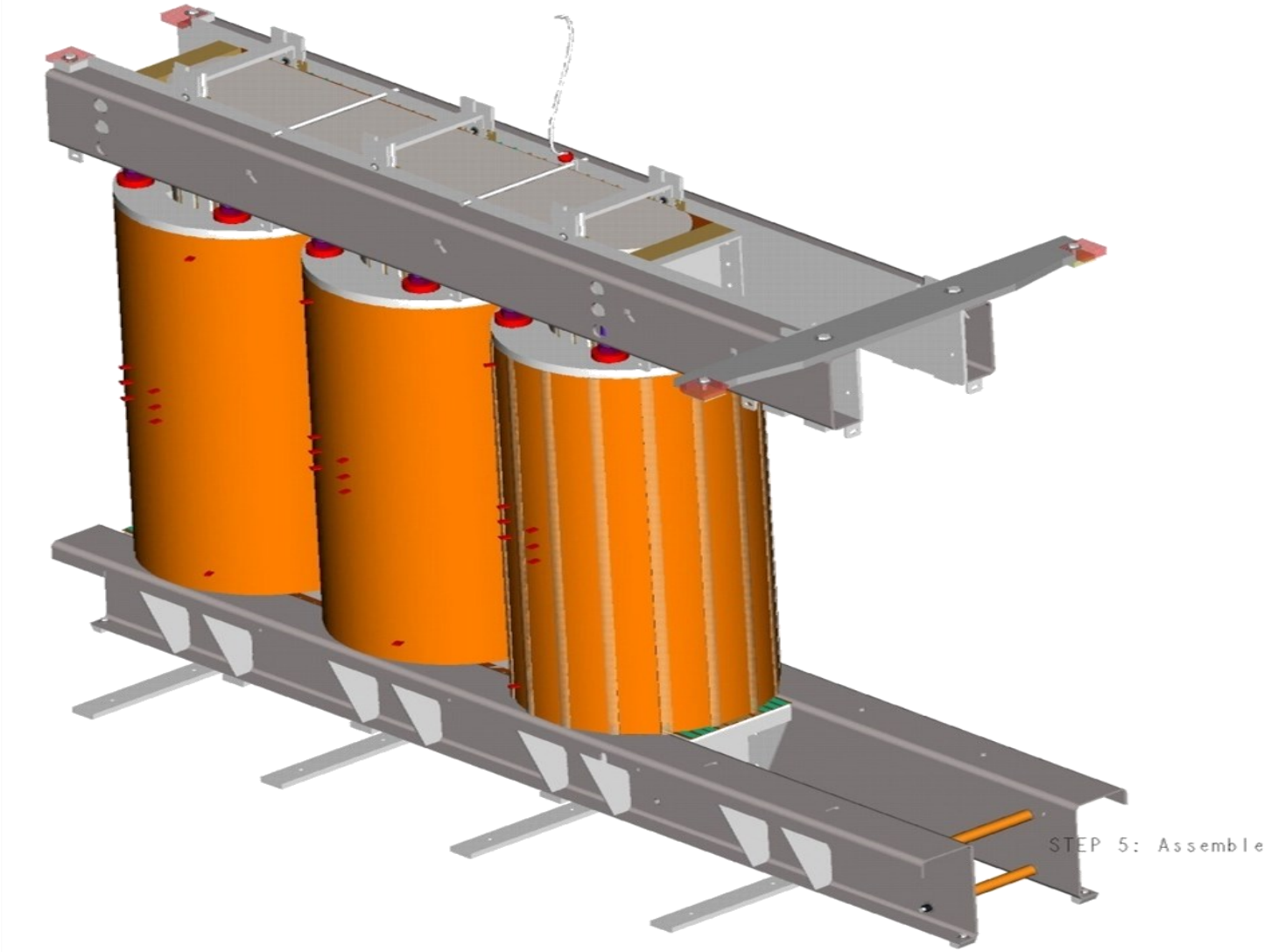
Acceptance Criteria

- Minimum standard acceptance limit is 100 megaohms when corrected to 20°C
- Test is sensitive to temperature, moisture and contamination
- Measured values will be different in air and oil

Core Insulation Resistance (Core Megger)



Core Insulation Resistance (Core Megger)



Field Acceptance Testing – Transformer Assembly

Prior to Assembly

- Dew Point (initial) ☑
- Core Ground Test (initial) ☑

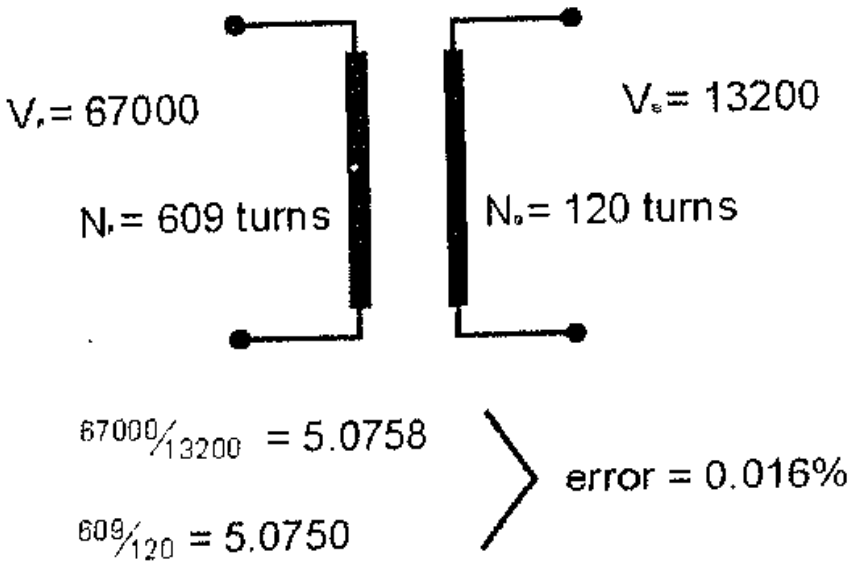
After Assembly, Prior to Filling

- Transformer Turns Ratio (AC)
- Current Transformer Testing (AC)

Post Vacuum Oil Processing/Filling

- Power Factor Testing (AC)
- Excitation Testing (AC)
- Frequency Response Analysis (AC)
- Insulation Resistance (DC)
- Winding Resistance Testing (DC)
- Core ground test (final)
- Controls and Alarm checks
- Oil Sample/DGA

Transformer Turns Ratio



Purpose

Test is done to verify all internal connections and winding configurations are correct.

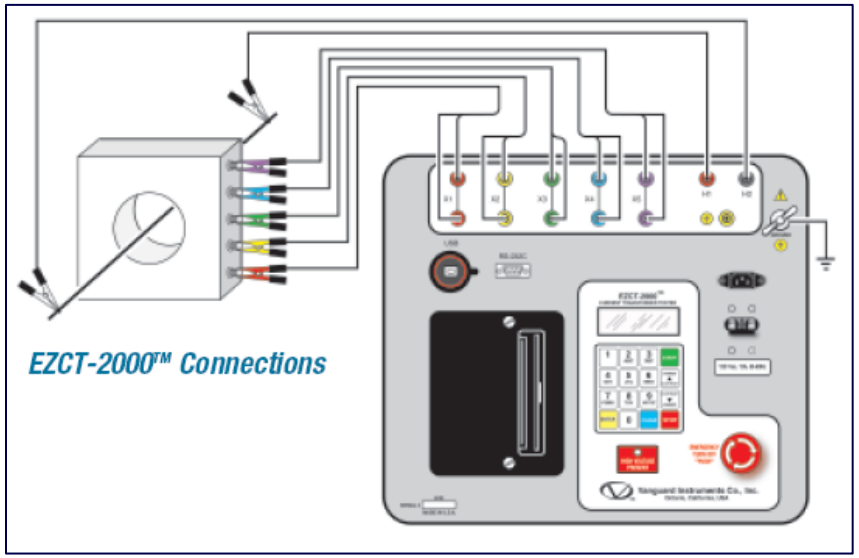
Method

Tests are conducted using low voltage ratio bridge or three phase power supply and voltmeters.

Voltage is applied to the primary winding and the voltage is measured on a secondary winding.

Test is conducted at multiple tap positions. Ratio is calculated in accordance with nameplate values.

CT Ratio, Polarity & Excitation Current



- Verify proper ratio and polarity of current transformers
- Ratio and excitation current can be verified either by primary current injection or secondary voltage injection
- Polarity is verified by battery polarization or buck/boost circuits
- Varied depending on relay accuracy and burden rating of the CT; generally ±1% of calculated ratio

Field Acceptance Testing – Transformer Assembly

Prior to Assembly

- Dew point (initial) ☑
- Core ground test (initial) ☑

After Assembly, Prior to Filling

- Transformer Turn Ratio (AC) ☑
- Current Transformer Testing (AC) ☑

Post Vacuum Oil Processing/Filling

- Power Factor Testing (AC)
- Excitation Testing (AC)
- Frequency Response Analysis (AC)
- Insulation Resistance (DC)
- Winding Resistance Testing (DC)
- Core ground test (final)
- Controls and Alarm checks
- Oil sample/DGA

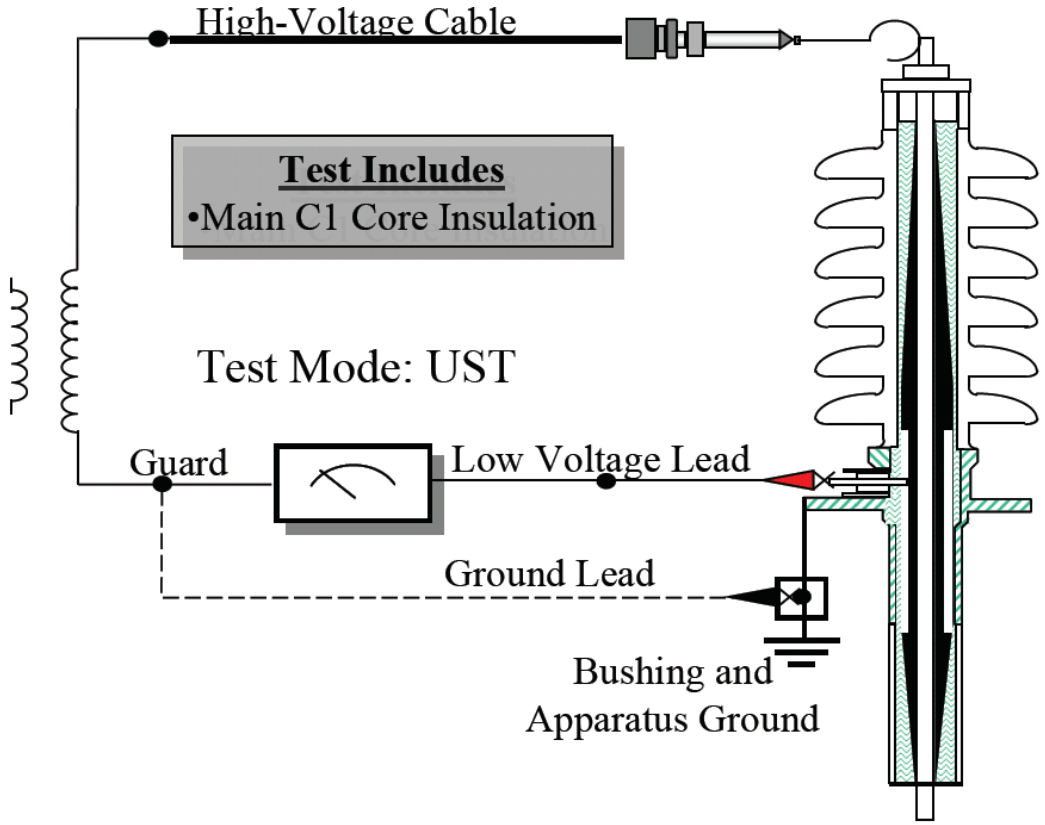
Power Factor Testing – Bushings

Purpose

Detection of moisture or foreign contamination in the insulation structure or damage or excessive contamination to external surfaces.

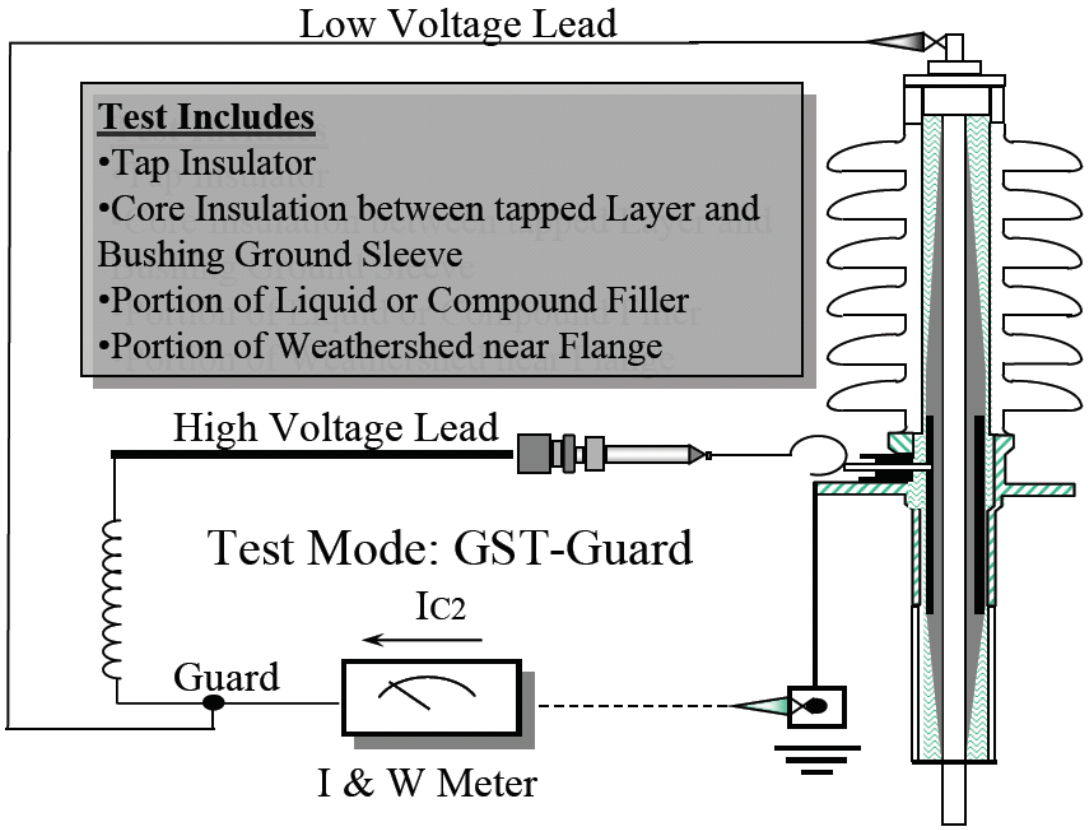
Method

- Insulation power factor bridge is used to measure power factor and capacitance of bushings.
- Test voltages are determined by bushing design and construction.
- Power factor bridge shall be capable of a test voltage of 10 kV.
- Readings are corrected to standard temperature.
- Testing is highly susceptible to temperature, humidity and contamination.



Power Factor Testing – Bushings

- C1 test checks main core insulation
- C2 test checks tap insulator and core insulation between capacitance tap and ground flange
- Hot collar tests can be done for solid bushing



Power Factor Testing – Bushings

Acceptance criteria

Standard acceptance limit for bushings is 0.5% when corrected to 20°C.

Typical maintenance limits:

Good < 0.5%
Deteriorated 0.5% - 1.0%
Investigate > 1.0%

- Recommended that the readings be compared to nameplate values. Bushings should be replaced when the measured power factor doubles the nameplate value or capacitance is in excess of 110% of the nameplate value.
- Natural ester filled units will have higher measured power factor by 2 to 4 times those of mineral oil filled transformers

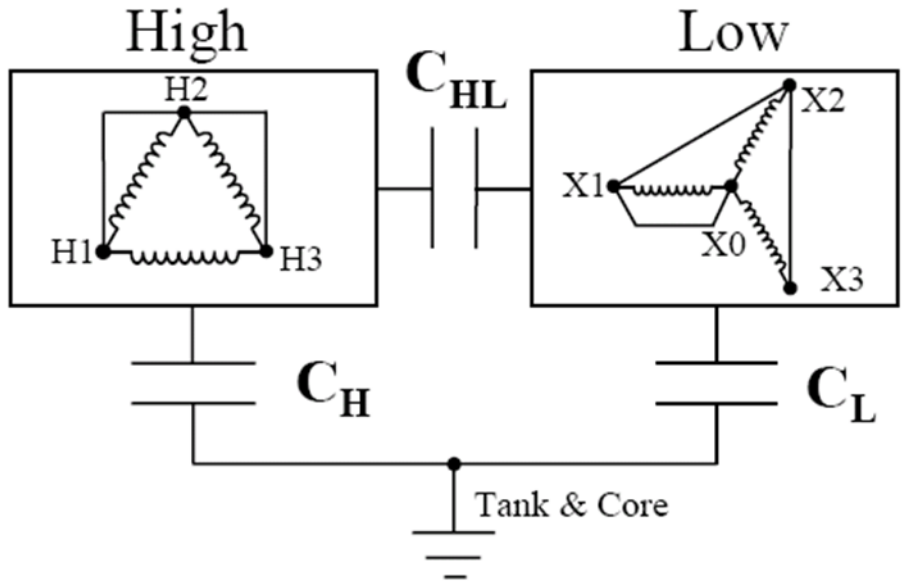
Power Factor Testing – Windings

Purpose

- Detection of moisture or foreign contamination in the insulation structure.
- Test can also detect changes in geometrical configuration of windings or damage to ground and static shields.
- Sensitivity to temperature, moisture, contamination

Method

- Insulation power factor bridge is used to measure power factor and capacitance of windings.
- Power factor bridge shall be capable of a test voltage of 10kV.
- Tests typically completed at 10kV.
- Testing his highly susceptible to temperature, humidity and contamination.



Power Factor Testing – Windings

Acceptance criteria

Standard acceptance limit for new transformer windings is 0.5% when corrected to 20°C.

Natural ester fluid filled transformers will have a higher power factor typically 2 to 4 times greater than measured in mineral oil.

For maintenance testing, the following limits are defined by Doble Engineering:

Less than 0.5%	Good
> 0.5% but < 0.7%	Deteriorated
> 0.5% but < 1.0% & Increasing	Investigate
>1.0%	Bad

Winding Excitation

Purpose

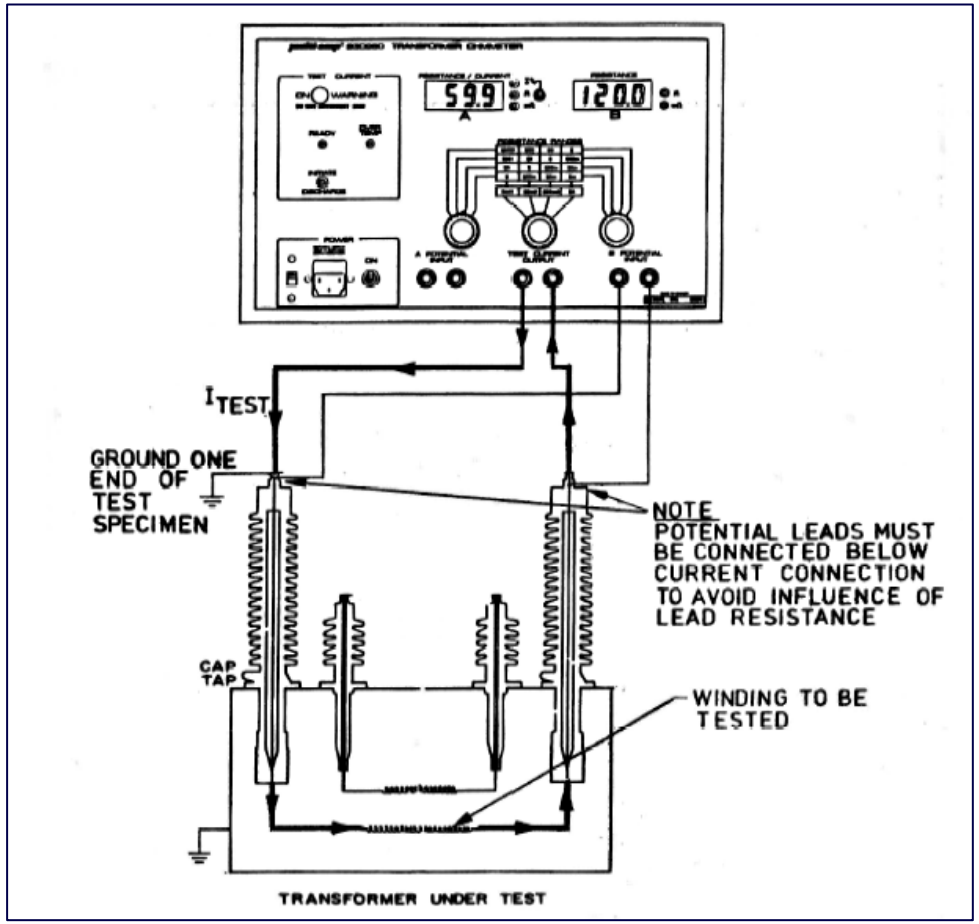
Maintenance test generally recognized to detect any changes in the magnetic circuit. Verify internal connections and detection of any poor connections.

Method

- Voltage source is applied to winding and exciting current is measured.
- Test is most often done with power factor bridge test set at 10 kV.
- Test is very sensitive to temperature and must be corrected.

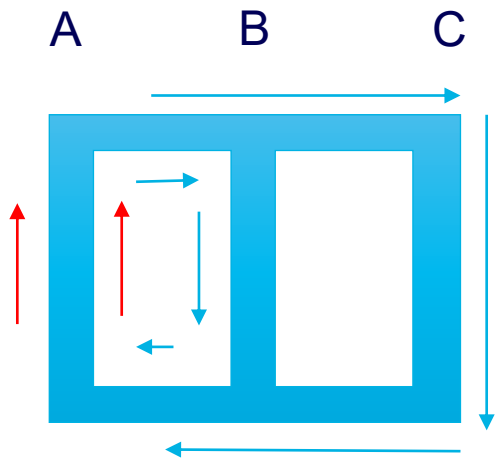
Acceptable Criteria

This is a repeat test. All subsequent tests are compared to original baseline test for indications of variance. Recommend no more than 5% phase to phase variation on field measurements.

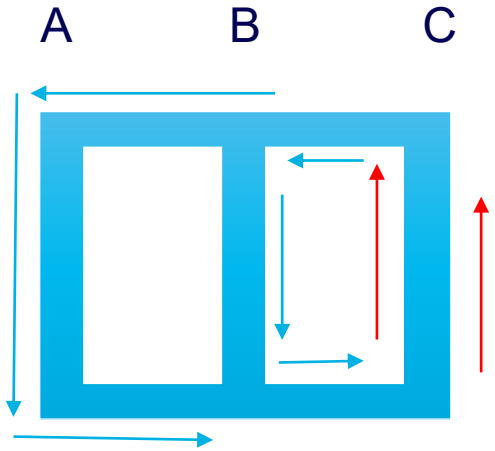


Winding Excitation

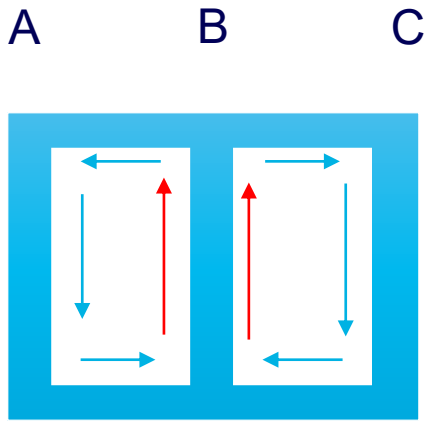
A Phase Excitation



C Phase Excitation



B Phase Excitation



A = C

B < A and C

Winding Excitation

Acceptance Criteria

- This is a repeat test. All subsequent tests are compared to original baseline test for indications of variance. Residual magnetism can effect results.
- Typical 2 High, 1 Low pattern for typical 3 limb core form transformer. Center phase should be the phase with lower current.
- Shell form and 5 leg core form design may have different current pattern.
- LTC with a reactor/preventive auto will have different current patterns in bridging and non-bridging positions.

Test No.	Test Mode	Energize	UST	Ground	Float	I_e
1	UST	H_1	H_0	*	H_2H_3, $X_1X_2X_3$ ($Y_1Y_2Y_3$)	H_1–H_0
2	UST	H_2	H_0	*	H_1H_3, $X_1X_2X_3$ ($Y_1Y_2Y_3$)	H_2–H_0
3	UST	H_3	H_0	*	H_1H_2, $X_1X_2X_3$ ($Y_1Y_2Y_3$)	H_3–H_0

*Normally grounded terminal(s) of the X and/or Y windings must be grounded.

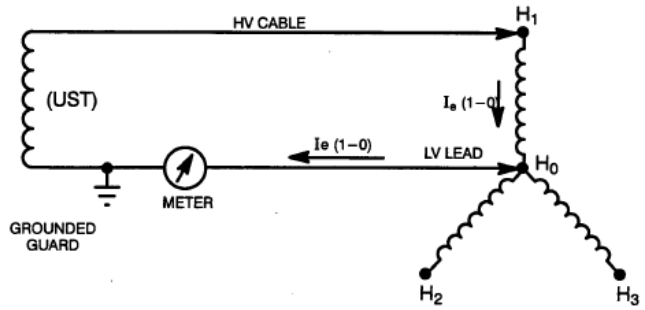


Figure 5.18 Measurement of I_e in a Wye-Connected Transformer Winding (Routine Method)

Frequency Response Analysis

Test Methods

- Impulse method (Framit)
- Sweep Frequency Method (Doble)
- Traces are not comparable between methods

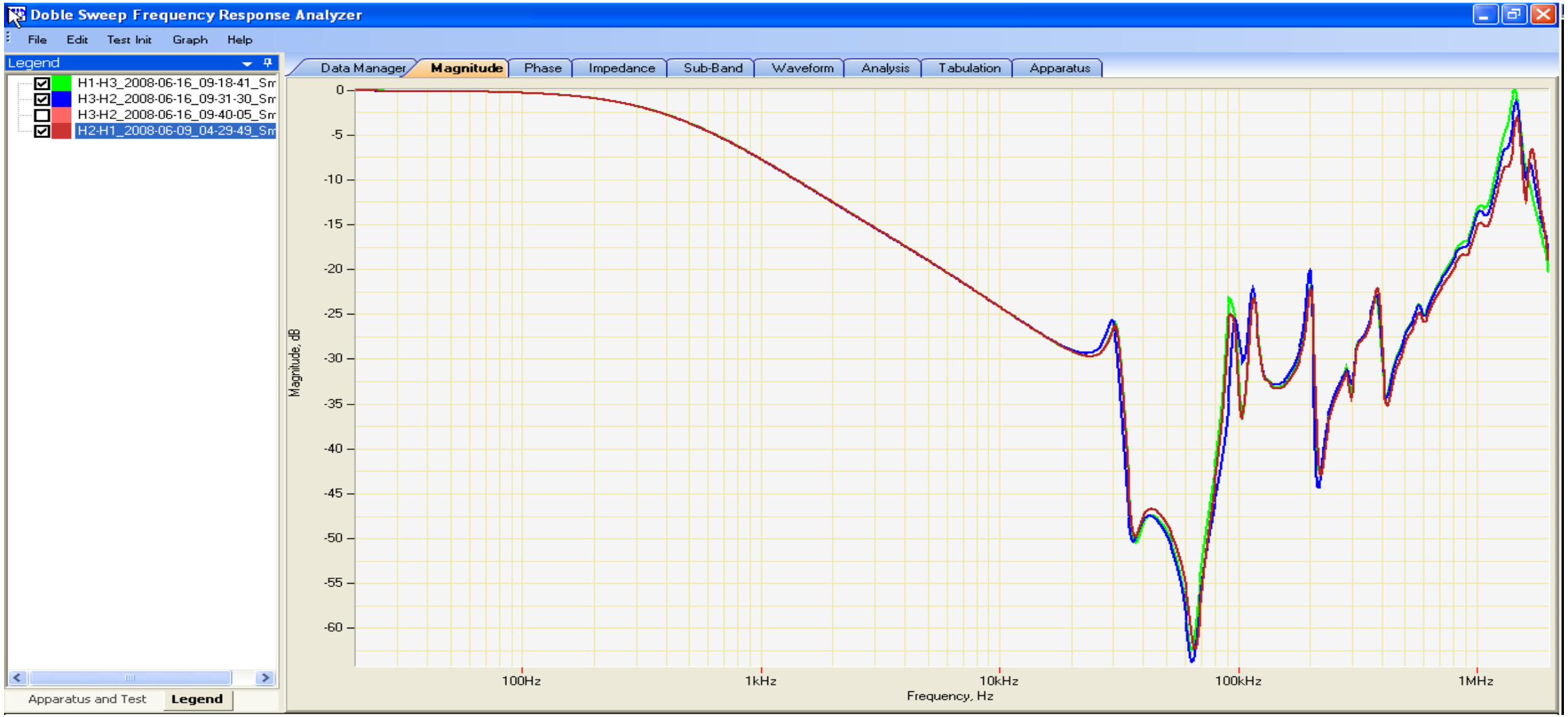
Test for Winding Movement

- Deformation
- Winding Clamping
- Short Circuit Damage

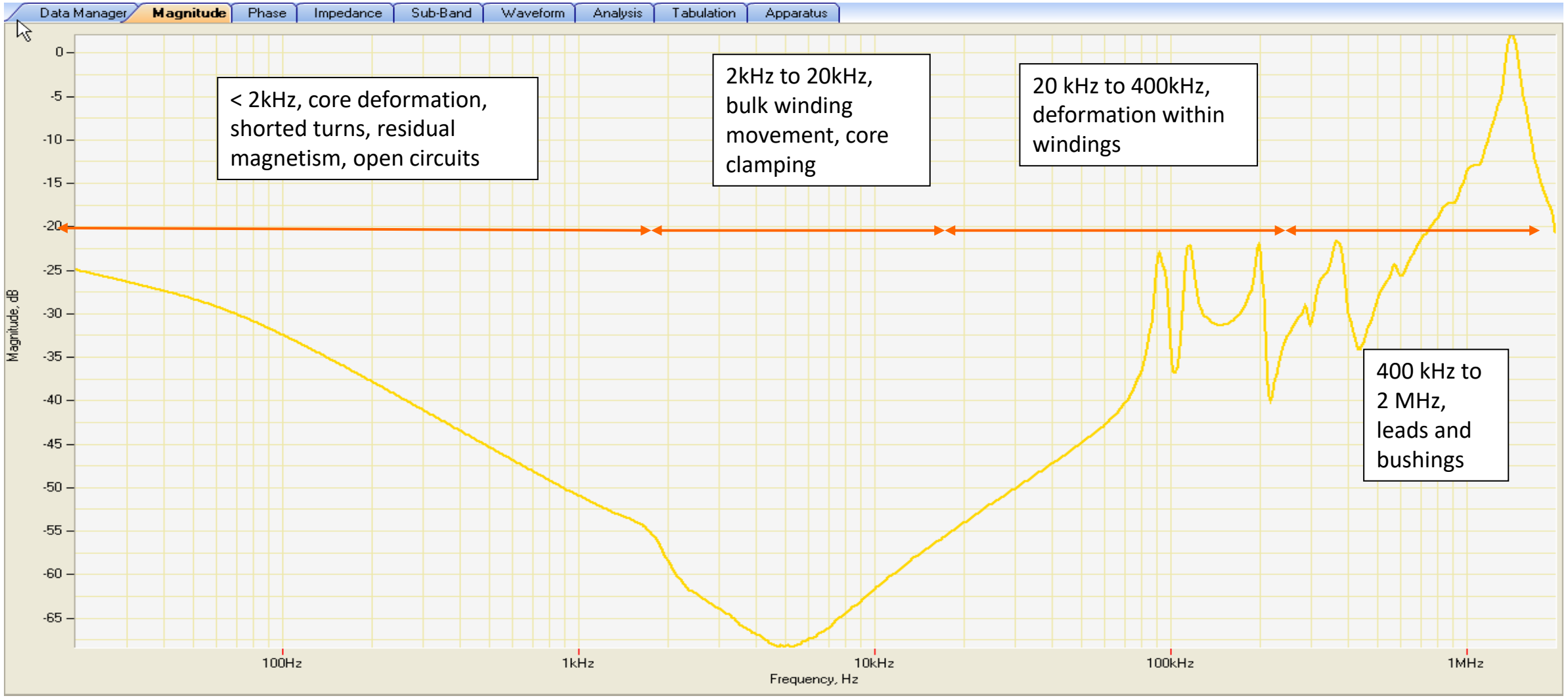
Comparison Test

- Identical 1-Phase Units
- Phases on 3-Phase Unit
- Against Previous Test

Doble SFRA Test



Doble SFRA Test



Insulation Resistance (Megger)

Purpose

Prove insulation integrity between windings and between the winding and ground potential.

Severe contaminants or insulation failure can be detected.

Polarization index can detect changes in insulation structure over time.

Method

Using megger instrument, 1000V to 5000V is applied for one minute between windings and between windings and ground. If polarization index (PI) measurement is required, test voltage must be applied for 10 minutes in each test configuration.

Test is sensitive to moisture, temperature and contamination.

Insulation Resistance (Megger)

Acceptance Criteria

Minimum standard acceptance limit is 1000 Megaohms when corrected to 20°C.

Test is sensitive to temperature, moisture and contamination.

Measured values will be different for different fluids. Natural ester fluid filled transformers will have a reduced megger value up to 10 times less than measured in mineral oil.

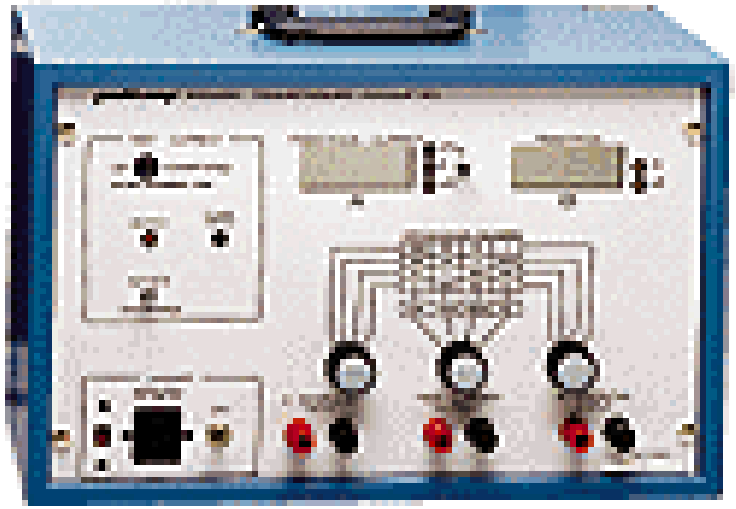
Winding Resistance

Purpose

- Verify internal connections and detection of any open or poor connections. This is often done as a maintenance type test

Method

- Using Wheatstone or Kelvin bridge, resistance of the transformer winding is measured.
- Test is very sensitive to temperature and must be corrected to standard temperature for comparison.
- The test is generally performed single phase of each section of a winding.



Winding Resistance

- Measurements must be corrected to a standard temperature for comparison
  - 75°C is standard temperature correction for 55°C rise
  - 85°C is standard temperature correction for 65°C rise
- Test correction equations for 55°C Rise
  - Copper Winding
    - $R_{75} = \frac{R_T (234.5 + 75)}{(234.5 + t)}$
  - Aluminum Winding
    - $R_{75} = \frac{R_T (228.1 + 75)}{(228.1 + t)}$
    - t = test temperature in degree C
    - R_T = test resistance

Controls Verification

- Control and relays function of the transformer must be verified. Cooling controls, gas detection system, fault detection systems, flow gauges, liquid level gauges, and temperature gauges must be checked for operation and calibration in accordance with manufacturer's specification.
- Control wiring insulation is tested for shorts, cracks, or other weaknesses.
- Wiring receives "hipot" test at
  - 2500 VDC for current transformer wiring
  - 1500 VDC for all other control wiring
  - Sensitive electronic devices must be disconnected

Field Acceptance Testing – Transformer Assembly

Prior to Assembly

- Dew point (initial) ☑
- Core ground test (initial) ☑

After Assembly, Prior to Filling

- Transformer Turn Ratio (AC) ☑
- Current Transformer Testing (AC) ☑

Post Vacuum Oil Processing/Filling

- Power Factor Testing (AC) ☑
- Excitation Testing (AC)☑
- Frequency Response Analysis (AC) ☑
- Insulation Resistance (DC) ☑
- Winding Resistance Testing (DC) ☑
- Core ground test (final) ☑
- Controls and Alarm checks ☑
- Oil sample/DGA

Difference Between Factory and Field Testing

Dew Point

Factory

- Secured with Pressure
- Measured in Controlled Environment

Field

Must be measured properly:

- Temperature Swings
- Below Freezing measurement
- Sun Exposure

Conclusion

- Actual meter reading may not be the same
- % moisture is repeatable for measurement on rail car or truck from factory
- Measure in morning just before sun rise
- Do not measure in freezing temperatures
- Future readings have no correlation with factory or initial measurement

Core Insulation Resistance (Core Megger)

Factory

- Measured on Test Floor
- Measured just before shipping

Field

- Measured upon receipt of transformer in shipping condition
- Measured after assembly
- Measured during PM testing or after repairs

Conclusion

- Do not use previous measurements as baseline
- Too much variability in measurements

Bushing Power Factor (C1 & C2)

Bushing Factory

- Fresh processing of insulation material
- Measured in rack with measurements recorded on the nameplate

Transformer Factory

- Typically not measured separately in the factory

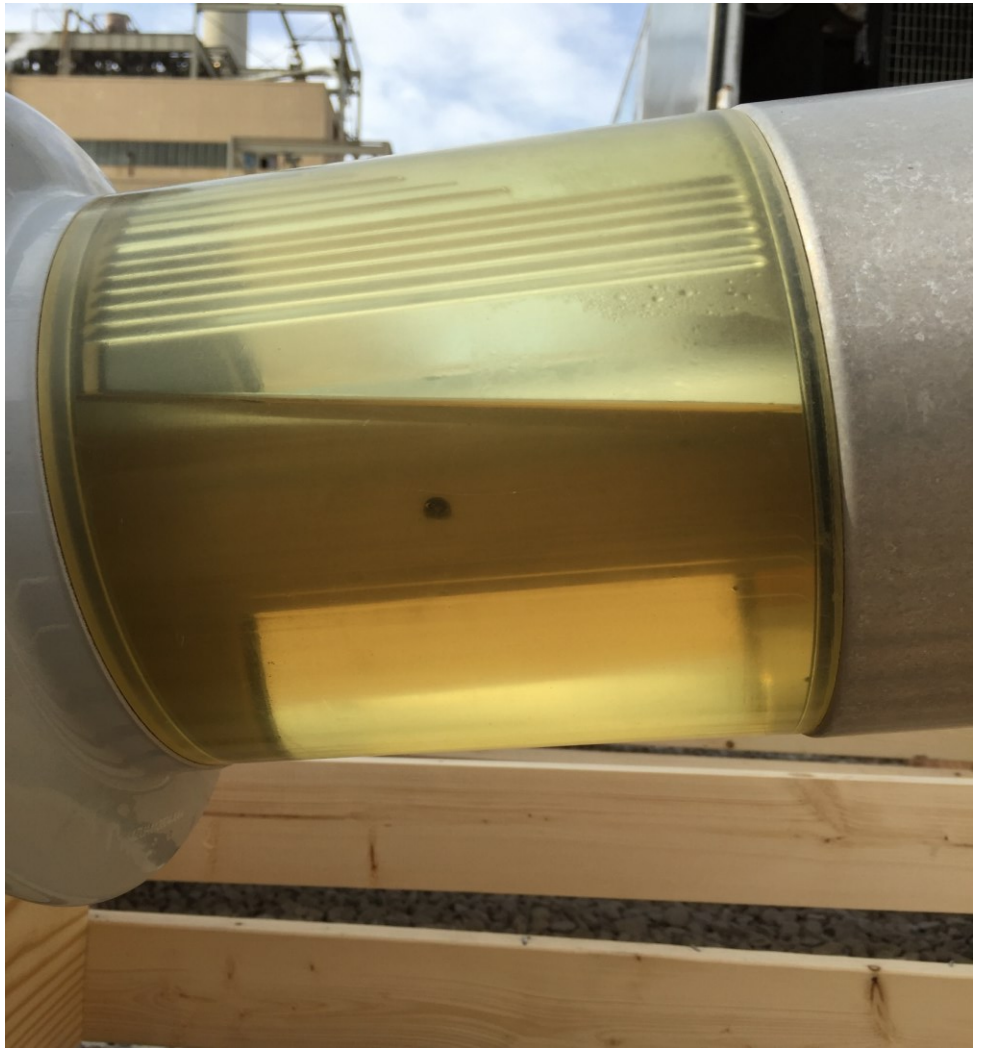
Field

- Must make adjustments if shipped horizontally
- Must clean the bushings properly and use clean slings or rack
- Do not measure in shipping crates
- Can not measure if freezing

Conclusion

- If measured outside transformer, power factor and capacitance measurements should match nameplate (both C1 and C2)
- If measured inside transformer:
  C1 power factor and capacitance measurements should match nameplate — the nameplate can be used as baseline for future measurements
  C2 measurements may change — use the measured C2 values after installed as baseline for future measurements

Bushing Power Factor (C1 & C2)



CT Tests

CT Factory

- Everything is tested
- CT is certified and factory report is available

Transformer Factory

- Typically: polarity, ratio and control wiring hi pot completed

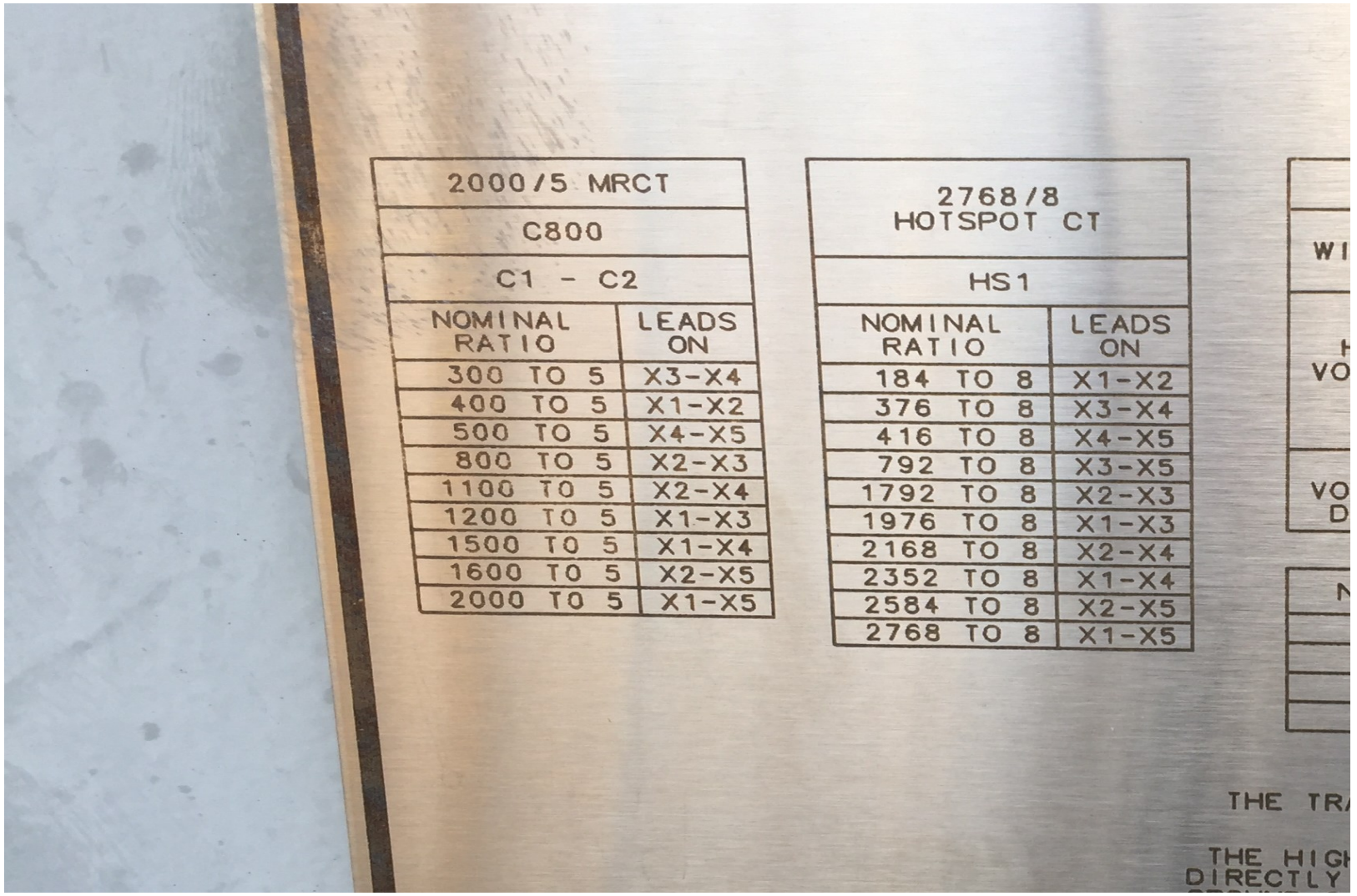
Field

- Polarity, ratio, saturation 1–5
- Sometimes resistance, insulation resistance

Conclusion

- The Transformer nameplate is base line.
- These are repeatable test.

CT Tests



2000/5 MRCT	
C800	
C1 - C2	
NOMINAL RATIO	LEADS ON
300 TO 5	X3-X4
400 TO 5	X1-X2
500 TO 5	X4-X5
800 TO 5	X2-X3
1100 TO 5	X2-X4
1200 TO 5	X1-X3
1500 TO 5	X1-X4
1600 TO 5	X2-X5
2000 TO 5	X1-X5

2768/8 HOTSPOT CT	
HS1	
NOMINAL RATIO	LEADS ON
184 TO 8	X1-X2
376 TO 8	X3-X4
416 TO 8	X4-X5
792 TO 8	X3-X5
1792 TO 8	X2-X3
1976 TO 8	X1-X3
2168 TO 8	X2-X4
2352 TO 8	X1-X4
2584 TO 8	X2-X5
2768 TO 8	X1-X5

Transformer Turns Ration (TTR)

Factory

- Testing is compared to the nameplate and winding configuration drawings

Field

- Equipment is important
- Can have external influence

Conclusion

- Ratio results are repeatable.
- Usually the nameplate can be used as a baseline.
- Factory test data is better as a baseline.
- If heavy external influence in the field or equipment differences, then use first field test as baseline.

Winding Insulation Resistance (Winding Megger)

Factory

- Megger is not an accurate measuring with large insulation packages.
- Looking for large numbers

Field

Can use factory for ballpark:

- If large difference, then use another piece of equipment.
- If large difference remains after changing equipment, as long as high number and power factor are “on,” test is acceptable.

Conclusion

- Megger equipment is not very repeatable.
- Always look for large number.
- If question with megger readings, refer to Power Factor Readings.

Winding Power Factor

Factory

- Transformer has just been processed
- Factory provides a controlled environment

Field

- Bushings have to be cleaned properly
- Field environment is not controlled

Conclusion

- Do not expect direct correlation between factory and field measurements
- After first field test, use previous test as baseline
- Trend results

Excitation

Factory

- Test is usually performed before losses are measured
- No external influences
- Factory provides a controlled environment

Field

- Field sometimes has other units or overhead lines, etc.

Conclusion

- Dependent on residual magnetism
- Use first field test as a baseline
- Trend results
- The % are fairly repeatable.
- All subsequent tests are compared to original baseline test for indications of variance

Frequency Response Analysis

Factory

- Only measured if required in customer's specification
- Test floor
  - Oil-filled: All bushings installed
- Shipping configuration
- Factory provides a controlled environment

Field

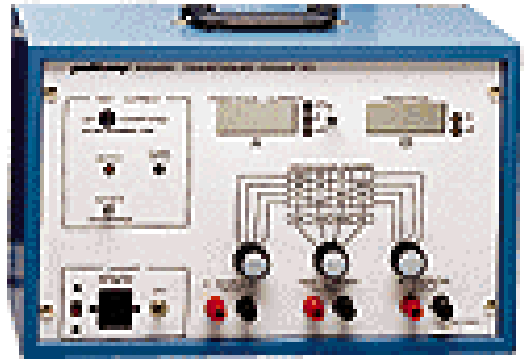
- Shipping configuration
- After assembled and filled

Conclusion

- Factory test are bae line for first test in the field
- First field test should be baseline for the rest of the transformer life
- If no test are available from factory or field then compare phase to phase.

Winding Resistance Factory Measurements

- Why temperature is so important in the factory
- Cold resistance reading (simplified)
  - Transformer filled for days
  - Never energized
  - Transformer is stored inside building
  - Core, oil and winding temps are ambient
  - Thermocouples are located at the top and bottom of the radiator or cooler bank
  - At this point, measurements are compared phase-to-phase to calculations
- Temperature rise resistance
  - Resistance measurements are used to determine the temperature of the windings
  - Using Temperature correctly:
    - Rs = Rm (Ts + Tk / Tm+ Tk)
    - Rs = resistance at desired temperature
    - Rm = resistance measured
    - TS = desired reference temperature (deg C)
    - Tm = temperature at which the resistance was measured (deg C)
    - TK= constant 234.5 for copper or 225.0 for aluminum



Winding Resistance Field Measurements

Temperature Considerations

Measurement Methods

- Place a thermometer in contact with the tank wall
- Use a liquid temp indicator
- On nitrogen units, you can open a manhole and drop a temp indicator in the oil

Issues

If just taken out of service, the core and coil will be hotter than the oil temperature as they are the source of heat of the oil temperature

If just processed, temperatures will be inconsistent top to bottom and core to oil

Sun pounding on the transformer during the day will make the ambient changes swing much more than in the factory

Conclusions

- Phase-to-phase comparisons are used in the field
- % are usually repeatable

Common Issues Found With Test

1) **Bushing Power Factor**
    1) Power Factor in Crate
    2) Hard to PF Bushings on Straps if Large Bushing
    3) Supposed to have standing up for 24 hours
2) **Resistance Readings not making since**
    1) Make sure that you have give enough time to let readings settle
    2) If taking too long then check into different setups
3) **SFRA or Excitation not correct**
    1) Check for magnetized core
4) **Megger should show inductive kick**
    1) How often do you 20,000 Meg Ohms +
    2) If no inductive kick then core ground might not be connected to the core ground.

Field Acceptance Testing

Test	Type of Faults Detected	Good	Caution	Concern
Bushing Power Factor (% at 20°C)	Bushing insulation defect	<0.5%	0.5%-1%	>1%
Bushing Capacitance	Shorted condenser or test tap problems	<10% change from baseline		>10% change from baseline
Winding Power Factor (% at 20°C)	Defects in winding insulation or moisture	<0.5%	0.5%-1%	>1%
Winding Capacitance	Winding deformation / Open core ground	<10% change from baseline		>10% change from baseline
Leakage Reactance/LV Impedance	Winding deformation / Through fault damage	<3% change from baseline		>3% change from baseline
Transformer Turns Ratio	Open or shorted windings / improper polarity	< 0.5% standard deviation		>0.5% standard deviation
Winding Insulation Resistance (20°C)	Defects in winding insulation or moisture	> 1000 MΩ		< 1000 MΩ
DC Winding Resistance	Poor connections - winding, bushings, tap changer	<2% phase to phase deviation	2-5% phase to phase deviation	>5% phase to phase deviation
Winding Excitation	Core problems /shorted turns	<10% change from baseline		>10% change from baseline
Core Insulation Resistance (20°C)	Shorted core/damaged core insulation	> 100 MΩ		< 100 MΩ

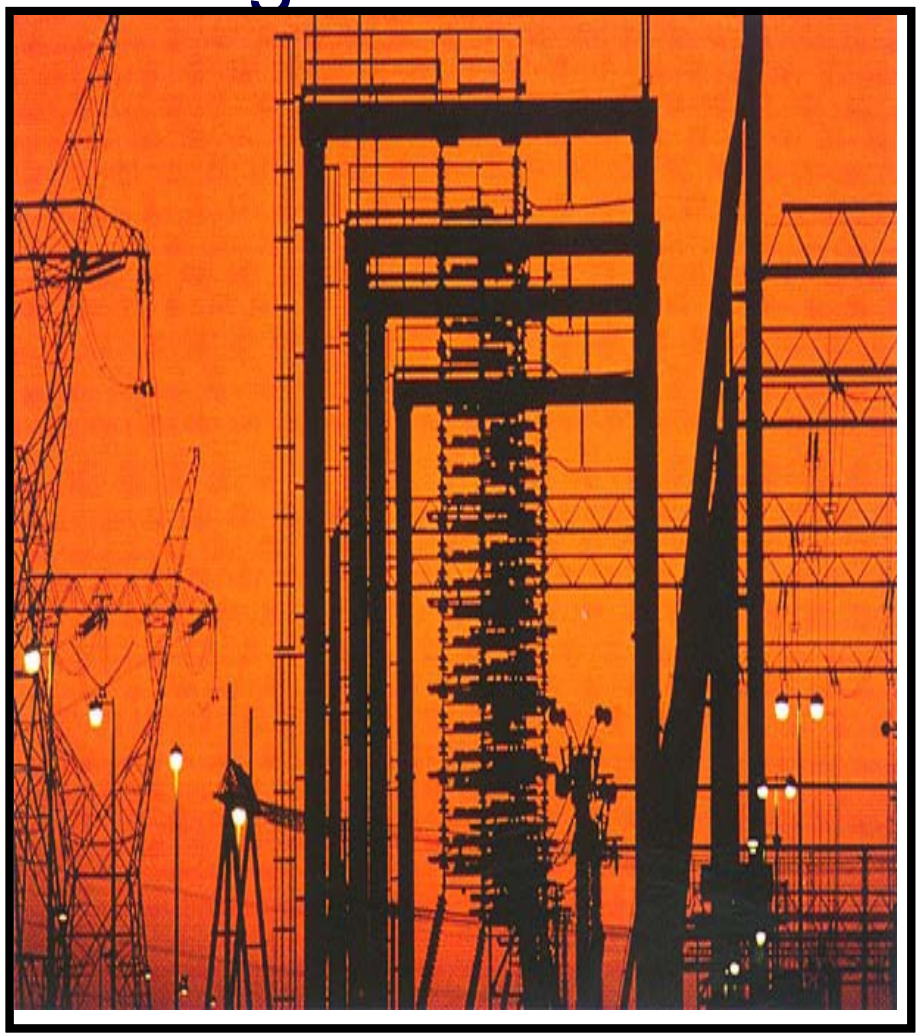
Energization Procedures

- Prior to energizing transformers, verify the following
  - Electrical and oil tests have been complete and have met minimum standards
  - Stand time after oil filling has been met
  - Cooling controls have been set to automatic operation
  - All temporary grounds and shorting wire have been removed
- Energize the transformer with no load from either the high voltage or low voltage side. If possible, it is recommended that voltage be raised in increments.
- Based upon primary voltage class, IEEE recommends a soak period before an operator begins to pick up load on a transformer.

Voltage Class	Suggested Minimum Energizing Period (hours)
230 ≥ 800 kV	12
0 < 230 kV	8

Source: IEEE C57.93-2019

Energization Procedures



- **During the energization period without load, it is recommended that close observation of the transformer be made.**
  - Excessive audible noise
  - Check of liquid temperatures, winding temperatures, and ambient temperature
  - Check of tank pressure
  - Check of oil level indicators
  - Check of gas detector relay.
- **Within the first month of operation, a DGA sample should be taken for baseline analysis**

Test References

- IEEE Guide for Installation of Liquid Immersed Power Transformers (C57.93-2007)
- IEEE Guide for Maintenance and Acceptance of Insulating Oil in Equipment (C57.106-2006)
- IEEE Guide for Interpretation of Gasses Generated in Electrical Equipment (C57.104-2008)
- NETA Acceptance Testing Specification 2010
- IEEE Guide for Failure Investigation, Analysis, and Documentation of Power Transformers and Shunt Reactors (C57.125-1991 Appendix A)
- IEEE C57.152 Field Diagnostics Guide (New)