

Single and Three Phase Transformer Testing Using Static Motor Circuit Analysis Techniques

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Introduction

Field and shop testing of pole and pad mount transmission and distribution (T&D) transformers can be costly and time consuming. With the onset of utility generation deregulation across the country, T&D becomes a greater issue due to varying power demands and power quality. A simple test method for quickly and accurately testing the condition of T&D equipment is a necessity as, if a transformer fails, both the end user and generating facility will complain. Through the use of an existing technology, originally designed for motor winding testing, an initial transformer evaluation can be performed.

For conceptual reasons, consider that an AC induction electric motor is a transformer with a rotating secondary. In this way, the capabilities that static Motor Circuit Analysis (MCA) provides an electric motor can be extended to a transformer. These include detecting winding shorts, high resistance connections, open windings and insulation to ground fault detection as well as preliminary internal circuit impedance balance. Specific information on the transformer is not required for most applications of MCA because the test equipment is used as a winding comparator.

An MCA device which provides readings of resistance, impedance, inductance, phase angle and a special test called current/frequency response (I/F) has been applied to transformers, for the purposes of this paper. Because the test method is off-line, the MCA device generates its own voltage and frequency output. Therefore, the ALL-TEST IV Pro™ 2000 motor circuit analyzer was selected. This unit weighs under 2 lbs, is handheld, and has a proven track record with AC/DC motors and generators from fractional to over 10 MW.

The first set of transformers tested included pole and pad mount transmission and distribution transformers from a few kVA to over 2500 kVA with primary voltage ratings of 480 Volts to 28.8kV. Following initial testing and analysis, procedures were developed to allow for general testing of any type of pole and pad mount transformer with a simple resistance greater than 0.001 Ohms. The results included the capability of testing the primary and secondary of any type of transformer in about 5 to 10 minutes with a greater than 99% success rate on either wet or dry-type transformers.

Basic Transformer Concepts

To understand the basic concepts of a transformer, we shall start with an —ideal transformer,“ or a theoretical transformer that has no losses. The purpose of the transformer is to convert one level of voltage and current to another level of voltage and current for distribution and application purposes. This is achieved by having a primary winding located close to secondary winding and allowing for mutual induction to occur between the windings.

When a sine-wave voltage is applied to the primary windings a magnetic field is established that expands and contracts based upon the applied frequency. This field interacts with the secondary winding producing a voltage within the secondary that is directly proportional to the turns ratio, while current is inversely proportional to the turns ratio.

Equation 1: Voltage Turns Ratio

$$N1 / N2 = a$$

Where N1 is the number of turns in the primary and N2 is the number of turns in the secondary Equation 2:

Current Turns Ratio

$$N2 / N1 = 1/a$$

For example, an ideal transformer with 100 turns in the primary and 50 turns in the secondary, with 480 Volts applied to the primary and a 100 amp load on the secondary would have: a voltage turn ratio of 2; a current turn ratio of 2; a 480 V₁, 50 A₁ load reflected on the primary and a 240 V₂, 100 A₂ load on the secondary.

Equation 3: Load Impedance

$$Z_L = V_2 / I_2$$

Equation 4: Equivalent Primary Impedance

$$Z'_L = a^2 Z_L$$

Equations 3 and 4 can be used to reference the impedance from the secondary to primary. This can also be used inversely. Internal impedance can be matched to load impedance as found in Equation 5.

Equation 5: Internal Impedance

$$Z_s = a^2 Z_L = Z'_L$$

In a —real transformer— there are certain losses, including core losses (hysteresis and eddy-currents), the magnetizing current, and leakage. In addition, supply voltage and load currents may have harmonic loads and other issues that would impact the effectiveness of a transformer. The purpose of static MCA is to reduce or eliminate these issues to isolate transformer testing.

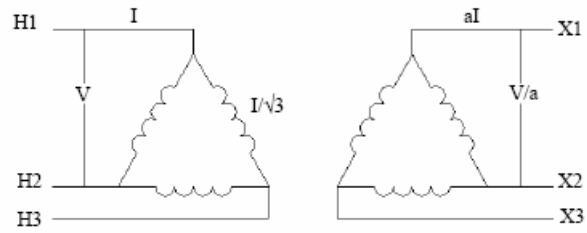
Transformer Types and Connections

Transformers of both single and three phase have a variety of connection types for a variety of loads. In a three-phase circuit, these connections are: Wye-Delta; Delta-Wye; Delta-Delta; and Wye-Wye. Single-phase, pole mounted transformers normally have a single-winding primary with a two-winding or center-tapped secondary.

Three phase transformer connections are developed for a variety of applications:

1. Delta-Delta: Lighting and power applications, normally used when power loads are greater than lighting loads.
2. Open-Delta: Lighting and power applications, used when lighting loads are greater than power loads.
3. Wye-Delta: Power applications, used when stepping power up in voltage (ie: 2400 to 4160 Volts).
4. Wye-Delta: Lighting and power applications.
5. Open Wye-Delta: Will allow 57% capacity if one phase is disabled.
6. Delta-Wye: Normally provides a 4-wire on the secondary which allows for balanced single-phase loads between neutral and each phase.

Figure 1: Delta-Delta Transformer



Three phase transformer connections are labeled H1, H2, and H3 on the primary and X1, X2, X3, with X0 as the neutral, on the secondary.

Figure 2: Delta-Wye Transformer

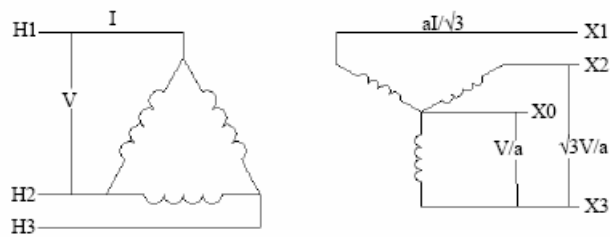


Figure 3: Wye-Delta Transformer

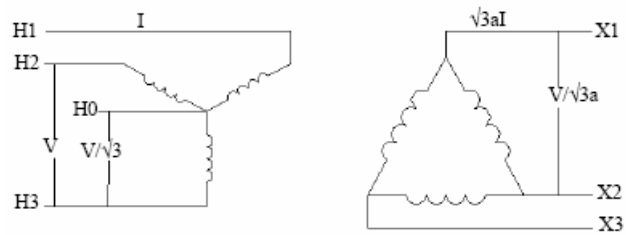


Figure 4: Wye-Wye Transformer

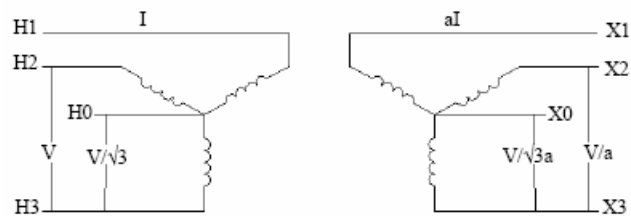


Figure 5: Delta-Wye Transformer Connection

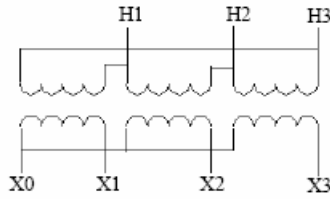
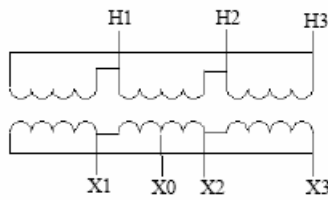
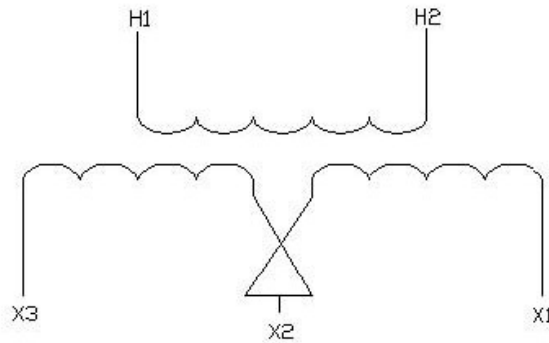


Figure 6: Delta-Delta Transformer Connection



Single-phase pole mounted transformers are often connected and labeled H1 and H2 on the primary and X1, X2 (center tap), and X3.

Figure 7: Single-Phase Transformer Connection



Motor Circuit Analysis Basics

Motor Circuit Analysis is the art of troubleshooting and pinpointing faults within an inductive or capacitive circuit by using readings of resistance, impedance, inductance, phase angle, insulation resistance and I/F.

The ALL-TEST™ static MCA instrument puts out a low voltage, 100 to 800 Hz signal, as a true sine-wave which it then evaluates the response using a series of bridges. These readings relate as follow:

1. Resistance (Ohms): The simple DC resistance of the circuit.
2. Inductance (Henries): The magnetic strength of a coil.
3. Capacitance (Farads): Measurement of leakage.
4. Inductive Reactance (X_L): The AC resistance of a coil. $X_L = 2\pi fL$
5. Capacitive Reactance (X_C): $X_C = 1/(2\pi fC)$
6. Phase Angle (Φ , degrees): The angle of the lag of current to voltage.
7. Impedance (Z): The complex resistance of an AC circuit. $Z = \sqrt{R^2 + (X_L - X_C)^2}$
8. Current/Frequency Response (I/F): Percentage change in current when the frequency is doubled by the instrument, as $I = V / Z$.
9. Insulation Resistance (Meg-Ohms): Measurement of leakage to ground, ground-wall insulation strength.

When taken as a group, these readings can assist the analyst in determining, first, if a fault exists, then the type of fault. Using the ALL-TEST IV Pro™ 2000, these readings can be taken in less than 5 minutes per transformer. The key to MCA testing is to compare readings between similar windings or transformers and to look at the variations and patterns between phases.

Figure 8: Motor Circuit Analysis Instrument



Transformer Field Test

The initial set of tests were performed using the same type of procedure that would be used on an electric motor, first for the primary windings, then for the secondary windings. Table 1 represents a sample of one of 30 transformers that were tested over a period of 90 minutes.

Table 1: Initial Transformer Test Data: 2500 kVA Transformer

	Primary			Secondary		
	H1-H2	H1-H3	H2-H3	X1-X2	X1-X3	X2-X3
Resistance	258.5	48.45	153.3	0.198	0.125	0.132
Impedance	15633	11028	11035	566	411	420
Inductance	24878	17552	17562	902	655	669
I/F	-50	-23	-18	-44	-46	-44
Phase Angle	9	90	90	90	85	90
Meg-Ohm	>99			>99		

An issue that became immediately apparent was the unusual and extremely unbalanced readings. All of the tests identified similar results and it was also noticed that resistance varied from test to test and that the impedance and inductance changed from test to test. Upon evaluation of these phenomena, two theories were developed:

1. The sinusoidal voltage output of the ALL-TEST was inducing into the opposite set of windings resulting in reflected impedance and inductances that would increase during each test because of a resulting static charge.
2. Electro-Magnetic Interference (EMI) from surrounding operating equipment, transformers, lighting, etc. would cause stray currents because the transformer windings and core would act as an excellent EMI antennae. This scenario would explain varying resistances from test to test.

To resolve both issues, the connections on the side opposite of the side being tested should be grounded to a proper earth ground. The result was predicted to shunt all induced currents direct to ground resulting in the ability to fully test just the winding being tested. This would also allow for tighter testing tolerances. The results are found in Table 2 and test time remained under 5 minutes per transformer.

Table 2: Final Transformer Test Data: 2500 kVA Transformer

	Primary			Secondary		
	H1-H2	H1-H3	H2-H3	X1-X2	X1-X3	X2-X3
Resistance	3.703	3.623	3.648	0.103	0.100	0.096
Impedance	220	217	218	15	14	14
Inductance	87	86	86	2	2	2
I/F	-49	-49	-49	-48	-48	-49
Phase Angle	88	88	88	75	75	75
Meg-Ohm	>99			>99		

These results were found to be repeatable in all cases. Transformers that tested bad tended to have drastic variations in readings.

Table 3: Shorted Transformer

	Primary			Secondary		
	H1-H2	H1-H3	H2-H3	X1-X2	X1-X3	X2-X3
Resistance	116.1	98.2	48.5	0	0.005	0.005
Impedance	4972	1427	2237	0	1	1
Inductance	7911	2267	2237	0	0	0
I/F	-33	-29	-29	0	-20	-20
Phase Angle	23	21	20	0	5	5
Meg-Ohm	9.132			0		

It was found that the 500 kVA transformer had a shorted primary with damage between the primary and secondary windings.

Transformer Testing Procedure

Figure 9: Transformer Test



The results of the study produced simple test procedures for both three phase pad and single phase pole mounted transformers. The key to testing any type of transformer is to ground all of the leads on all of the connections of the winding opposite of the winding being tested.

A good transformer should have unbalances less than:

1. Resistance: No more than 5% unbalance above 0.250 Ohms and 7.5% below 0.250 Ohms.
2. Impedance: < 2% unbalance
3. Inductance: < 5% unbalance
4. Phase Angle: No more than 1 degree between phases
5. I/F: No more than 2 digits difference and the readings should fall between ≈ 15 and ≈ 50 .
6. A "shift" in readings should be flagged for further testing or trending. For instance, a winding that tests as I/F: -48; -48; -46 and Phase Angle: 70° ; 70° ; 69° , should be checked further.

Normally, a winding is beginning to experience inter-turn shorts when the Phase Angle and I/F begin to shift. A corresponding unbalance in inductance and impedance indicates a severe fault. A change in Phase Angle with a fairly balanced I/F normally indicates a phase short.

The basic steps for three phase transformer testing are as follow:

1. All of the leads on the side opposite of the side being tested must be grounded to an earth ground.
2. Test the primary from H1 to H2, then "retest" to verify that the readings are repeatable. If they are not repeatable, check the ground and continue.
3. Test from H1 to H3, then H2 to H3, and, finally a ground insulation test.
4. Save the readings and check condition.
5. Test the secondary winding by first checking X1 to X2, then "retest" to verify that the readings are repeatable. If they are not repeatable, check the ground and continue.
6. Test from X1 to X3, then X2 to X3, and, finally, a ground insulation test.
7. Save the readings and check condition.

Single-phase transformers are tested slightly differently and require a known reading for the primary to be compared to, such as with a similar transformer or a past test on the same transformer. The basic steps for single phase transformer testing are as follow:

1. All of the leads on the side opposite of the side being tested must be grounded to an earth ground.
2. Test the primary from H1 to H2, then —retest “to verify that the readings are repeatable. If they are not repeatable, check the ground and —retest”
3. Ground the primary then test X1 to X2, then —retest “to verify that the readings are repeatable. If they are not, then check the ground and —retest.”
4. Test from X2 to X3, then save readings. Compare the second and third reading to each other and the first reading to a standard.

These procedures can be used on three phase pad mount and single phase pole mount transformers regardless of connection type.

Conclusion

Static Motor Circuit Analysis techniques provide an excellent method for analyzing the primary and secondary windings of either three-phase pad and single-phase pole mounted transformers. A simple procedure incorporating grounding the side opposite of the side being tested allow for very accurate test results. Measurements of resistance, impedance, inductance, phase angle, current response and insulation resistance can be compared for troubleshooting purposes and measurement patterns for pinpointing faults.

Test equipment required for MCA testing transformers must have the following capabilities:

1. Resistance, impedance, inductance, phase angle, I/F and insulation resistance in engineering units.
2. Sine-wave voltage output in a variety of frequencies.
3. Onboard memory with software to upload and download readings.
4. Cost effective and accurate.

The procedures described require about five minutes per transformer with a greater than 99% test result accuracy.

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About the Author

Dr. Howard W. Penrose, Ph.D. has over 15 years in the electric motor and electric motor repair industry. Starting as an electric motor repair journeyman in the US Navy to field service and evaluation of small through large rotating equipment of all types, as the Chief Engineer of a large Midwestern motor repair shop. Dr. Penrose has been directly involved in rewinding, training and troubleshooting AC, DC, wound rotor, synchronous, machine tool, and specialty equipment. His further studies involve electric motor and industrial reliability, test methods, energy efficiency and maintenance impact on production. Dr. Penrose is a past Chair of the Chicago Section of IEEE, a past Chair of Dielectrics and Electrical Insulation Society of IEEE Chicago, a Professional Member of the Electrical Manufacturing Coil and Winding Association, a US Department of Energy Certified MotorMaster Professional, a Vibration Analyst, Infrared Analyst and Motor Circuit Analyst.

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