Transformer Testing

The purpose of this paper is to provide a list of the standard battery of tests performed on reconditioned/repaired and new transformers--while providing an introductory explanation of the purpose and scope of the most common routine factory and diagnostic field tests. Factory testing is performed in lieu of ANSI C57.12.00 and ANSI C57.12.90 for liquid-immersed distribution, power, and regulating transformers and ANSI C57.12.01 and ANSI C57.12.91 for dry-type distribution and power transformers.

Tests Performed on Reconditioned Transformers IEEE C57.12.00 & IEEE C57.12.90 (Liquid-Immersed) IEEE C57.12.01 & IEEE C57.12.91 (Dry-Type)	**600V Dry**	**MV Dry**	**3-Ph Liquid**	**Power Sub**
Transformer Turns Ratio (TTR) (All Tap Voltages)	•	•	•	•
Winding Resistance (Rated Voltage	•	•	•	•
Impedance Voltage and Load Loss (Rated Voltage)		•	•	•
Polarity/1-Ph, Phase Relation/3-Ph (Rated Voltage)		•	•	•
Excitation & No-Load Loss (Rated Voltage)		•	•	•
Applied Voltage				
Induced Voltage				
Impulse				
Insulation Resistance/Megger (Rated Voltage)	•	•	•	•
Insulation Power Factor				•
Temperature Rise				
Partial Discharge				
Audible Sound Level				
Short-Circuit Capability				
Pressure (Mechanical)				
Leak (Quality Verification)			•	•

<u>Test Classifications</u> (as defined in IEEE C57.12.80-2002):

Routine Tests: “Tests made for quality control by the manufacturer on every device or representative samples, or on parts or materials as required, to verify during production that the product meets the design specifications” (Section 3.393).

***Routine* Tests for New Transformers** IEEE C57.12.00 & IEEE C57.12.90 (Liquid-Immersed) IEEE C57.12.01 & IEEE C57.12.91 (Dry-Type)	**600V Dry**	**MV Dry**	**3-Ph Liquid**	**Power Sub**
Transformer Turns Ratio/TTR (All Tap Voltages)	•	•	•	•
Winding Resistance (Rated Voltage)	≥ 300 kVA	≥ 300 kVA	> 2500 kVA	•
Impedance Voltage and Load Loss (Rated Voltage)	•	•	•	•
Polarity, 1-Ph / Phase Relation, 3-Ph (Rated Voltage)	•	•	•	•
Excitation & No-Load Loss (Rated Voltage)	•	•	•	•
Applied Voltage	•	•	•	
Induced Voltage	•	•	•	
Lightning Impulse			•	
Insulation Resistance (Rated Voltage)	≥ 300 kVA	≥ 300 kVA		•
Insulation Power Factor				•
Temperature Rise				
Partial Discharge				
Audible Sound Level				
Short-Circuit Capability		Cast Coil > 1.2 kV		
Pressure (Mechanical)				
Leak (Quality Verification)	Sealed Units (Mechanical)	Sealed Units (Mechanical)	•	•
Dissolved Gas in Oil Analysis				
Operation Test of All Devices			•	•
Low Frequency			•	
Dielectric Withstand (Hipot)				•

Design Tests: “Those tests made to determine the adequacy of the design of a particular type, style, or model of equipment or its component parts to meet its assigned ratings and to operate satisfactorily under normal service conditions or under special conditions if specified, and to demonstrate compliance with appropriate standards of the industry. *Syn:* **type test** (IEC)" (Section 3.99).

***Design* Tests for New Transformers** IEEE C57.12.00 & IEEE C57.12.90 (Liquid-Immersed) IEEE C57.12.01 & IEEE C57.12.91 (Dry-Type)	**600V Dry**	**MV Dry**	**3-Ph Liquid**	**Power Sub**
Transformer Turns Ratio (TTR) (All Tap Voltages)				
Winding Resistance (Rated Voltage	< 300 kVA	< 300 kVA	≤ 2500 kVA	
Impedance Voltage and Load Loss (Rated Voltage)				
Polarity, 1-Ph / Phase Relation, 3-Ph (Rated Voltage)				
Excitation & No-Load Loss (Rated Voltage)				
Applied Voltage				
Induced Voltage				
Lightning Impulse	•	•	•	•
Insulation Resistance (Rated Voltage)				
Insulation Power Factor				
Temperature Rise	•	•	•	•
Partial Discharge				
Audible Sound Level	•	•	•	•
Short-Circuit Capability			•	
Pressure (Mechanical)	Sealed Units (Mechanical)	Sealed Units (Mechanical)	•	•
Leak (Quality Verification)			•	•
Dissolved Gas in Oil Analysis				
Operation Test of All Devices				
Low Frequency				
Dielectric Withstand (Hipot)				

Other Tests: "Tests so identified in individual product standards that may be specified by the purchaser in addition to design and routine tests. (Examples: impulse, insulation power factor, audible sound.)" (Section 3.311)

***Other* Tests for New Transformers** IEEE C57.12.00 & IEEE C57.12.90 (Liquid-Immersed)	**600V Dry**	**MV Dry**	**3-Ph Liquid**	**Power Sub**

IEEE C57.12.01 & IEEE C57.12.91 (Dry-Type)				
Transformer Turns Ratio (TTR) (All Tap Voltages)				
Winding Resistance (Rated Voltage				
Impedance Voltage and Load Loss (Rated Voltage)				
Polarity, 1-Ph / Phase Relation, 3-Ph (Rated Voltage)				
Excitation & No-Load Loss (Rated Voltage)				
Applied Voltage				
Induced Voltage				
Lightning Impulse	•	•	•	•
Insulation Resistance (Rated Voltage)	< 300 kVA	< 300 kVA	•	
Insulation Power Factor	•	•	•	
Temperature Rise	•	•		
Partial Discharge	•	•	•	•
Audible Sound Level			•	•
Short-Circuit Capability	•	•	•	•
Pressure (Mechanical)				
Leak (Quality Verification)				
Dissolved Gas in Oil Analysis			•	•
Operation Test of All Devices				
Low Frequency				
Dielectric Withstand (Hipot)				

Transformer Turns Ratio (TTR)

Every two-winding transformer has a ratio. The ratio is the relationship between the number of turns on the primary and secondary windings of a transformer. To understand the basic function of a transformer, you could think of it as a *ratio box*. No matter what you put into it, it will always produce a result proportionate to the ratio. An example of a 1:1 ratio would be where the input and output voltages are the same (for every 1 turn on the primary winding, you would have 1 corresponding turn on the secondary). For a 2:1 ratio, the secondary (output) voltage is half of the primary (input) voltage--for every two turns on the primary winding, you have one corresponding turn on the secondary side, and so on. If you applied 10 volts to the primary of a transformer with a 2:1 ratio, the result would be 5 volts on the secondary; if you put 20 volts into the same transformer, you would get 10 volts out. This predetermined relationship between the primary and secondary windings for any given transformer is called the calculated ratio. The turns ratio test (TTR) is performed to confirm the unit's tested ratio lies close enough to the calculated value per ANSI standards.

To find the calculated ratio, divide the rated primary phase voltage by the rated secondary phase voltage as depicted on the nameplate of the transformer. When determining the calculated ratio for a transformer, it is important to refer to the coil (phase) voltage--the phase voltage determines the number of turns at the transformer coils. For a Delta connected winding, the phase voltage is the same as the line-to-line voltage, but for a Wye connected winding, the line and phase voltages are different. For a Wye winding, the coil or phase voltage is represented by the second smaller number (line-to-neutral) when written as follows: *13200 Y/* ***7620***. For example, a transformer which is *13200 Y/ 7620 - 480 Y/ 277* would have a calculated ratio of 27.51, whereas a transformer with a Delta primary such as, *13200 D - 480 Y/ 277* would have a calculated ratio of 47.65.

When a transformer is built at the factory, the actual ratio at the coils will differ slightly from the calculated value due to the many variables involved in the manufacturing process. The easiest way to understand this variance is to imagine yourself trying to hit the same spot on a target at 70 meters with a bow and arrow. A champion archer may be able to land three arrows in the bullseye, but his chances of landing all three on top of each other like Robin Hood are significantly lower. ANSI allows a 0.5% variance above and below the calculated value for tested ratios. This standard is used by Maddox, and it is the same standard employed by field testing companies and associations such as NETA. Maddox performs a standard TTR test on all used units when they are brought into inventory, and again after the reconditioning process is complete. Test values are provided for all tap positions on reconditioned units.

Winding Resistance

A winding resistance test helps us evaluate the condition and quality of the current carrying path of the windings in a transformer--this also includes the current paths for the internal buswork and components of the transformer such as the tap changer. For new factory built pad-mounted transformers, this test is only required for sizes above 2500 kVA (IEEE C57.12.00), however, Maddox utilizes the winding resistance test for all reconditioned medium voltage units. Winding resistance provides essential diagnostic information which may aid in the initial review of a unit which is being taken into consideration for repair or reconditioning. Issues such as loose internal connections, faulty tap changers, open circuits, and broken conductor strands or crimp connections may be identified with this test. Similar to insulation resistance, a specified DC voltage (generally 5%-10% of the winding's rated current) is applied across sections of the coils. In the case of a Delta connection, measurements are made phase to phase (H1-H2, H2-H3, H1-H3). With a Wye connection, measurements may also be made phase to phase (H1-H2, H2-H3, H1-H3) as well as phase to neutral (H1-H0, H2-H0, H3-H0).

This test is measured in ohms, and the value is typically low (tenths or hundredths of a decimal). Keep in mind that when this test is performed (especially in the field), it is typically done at the bushings of the transformer, and, as a result, measurements will include any components in the current carrying path of the windings such as tap changers, fuses, switches, and cable leads--which may affect test results. A questionable reading may not always indicate a problem with the coils themselves. For instance, if one phase of a transformer has a significantly longer section of internal buswork between the bushing and the winding lead it connects to, you may see a higher measured value across that particular phase. In this case, the test data would not indicate a problem, but a simple fact inherent to the mechanical design of the unit. The same type of variance, however, could show up on a phase with a loose or frayed cable connection at the tap changer--where the variant reading would indicate a mechanical problem which would need to be addressed during the reconditioning process. For this reason, the proper performance of a winding resistance test requires a proficient mechanical knowledge of the internal workings of the transformer as well as an aptitude for evaluating the available test data. Results between phases which fall within 5% of each other are generally considered acceptable (IEEE Std 62-1995, p. 7, section 6.1.1)

Insulation Resistance (*Megger*)

While insulation resistance (or *Megger*) testing is not recognized by ANSI for determining pass/fail criteria on newly manufactured transformers (we'll discuss that more in the following paragraph), it is a useful supplementary test for units which have spent some time in service out in the field. As the title indicates, the purpose of this test is to determine the quality of the insulation on a piece of electrical equipment. Insulation resistance testing is used on a variety of electrical apparatus such as conveyors, motors, fans, refrigerators, HVAC, and cables. In this test, we are measuring the resistive capability of the insulation material surrounding the bare copper conductor carrying electrical current in a system or piece of equipment--commonly measured in megohms. The test is performed by applying a specified DC voltage through the conductor(s) of the equipment. Over time, the insulation coating around a wire may degrade from factors such as--overheating, external physical stress, or moisture. This degradation can lead to leaking. In a leaking garden hose, the worst scenario is usually a flooded flower bed or soggy patch of grass, but in an electrical conductor, leaking voltage could result in serious damage to equipment, fires, and/or physical harm to nearby personnel.

Transformers do not see the kind of mechanical and physical stressors common to motors and cables in a raceway. Due to the design of distribution class transformers, test results can yield inconclusive values and may puzzle a field technician who is used to meggering stand alone cables in a raceway. Core grounding methods as well as the inclusion of components such as switches, fuses, and tap changing devices may also affect the results of insulation resistance testing on transformers. For this reason, insulation resistance tests for transformers should be treated as *supplementary* to the battery of standard routine tests outlined under IEEE C57.12.00, and not the be-all and end-all of determining a good transformer from a bad one. Insulation resistance is performed on the High side windings to Low side windings, High side windings to Ground, and Low side windings to Ground.

So, why does Maddox use insulation resistance testing? Oftentimes, transformers--both dry and liquid filled--will accrue moisture around the windings (this could be caused from a variety of factors and in many cases is unavoidable under certain service conditions). In this case, the insulation resistance test will yield a lower megohm reading (as you might figure). The presence of moisture around the coils creates a higher path of conductivity between the layers of cellulose insulation separating the windings. So, is that it? Should you throw your transformer away if it *Meggers* poorly and start over? Not at all. You simply need to remove the moisture. To accomplish this, the core and coil is removed from the enclosure and placed in a state of the art oven where the coils bake at high temperatures for several hours. Once the bakeout process is complete, the coils are removed from the oven and tested again. Generally, anything in the gigohms realm is more than acceptable for a distribution class transformer. If the bakeout process is performed properly, a reconditioned transformer can test as high as a newly manufactured unit. If high moisture content is not checked and fixed, it can eventually lead to larger problems including deteriorating cellulose insulation in the windings. For these reasons, insulation resistance testing is a crucial part of the repair and reconditioning process. No accepted standard exists for the interpretation of insulation resistance test results, but a comparison of similar units from previous test experience may provide helpful guidance. It is important to establish a baseline value at the time of commissioning to facilitate the interpretation of future tests on any given unit.

Impedance Voltage (Positive Sequence), Load Loss

When we do an impedance test, we are measuring the losses in the transformer--watts/power which is wasted or *lost* during electrical operation. The quality of construction along with the type of materials used in the building of the transformer's core and coil assembly play a role in determining the results of this test. Unlike the insulation and winding resistance tests which serve as a supplementary evaluation for distribution class transformers, the impedance/load loss test yields concrete results which can be taken at face value. This test may be used to confirm the design values for a given unit where a certain number of losses is requested by a customer on new factory built units.

ANSI standardizes impedances for distribution class transformers above 500 kVA at 5.75% (+/-7.5%), however, sometimes customers will request something different. This can largely be accomplished with the design of the core itself. The impedance may be raised above the standard 5.75% by making the core shorter and stouter, while a lower impedance may be achieved with a taller and thinner core design. The impedance (%IZ) of a transformer is affected by the resistive (%IR) and reactive (%IX) components in the transformer. It is during this test that the reactive and resistive components of impedance are identified as well as the resulting X/R ratio of a unit. For reconditioned transformers, these values will be determined by how the unit was originally manufactured at the factory. Impedance/load loss testing is a standard routine factory test (IEEE C57.12.00) which is required for all new factory built pad-mounted distribution class transformers, and it is performed on all transformers which are repaired or reconditioned by Maddox. The tolerance from the specified value for two-winding transformers is ±7.5%; for zigzag, autotransformers, and transformers with three or more windings the tolerance is ±10% (IEEE C57.12.00-2020, p. 64, 9.2).

Excitation, No-Load Loss

With an excitation test, we are testing the flow of magnetic flux in the transformer core. If the words magnetic flux sound a bit too technical, think about a simple magnet with two ends or poles (one south and the other north). If you sprinkled iron shavings on a table near the magnet, you would see the iron shavings line up in long oval loops springing from one end of the magnet to the other (these invisible phenomena are referred to as *magnetic lines of flux*). These magnetic fields are all around us, and it is this same principle which is behind the invention of the directional compass. A transformer's ability to produce these lines of flux is what we are after here in the excitation test. To perform this test, voltage is applied to the low side of the transformer windings with the high side windings open; this allows the amount of magnetic flux required for operation to flow through the core.

Another way to think of excitation is to think of it as the amount of work required to start the transformer. The quality of the core and coil assembly and its construction influence how much excitation is needed during energization. Imagine trying to roll a car with a dead battery down the street to a nearby parking lot. You would have to do some amount of work to get the car going which would require a bit more heaving and grunting in the beginning--this extra heaving and grunting would merely be spent in getting the object out of it's stationary state. In the same way, a poorly built (or damaged) core and coil assembly will require more *heaving* and *grunting* when the transformer is energized. The additional work which is lost at startup is what we refer to as "no-load losses". A good transformer core will direct and strengthen the electromagnetic lines of force generated by the coils when an AC voltage is applied with the least amount of stray/leakage flux (lost energy). The quality, orientation and construction of the laminated core steel in a transformer will affect the exciting current. For distribution class transformers, the DOE has standardized the type of core steel required and set minimum percentages for efficiencies in distribution class transformers up to 2500 kVA.

Modern advances in technology and the DOE's regulations on transformer efficiencies have helped to regulate the quality of transformer core construction. Excitation/no-load loss testing is another standard factory routine test for new built transformers (IEEE C57.12.00), and it is an essential part of the repair and reconditioning process at Maddox. The presence of higher than normal exciting current often can lead to the discovery of internal problems such as shorted turns, a damaged core assembly, or a faulty tap changer. Some of these issues can be fixed in the repair process. This test is also used as a baseline for determining the viability of a unit for repair or reconditioning, and it is performed on all 3-Ph distribution class transformers.

Phase Relation

The phase relation test confirms the angular displacement and phase sequence between each winding on a three-phase transformer. In layman's terms, it confirms the coils are connected correctly inside the transformer tank. For example, if you apply a voltage across H1 and H2 at the primary winding, you would expect to measure a corresponding voltage across X1 and X2 of the secondary winding. Let's say for the sake of this example when you applied a voltage across H1 and H2, you instead found the corresponding voltage across X2 and X3 on the low winding; in this case, the primary and secondary windings would be out of sequence, and the internal winding connections would need to be fixed accordingly.

With two-winding transformers, the coils may be connected in Delta or Wye. For a 3-Ph transformer connected Delta on the primary and Wye on the secondary, a 30 degree phase shift will be present--which can be either leading or lagging. For a transformer connected Delta on the primary and Delta on the secondary, there is a zero degree (or no) phase shift (the same scenario exists where a Wye connection is on both the primary and secondary side). The phase relation test confirms the internal connection of the coils matches the vector grouping diagram on the nameplate of a given transformer. This information is vital to the proper operation of an electrical system--especially where multiple units are tied together. Verifying proper phasing is a basic part of the repair and reconditioning process. This test is another routine test required for all new factory built transformers (IEEE C57.12.00), and it is performed on all units brought into the Maddox facility for repair and reconditioning.

Leak Test

Following the repair and reconditioning process, each unit is tested to verify the transformer tank will hold and maintain pressure when put into service. A visual inspection is made to verify no fluid leaks exist around any gaskets or seals. In the case where a radiator(s) was repaired or replaced, additional care is taken to verify a successful repair which will hold up to usual service conditions in the field.

Applied Potential

The applied potential test is currently not part of the standard battery of tests for reconditioned transformers. It is a routine test per IEEE C57.12.00, and applied potential is performed on all new factory built Maddox transformers. The purpose of this test is to ensure the integrity of the insulation system in a given unit by putting the insulation under stress via an overvoltage. For this test a voltage is applied and gradually increased across the winding being tested with the starting voltage being no more than one quarter of the full value. The specified duration of the test is one minute per IEEE C57.12.90. This test is often omitted in the field for in-service transformers as it requires a customer to have a replacement plan in place in the case where the test causes a failure of the transformer. Applied potential testing is designed to fail an insulation system which is already compromised; it is generally agreed that it will not result in damage or failure when performed on a unit with good insulation.

Induced Potential Test

The induced potential test is another overvoltage test like the applied potential test. It is also a routine IEEE test performed on all newly manufactured transformers. Like applied potential testing, this particular test is currently not included among the list of tests performed on reconditioned transformers. To perform this test, a voltage “greater-than-rated volts per turn to the transformer” (IEEE C57.12.90-2015, p. 52) is applied and gradually increased for a designated period of time--depending on the frequency at which the test is performed (the frequency supplied must be raised to prevent overexcitation of the core as the applied test voltage is significantly higher than the rated voltage). The formula for establishing the minimum test frequency is set forth in section 10.7.2 of IEEE C57.12.90.

Impulse Test

Impulse testing is another test which is only performed on newly manufactured units at the factory. The purpose of this test is to analyze a transformer's ability to withstand large voltage surges as would be common in a typical electrical system. During normal service conditions, transformers are often exposed to sudden high voltage spikes--resulting from lightning or the operation of switches. Along with induced and applied potential tests, we are again testing the dielectric strength of the insulation system in the transformer. In the case of lightning, the voltage wave can take a variety of forms; for this reason, the impulse test is designed to imitate both the form of the wave and the succession in which the various wave shapes may occur. These are: one reduced full wave, one full wave, two chopped waves, and two full waves. This particular portion of the impulse test requires a good amount of time, which is why it is designated only as a design test for distribution class transformers. A subclause is provided in the IEEE testing code to allow a basic routine quality control version of this test for distribution class transformers where high volume production lines cannot afford to perform the entire gamut of impulse testing. For distribution class transformers, only the first unit of a particular design will receive the entire sequence of full and chopped wave tests at the factory under standard routine test procedures.

Insulation Power Factor Test

Power factor testing is most commonly associated with larger class I & II power transformers, and it is a standard routine test for power units per IEEE C57.12.00. It is important to note this test is not recognized by ANSI/IEEE as an accepted method for determining pass/fail criteria on distribution class transformers. The test code laid out in IEEE C57.12.90 also notes the difficulty and potential problems associated with attempting to establish absolute values to apply across the board for this test (See Notes 1, 2 & 3 of Table 4, IEEE C57.12.90-2015, p. 56). Although test results can be difficult to interpret at times, power factor testing provides a diagnostic benefit when comparing test data for a single unit over a period of time--for example, if a more recent set of test results contrasts significantly with data from an earlier test for the same unit, this could alert a technician to the possibility of an issue which may need addressing. The use of an initial stand alone test to establish pass/fail criteria in distribution class transformers, however, is not advisable. Due to the physical construction and the presence of other ancillary components within the path of the test voltage such as tap changers and switches, results can vary widely for distribution class units.

While power factor testing is not performed under the standard battery of tests required by IEEE C57.12.00 for smaller transformers (generally below 10 MVA), it is required by many field service testing groups such as NETA. This can often become a point of contention between the NETA technician and the transformer manufacturer. It's important to note the values put forth by NETA for insulation power factor testing are suggestions which are recommended by NETA in the absence of an agreed upon standard (See Table 100.3, *NETA Standard for Maintenance Testing Specifications for Electrical Power Equipment and Systems*). When field test values fall outside what is recommended by the agency testing a given unit, the next course of action should be to perform the remaining battery of standard tests for field commissioning and evaluate the results. If the remaining tests pass, the transformer is more than likely ok to energize. The field technician will usually need to sign off on his end for any values which do not line up with NETA's recommendations, so it may be necessary for us to add clarification or verify the unit's test results are within acceptable limits according to factory standards.

Additional notes:

- Field Testing Conditions: Testing should never be conducted when the tank is under vacuum; the dielectric strength of the insulating material is severely reduced under negative pressure (IEEE Std 62-1995, p.6, section 5.3.4)

- Testing Voltages: For windings in a grounded wye configuration where the insulation is graded or reduced for applications on grounded systems, the test voltage should be applied based on the lowest insulation level of the tested winding (IEEE Std 62-1995, p.6, section 5.3.3)

- ANSI Tolerances for Quoted Losses: Sometimes, the specified no-load and load loss values may be slightly lower than the actual tested values after production on new transformers. This is not uncommon since an exact value is difficult to attain every time. For this reason ANSI allows a certain tolerance for specified losses. For specified losses, the no-load losses may not exceed 10%, and the total losses may not go above 6% (IEEE C57.12.00, p.65, 9.3)