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TRANSFORMER WINDING RESISTANCE MEASUREMENT:

FIELD CHALLENGES

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1. INTRODUCTION

A DC winding resistance measurement is a common diagnostic test performed on distribution and power transformers. This test can be used to detect internal issues such as shorted turns, burnt or open windings, broken strands, poor connections, and problems associated with On-Load Tap Changers (OLTC) and De-Energized Tap Changers (DETC). Although this test looks simple, in practice, it presents several technical complexities that can cause trouble for field technicians to obtain accurate readings.

This paper covers some of the less known facts associated with the DC winding resistance (WR) measurements, diving deeper into topics such as selection of the correct test current, and the importance of compliance voltage during the test. Phenomena as core saturation, current stabilization, the influence of winding inductance on readings, and the effect of temperature, are also explained. Different test techniques and safety procedures will also be covered.

Additionally, this paper will also make use of field test results to explain the issues and important factors highlighted above. At the conclusion, paper presents field cases on how to troubleshoot

2. PRINCIPLE OF OPERATION

The equivalent circuit of a transformer, shown in Figure 1 below, can be used to explain the challenges associated with WR measurements. In this case, the highlighted components in red, R_1 and R_2, are the ones the instrument will report as results. The inductive components shown, due to the geometry of the windings and the magnetic branch of the circuit, will play an important role while performing the test.

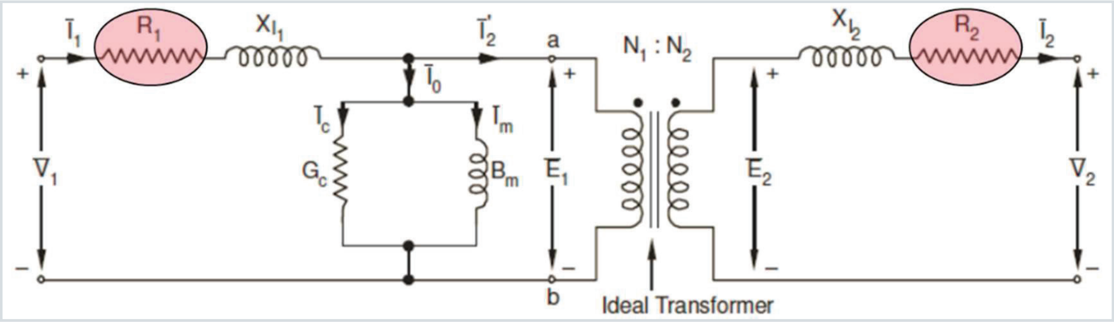


Figure 1. Equivalent circuit of a transformer

The winding resistance measurements are performed using a test instrument that will inject a direct current (DC) though the winding(s) to be tested, to then measure the corresponding voltage drop and thus determine the winding resistance (Figure 2). When using this method on a transformer, or any highly inductive circuit, several aspects are to be considered to obtain an accurate reading as a result.

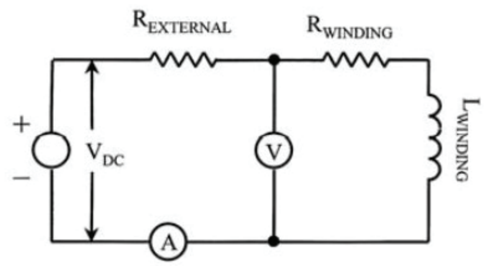


Figure 2. Simplified circuit of a WR measurement

From Figure 2, the equation A below can be used to determine the voltage drop being measured by the test instrument during the test.

$$V = RI + L\frac{\partial I(t)}{\partial t} + I\frac{\partial L(t)}{\partial t} \qquad \textit{Equation A}$$

The resistance R in the first component of the equation is the value the test will calculate as a result of the current and voltage drop measurements; the other two components are subjects of a deeper analysis as, they directly impact how quickly and accurately a test instrument will be able to provide a measurement.

During the first stage of a measurement, due to the inductive component of the circuit, the current flowing through the winding(s) under test will not be constant and thus, it will generate a magnetic field, which in turn will develop a back EMF across the inductor. This will result in the voltage drop described in the second component of equation A. If the current flow is maintained long enough to reach a stable value (depending on the L/R constant of the circuit), the magnetic flux establishing the back EMF will collapse and the voltage drop across the inductor will be zero. The core saturation is also required, as in that state, the magnetic domains of the core will be polarized and thus, the main source of inductance of the circuit will drop. Compared to a motor, generator or reactor, the third component of equation A will represent a worse complication when testing a transformer due the specific requirements for the transformer's core design, including the material selected for its construction, as shown in Figure 3 [1] below.

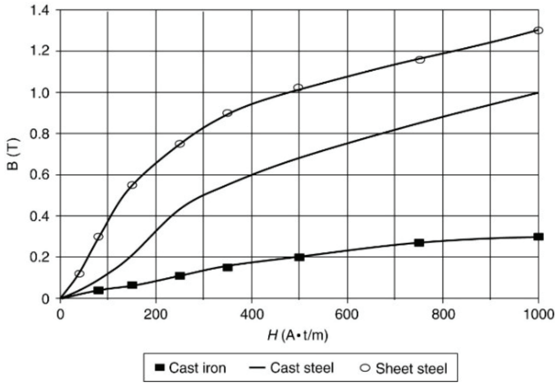


Figure 3. B-H curve for three different materials

3. FACTORS AFFECTING THE MEASUREMENT

3.1 TEST CURRENT

The selection of the test current is an important parameter to define before performing WR measurements, as it will directly impact the test efficiency and the accuracy of the results.

It is generally recommended to use a test current of at least 1% the rated current of the winding under test, as this will typically ensure that the test current is higher than the excitation current of the transformer. Ideally, the test current should be between 2-4 times the excitation current [2] and not higher than 15% of the rated current of the winding to avoid heating of the conductor and thus changes in the resistance values [3].

3.2 COMPLIANCE VOLTAGE

The magnetic flux required to reach core saturation depends on the voltage rating of the winding under test and will be directly proportional to the voltage applied to the winding and the time that voltage is applied. Because this relationship, the magnetic flux is sometimes referred to as *volts seconds* (Equation B).

$$\Phi = V \times T \qquad \textit{Equation B}$$

From equation B, it can be seen that to reduce the time to reach core saturation, we can either increase the voltage from the test set or apply the voltage for longer times. Typically, the compliance voltage of WR test instruments is not a user controllable setting, but rather a technical specification; thus, careful selection of the test instrument is advised. A higher compliance voltage would lead to faster core saturation.

3.3 TEMPERATURE

The electrical resistance of a conductor, such as copper or aluminum –the metals used for winding construction– is temperature dependent. It is highly important to avoid temperature changes caused by the WR measurements (as described above) and to note the temperature at which the WR measurements are taken. This consideration is particularly important when an individual will be comparing results to previous measurements of the same winding(s) - both measurements must be corrected to the same reference temperature for an accurate comparison. Most modern WR instruments will offer temperature correction of the results, so the user only needs to indicate the winding temperature at the time of the measurements. Per [3], temperature corrections are done with Equation C.

$$R_s = R_m \left(\frac{T_s + T_k}{T_m + T_k}\right) \qquad \textit{Equation C}$$

Where,

R_s = resistance at desired temperature T_s

R_m = measured resistance

T_s = desired reference temperature (˚C)

T_m = temperature at which resistance was measured (˚C)

T_k = 234.5 ˚C for copper, 225 ˚C for aluminum (may be as high as 230 ˚C for alloyed aluminum)

The temperature measurements in the field have proven to be difficult, and the methods commonly used include the following [3]:

- Place a thermometer in contact with the tank wall. If the transformer has been recently removed from service, this does not give an accurate indication of the real winding temperature.
- Use values obtained from the permanently installed temperature indicators. If the transformer has recently been removed from service, this may be the only means available for estimating the winding temperature.

3.4 WINDING CONFIGURATION

When dealing with 3-phase transformers, the user will need to pay attention to the winding configuration of the transformer under test and how the measurements are taken. To cover both delta and wye-connected windings, the paper will use a Dyn transformer as a first example:

To take measurements on the low side of the transformer, the user can select from two options:

- Take measurements per phase: Three measurements will be taken, X1-X0, X0-X2, X3-X0
- Take a 2-phase measurement, then the remaining third-phase measurement:
    - Current injection from X1-X3, to measure both X1-X0 and X0-X3 resistances.
    - X2-X0 measurement

The second option for this wye-connected winding will save the user a few minutes if using a singlephase instrument –as connections need to be changed for each measurement –but presents the disadvantage of making more difficult to identify an issue on the X0 bushing connection to the winding, as in the measurement including the first two phases, there is no current flow through the X0 bushing. In this case, the X0 busing is only being used to measure the voltage drop across the two individual phases involved in the measurement. If a problem exists in the X0 bushing connection to the winding it might be revealed during the X2-X0 measurement, but then again, the analysis turns out to be more complex.

The time savings of the second method described above are comparable to a per-phase measurement when using an instrument with 3-phase connection provision, in a way that per-phase measurements are possible without the need of switching connections each time a measurement is made.

The measurements on the delta side of the transformer will potentially take considerably longer time, due to the challenges described in the previous sections. During a per-phase measurement, the current injected by the test instrument will flow through all the phases of the delta, causing slower saturation of the core and thus, extending the time necessary to get a stable reading. The result of each measurement, is the resistance of the phase under test, in parallel with the series resistance of the two untested windings, as described in Figure 4. This becomes particularly important to take into account when comparing field results against factory data, when sometimes the measurements were taken with an open delta.

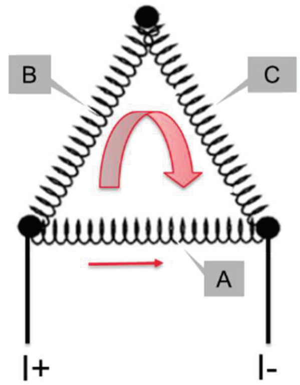


Figure 4. R Measured=R(A) // R(B) + R(C)

The results are usually interpreted based on comparing measurements made separately on each phase of a wye connected winding or between pairs of terminals on a delta connected winding. The resistance between phases should be within 2% of each other. Comparison may also be made with original data measured in the factory where agreement to within 5% for any of the above comparisons is usually considered satisfactory [3]. NETA Acceptance Testing Standard (ATS) and Maintenance Testing Standard (MTS) recommend performing WR test on dry type and liquid filled transformers. Temperature corrected readings should compare within 1% (dry type) and 2% (liquid filled) of previously obtained readings/factory test values or between adjacent phases. Performing winding resistance on each tap position of on load tap changers is optional but considered as best practice.

3.5 TRANSFORMER SIZE

As outlined in section 2 and 3, the inductance of the circuit will largely impact the time it will take for an instrument to take an accurate reading, thus, the winding geometry and the capacity (size) of the transformer will be important factors to consider when selecting the proper instrument to perform WR measurements on a given transformer.

4. BEST PRACTICES

4.1 IMPROVING TESTING EFFICIENCY

The WR resistance measurements are required to be taken using the 4-point or 4-wire method, to ensure that neither the test leads resistance nor the test lead to specimen contact resistance values are added to the reported results [4].

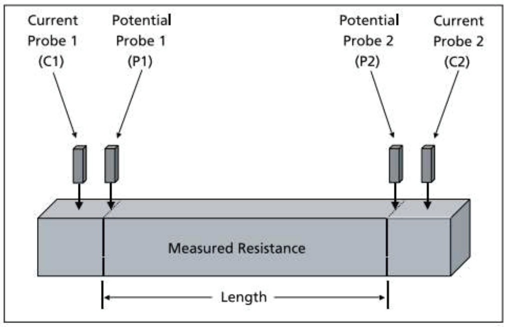


Figure 5. Simplified example of a 4-wire measurement.

Most modern WR instruments will use *Kelvin style* lead sets that incorporate both current and potential leads using a single clamp, as shown in Figure 6. Care is advised when connecting these probes to the terminal of the transformer to ensure proper contact of both potential and current portions of the probe.

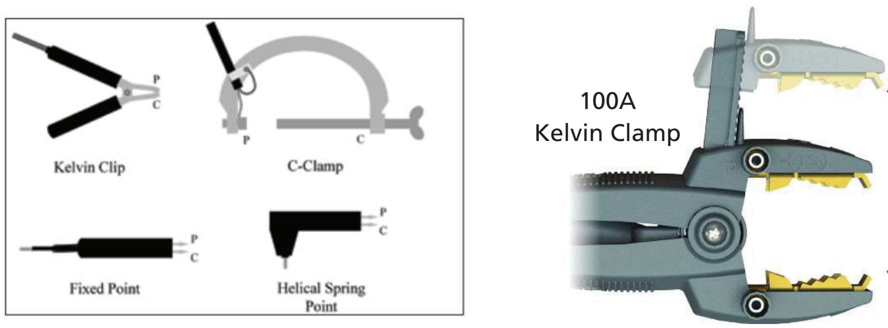


Figure 6. Kelvin Style Lead Sets

4.2 CURRENT DIRECTION

The polarity of the core magnetization should be kept constant during the resistance measurements. A reversal in magnetization of the core can change the time constant and result in erroneous readings [3]. When performing per phase measurements, all efforts should be made to maintain the direction/polarity of core magnetization throughout the testing duration. For instance, the direction of the B-phase test current should be based upon how the core has been magnetized when the A-phase was tested. A similar consideration should be given when testing the C-phase after the B-phase measurements. Figure 7 shows the orientation of the core magnetization after current injection in A-phase (H1→H0) of wye winding. This determines that when testing B-phase, the current should be injected from H0→H2 to maintain the same polarity for core magnetization. A similar conclusion can be drawn for a delta winding, as shown in Figure 8. Following test current direction should be used for a delta and wye winding as shown in Table 1 below.

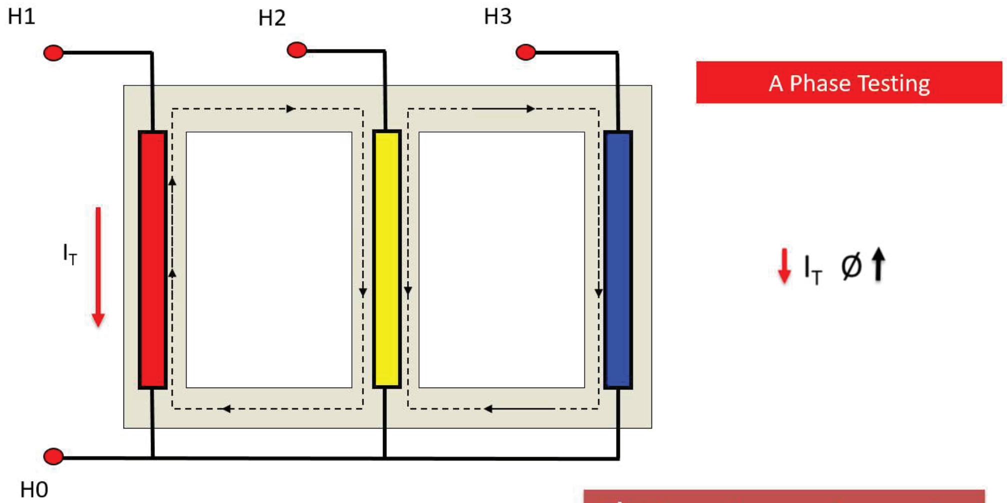
A Phase	H1-H3
B Phase	H1-H2
C Phase	H3-H2

(A)

A Phase	H1-H0
B Phase	H0-H2
C Phase	H3-H0

(B)

Table 1. Test current direction for per phase WR for (A) Delta winding (B) Wye winding



Phase	A	B	C
Flux	Up	Down	Down

Figure 7. Direction of flux after A phase testing (H1-H0) for a Wye configuration winding

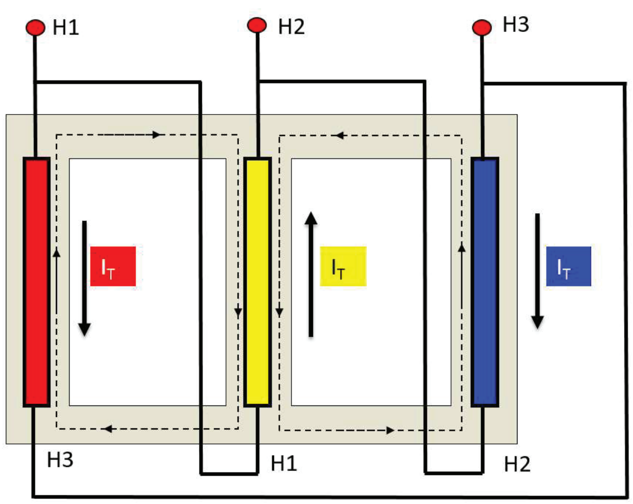


Figure 8. Direction of flux after B phase testing (H1-H2) for a Delta configuration winding

4.3 DUAL WINDING INJECTION

When dealing with large transformers, the dual injection method has proven to be effective in reducing testing times. The concept of this technique relies on injecting the test current using two windings of the same phase of the transformer, as outlined in Figure 9. This will result in an increased magnetomotive force (ampere-turn) by a factor of approximately the turns ratio of the transformer, and thus, helping saturate the transformer core faster than when injecting the test current using only one winding at a time.

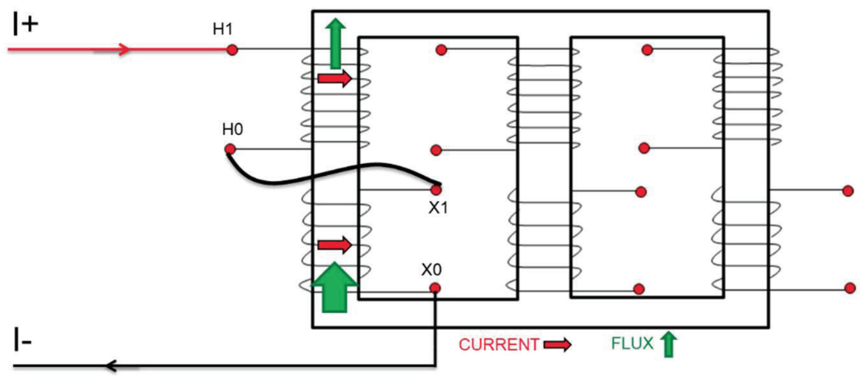


Figure 9. Dual injection Method

4.4 SINGLE PHASE VS. THREE PHASE TESTING

A single-phase WR measurement is performed with a single current source and moving the source from one phase to another. This is also called as per-phase testing. Per-phase testing can also be performed by making all the connections one time using a three-phase leads system, as shown in Figure 10 and utilizing source switching technique to test all three phases *sequentially* without changing the leads.

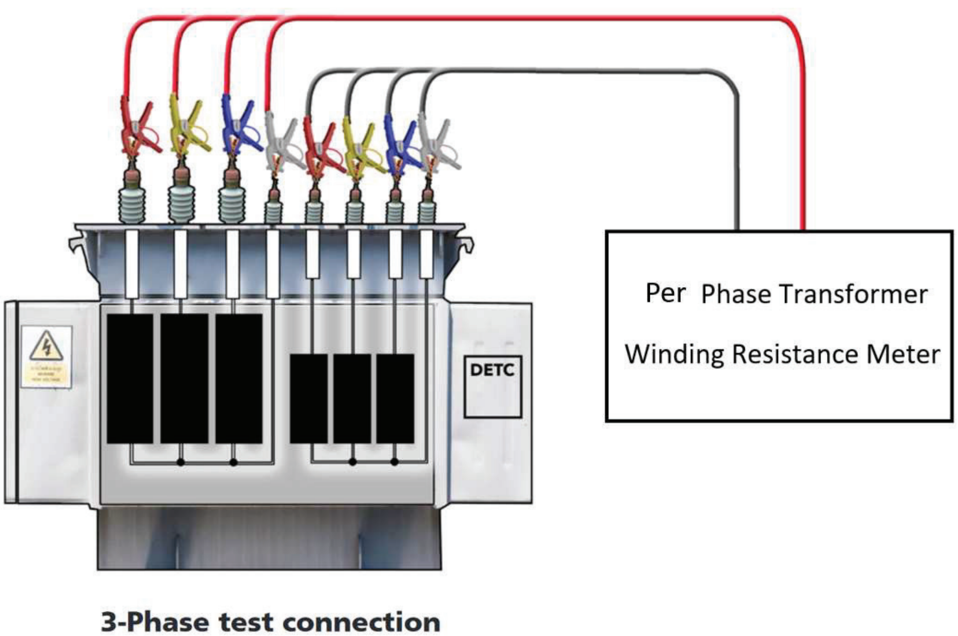


Figure 10. Single phase (per phase) WR testing with source switching technique

When performing a single-phase measurement, the current flows through the complete circuit of the winding under test (including both bushings), as shown in Figure 11. The voltage drop V1 is the resultant voltage drop of all the resistances present in the path of that current flow.

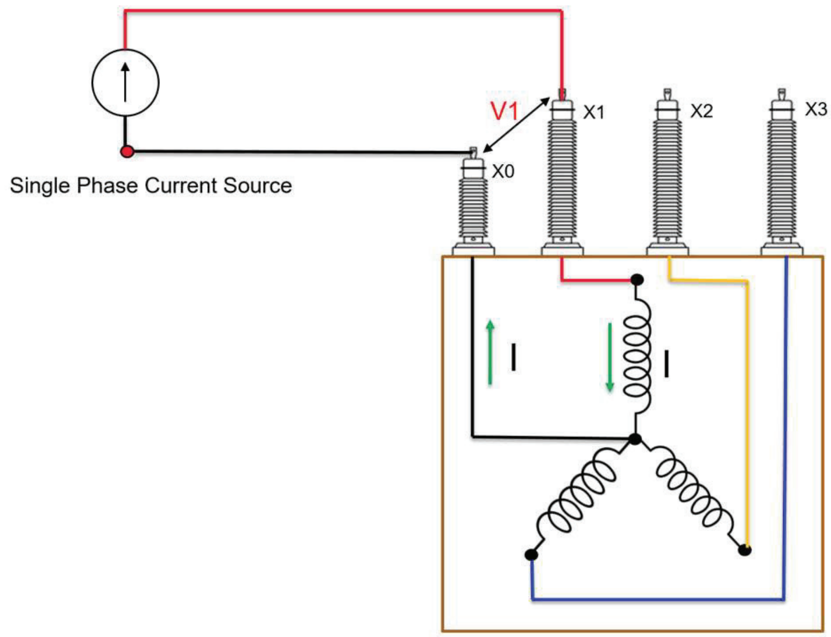


Figure 11. Single phase WR testing showing the flow of current and voltage drop across the winding

Three-phase testing includes utilizing three current sources simultaneously and injecting current into all three windings and measuring the voltage drop across them, as shown in the Figure 12 below.

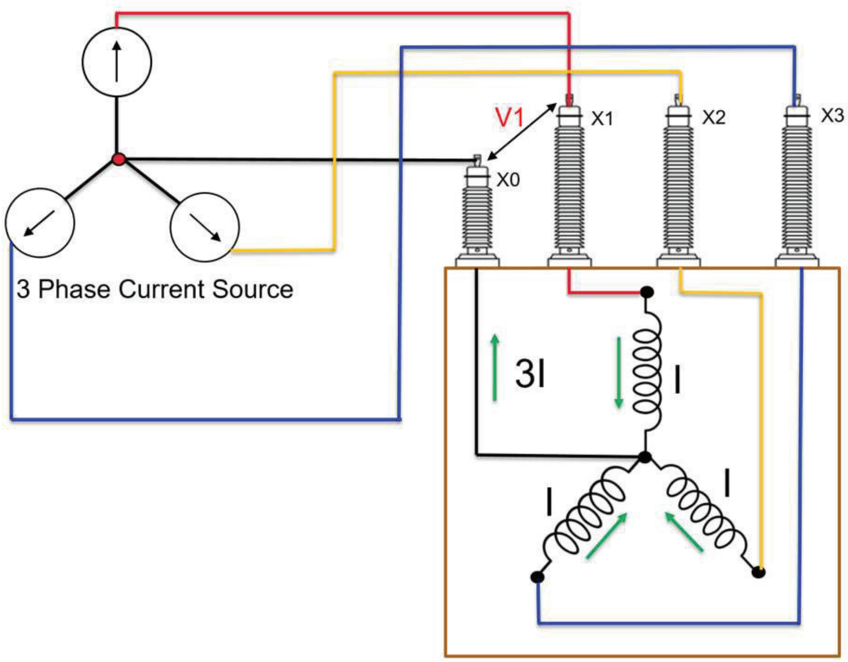


Figure 12. Three phase WR testing utilizing three current sources

There are some fundamental differences between single-phase and three-phase WR testing:

- Three-phase testing provides some time savings as all three phases are measured simultaneously and three currents are used to magnetize the core to achieve core saturation faster.
- Single-phase and three-phase testing results may differ slightly because of the measurement error introduced with a three-phase measurement, as current flowing through neutral is 3I as opposed to measured current I. The differences between the two results can be significant, pending WR measurement values (< 5 m ohms) and may cause variation of more than the 2% limit allowed. Three-phase measurement results would generally introduce a positive error.
- Three-phase testing can only be performed on a Wye winding. A closed loop delta winding would provide erroneous results when utilizing the three-phase WR method. Per-phase method of testing is recommended for delta winding.
- When performing a per-phase measurement, it is recommended to use the dual winding injection method to achieve faster core saturation. It cannot be used with three-phase WR method for any ANSI vector configuration.
- A Wye winding configuration, typically found with OLTC, can be tested with the three-phase WR method to speed up the test, however, "make before break" functionality has to be tested separately.

4.5 DE-ENERGIZED TAP CHANGERS (DETC) TESTING

In the United States, DETCs are typically found on the high voltage winding of the transformer and commonly have 5 taps. It is recommended to perform WR test on all the taps during commissioning and the in-service taps when performing scheduled maintenance. It is never recommended to change the DETC tap position if the switch has been in the same position for any considerable amount of time, unless explicitly advised to do so. It is very likely that the switch could be seized and suffer a failure when actuated, resulting in unnecessary down time.

When performing the test on a per-phase basis, for each tap it is recommended to test all the three phases sequentially, keeping the polarity of the core magnetization constant before operating the DETC and moving on to the next tap. The Table 2 below shows the results of a 5 tap DETC WR measurements.

HIGH VOLTAGE WINDING RESISTANCE

		Corrected Resistance to 75°C				
TAP	Current (amp)	H_1 - H_3	H_2 - H_1	H_3 - H_2	Reading Stability %	Winding Difference %
1	1.0049	12.94	12.97	12.95	99.9974	0.261
2	1.0165	12.63	12.66	12.64	99.9977	0.268
Nominal	1.0051	12.32	12.35	12.33	99.9974	0.260
4	1.0052	12.01	12.04	12.02	99.9994	0.254
5	1.0056	11.71	11.74	11.71	99.9990	0.247

Table 2. DETC temperature corrected winding resistance measurements

Readings between phases should be within 2% variation for all the tap positions.

4.6 ON LOAD TAP CHANGERS (OLTC) TESTING

OLTCs are normally present on the low voltage side of the transformer. Reactive type OLTCs are most common in North America. The number of taps present may vary based upon design, construction and load requirements. It is generally used to provide +/- 10% voltage regulation. It is recommended to perform WR measurement on all the taps of an OLTC, both during commissioning and scheduled maintenance. When measuring WR of an OLTC, it is recommended to charge one phase at a time and test all the tap positions from extreme raise to extreme low positions. This technique speeds up the testing as a winding is charged, the core is saturated, and readings can be obtained on all the tap positions faster. Once done, the current is discharged, and next phase is charged, and the taps are tested from extreme low to extreme raise positions. Similar concept is used for the remaining third phase. This is shown in Figure 13 below.

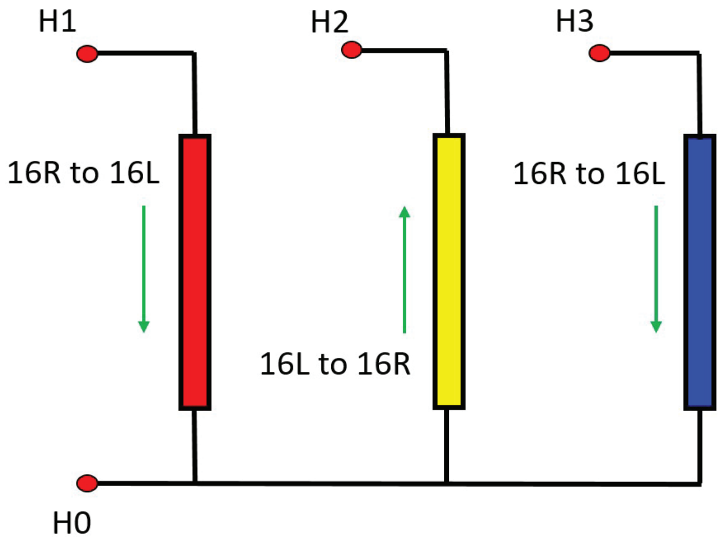


Figure 13. Direction of current and flow of testing of an OLTC

The results obtained, even if not temperature corrected can be compared between the phases for any given tap and should be within 2% variation.

An OLTC should make the contact with next tap before breaking the contact with previous tap to maintain an uninterrupted flow of current. The WR test is also useful to check “make before break” operation of an OLTC. During the transition from one tap to the other, the amount of current drop is monitored and if the percent current drop stays below a threshold for more than a defined time duration, it is considered as a “break before make” condition, which is not desirable. The Table 3 below shows the make before break OLTC test with a time sensitivity of 5ms.

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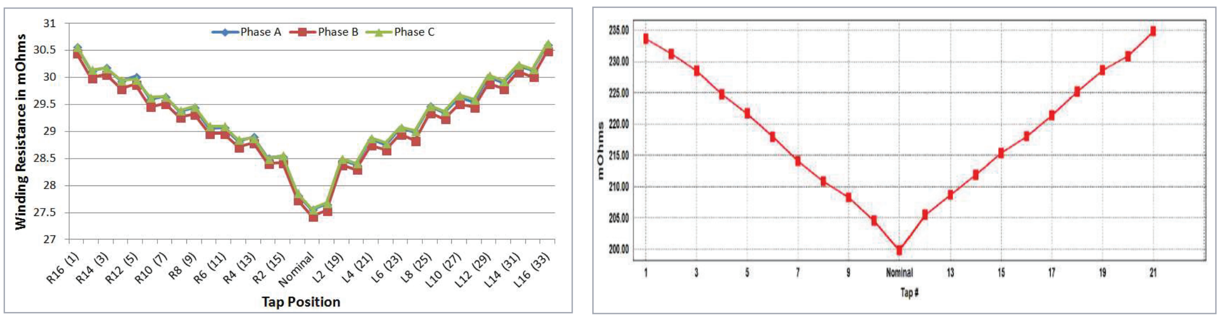
HIGH VOLTAGE WINDING RESISTANCE

Units mΩ

TAP	Current (amp)	Nameplate Voltage	Measured Resistance $H_1 - H_0$	$H_2 - H_0$	$H_3 - H_0$	Reading Stability %	Winding Difference %	Make/Break			
1	10.0313	269,500	540.1	514.8	514.4	99.9451	0.323	5 ms	Pass	Pass	Pass
2	10.0223	266,437	535.5	537.5	536.7	99.9695	0.379	5 ms	Pass	Pass	Pass
3	10.0129	262,375	530.9	533.0	532.3	99.9802	0.391	5 ms	Pass	Pass	Pass
4	10.0003	260,312	526.2	528.4	527.9	99.9798	0.416	5 ms	Pass	Pass	Pass

Table 3. OLTC measurements showing make before break test and % winding difference

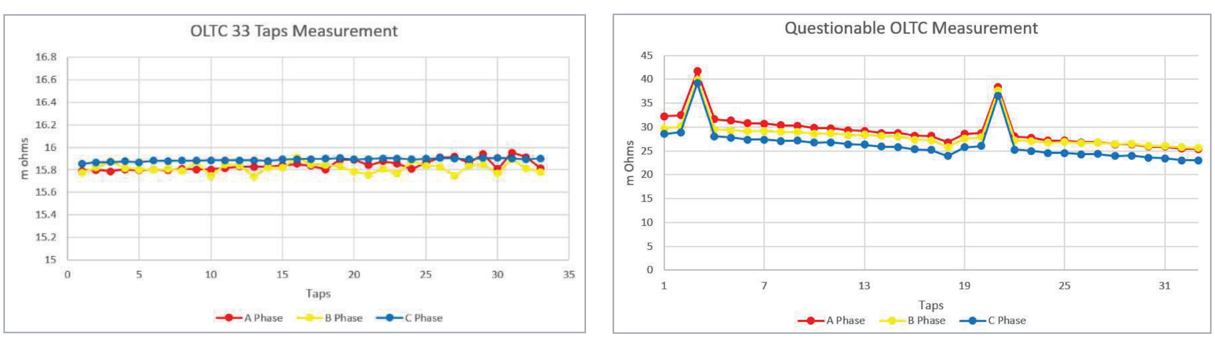
It is best to analyze the phase & tap resistance measurements of the OLTC on a graph. Based upon the construction and design OLTC may show different WR measurement graphs. Figure 14 below shows different OLTC graph patterns.



(A) (B)

Figure 14. (A) showing 33 tap WR results of an OLTC with preventive auto.
(B) showing 21 tap OLTC with a reversing switch and selector switch

In addition to comparing the % winding difference between phase values against recommended limits, graph can also be analyzed to look for any discrepancies. Figure 15 shows a good OLTC response and a questionable OLTC response. Graph (A) shows a uniform pattern for all the 33 taps and all three phases meet the IEEE recommended limits. Graph (B) although meeting IEEE phase criteria shows questionable readings for Tap 3 and Tap 21 when compared against other tap positions.



(A) (B)

Figure 15. OLTC WR results for a good measurement [Graph (A)] and a questionable measurement [Graph (B)]

4.7 SAFE DISCHARGE

When testing inductive equipment with a DC source, energy will be stored in the circuit and proper considerations should be taken to ensure such energy is safely dissipated upon completion of the measurements. The energy stored can develop extremely high voltages across the point where current is broken. The test equipment selected should include provisions to discharge the stored energy in the circuit to the ground, not only when properly finalizing a test, but also when the current is inadvertently interrupted, such as a lead falling off while the measurement is in progress. In this type of event, if a piece of test equipment is not properly designed to safely discharge the stored energy, it will pose important risks not only to the equipment itself and the specimen under test, but also to the individual(s) performing the test.

4.8 DEMAGNETIZATION

The electrical test industry largely agrees on advising the demagnetization of the transformer core right after any type of DC test has been performed. This procedure will ensure that any residual magnetization present in the core is eliminated, as this residual magnetization can cause an unwanted effect on subsequent AC test measurements, as well as to cause an increased inrush current magnitude when returning the transformer to service.

There are several methods available to perform the demagnetization process, such as [5]:

- Variable Voltage Constant Frequency (VVCF) source;
- Constant Voltage Variable Frequency (CVVF) source;
- Decreasing the amplitude of an alternating DC current.

The method to be used will be typically restricted by the instrument used to perform the tests, and the effect of each individual approach might be different depending on the specifications of the transformer. In general, the VVCF yields excellent results, however because of practical limitation of available voltages in the field, this method is not viable. For field use, the best available option is the demagnetizing procedure consisting of applying direct current to the windings and reversing polarity a number of times while reducing the current applied until the core is demagnetized [3].This method could be time consuming and could still leave the core with residual magnetism or remanence at the completion.

Alternatively, adaptive demagnetization (a more efficient version of direct current with reversing polarity and decreasing amplitude) adapts the direct current injection and polarity reversal unique to each transformer under test for most effective demagnetization in a relatively shorter duration with very low remanence at the completion. This technique is explained in detail in reference [5]. Complementary tests, such as excitation current, sweep frequency response analysis, and turns ratio magnetic balance could be used to truly determine the effectiveness of a demagnetization technique.

5. FIELD RESULTS AND COMPARATIVE ANALYSIS

5.1 TEST CURRENT

Test current selection can impact the time required for core saturation and reading stabilization. Care should be taken to have the test current between 1%- 15% of the rated winding current to avoid any erroneous readings. Table 4 below shows the test performed on low voltage winding of a delta-delta, 13.8 kV/2.4 kV, 3750 kVA transformer with different levels of test current and relative time for stabilization and accurate readings. It can be observed that a higher test current provides quicker core saturation and hence stable readings.

Amps (A)	X1-X2 (m ohms)	Secs to Stabilize
10	5.917	101 s
25	5.926	95 s
50	5.926	80 s

Table 4. Reading stabilization time for different levels of test current

It is to be noted that, for some transformers (based upon the excitation current requirement), a test current beyond a certain limit would provide no additional benefit and could be detrimental to core saturation.

5.2 COMPLIANCE VOLTAGE

Core saturation is a function of volts seconds. Instruments with higher compliance voltage could aid in providing faster and stable measurements. Table 5 below shows the results of testing a delta wye, 68.8 kV/ 13.09 kV, 25 MVA transformer with two instruments having different compliance voltage.

Compliance Voltage	Test I	X1-X0 (m ohms)		X2-X0 (m ohms)		X3-X0 (m ohms)	
67 V	10 A	13.84	38 secs	13.87	21 secs	13.94	33 secs
40 V	10 A	13.86	67 secs	13.88	35 secs	13.95	62 secs

Table 5. Reading stabilization time with instruments having different compliance voltage

5.3 DUAL WINDING INJECTION

Dual injection method tests two windings of the same phase on high and low voltage side of a transformer. It helps in achieving core saturation quicker and expedite the test by testing two windings simultaneously. Table 6 shows the comparison of single winding injection and dual winding injection readings and corresponding stabilization time.

Single Injection			
Amps	H1-H2 (mohms)	Secs to Stabilize	
10	257.2	60 s	
Amps	X1-X2 (mohms)	Secs to Stabilize	
10	5.917	101 s	
Dual Injection			
Amps	H1-H2 (mohms)	X1-X2 (mohms)	Secs to Stabilize
10	258.1	5.93	72 s

Table 6. Comparison of single injection testing and dual injection testing measurements

It is to be noted that dual injection is not effective if the turns ratio of the transformer under test is greater than 10 because the maximum current that could be injected is limited by the high voltage winding rated current. The selected test current may be too low for low voltage winding and can take much longer time to get stable low voltage side WR measurements. It is recommended to use single phase injection method in those cases.

5.4 SINGLE PHASE VS. TWO-PHASE MEASUREMENTS

In two-phase measurements, two windings of the same voltage side could be tested simultaneously. This can only be applied to wye voltage windings with an exposed neutral. The current is injected between two line terminals. For instance, A &C phase could be tested together and then, the B-phase is tested with standard per-phase WR measurement technique. Figure 16 below shows the connection diagram of single phase and two-phase measurement techniques.

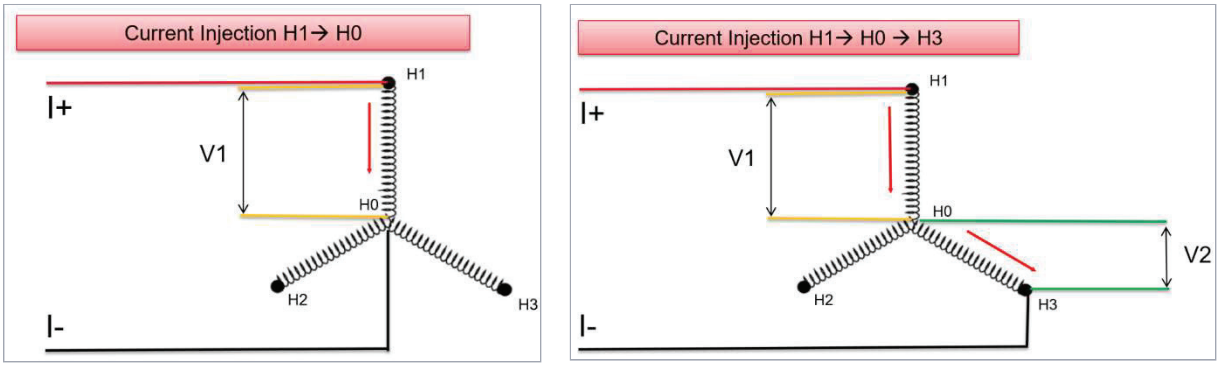


Figure 16. Connection diagrams for single phase and two phase WR measurement setup

When comparing A and C phase readings against B phase, there will be a slight difference because of the way connections are made. In the two-phase winding measurement, since there is no flow of current through the neutral bushing center conductor. AS such, the voltage drop across it is not measured as oppose to B-phase (per phase measurement) where current flows from H2 bushing to H0 bushing.

As shown in Table 7 below, two phase measurement technique on an OLTC introduced winding difference outside of 2% allowable limits. This is the result of 150 u ohms not recorded in A and C phase readings due to no voltage drop in X0 bushing. When 150 u ohms was added to A and C phases, all the results came within acceptable limits.

LOW VOLTAGE WINDING RESISTANCE

TAP	Current (amp)	Nameplate Voltage	Measured Resistance X_0 - X_3	Measured Resistance X_0 - X_1	Measured Resistance X_0 - X_2	Reading Stability %	Winding Difference %
1	10.0415	3,744	5.856	6.121	5.925	99.9910	4.444
2	10.0211	3,770	5.777	5.991	5.857	99.9955	3.632
3	10.0140	3,796	5.836	6.095	5.926	99.9967	4.350
4	10.0209	3,822	5.723	5.949	5.783	99.9959	3.888

Table 7. OLTC results showing the effect of two-phase measurement on % winding difference

Alternatively, results in Table 8 shows the comparison of per phase and two phase measurements on wye winding of a delta wye, 68.8 kV/13.09 kV, 25 MVA two winding transformer with % winding difference within allowed limits. This is due to the value of the winding resistance measured under test. When dealing with low readings in the range of 5 m ohms or less, two phase measurement can introduce error in the measurement. However, two phase measurement offers time savings when measuring resistances 10-15 m ohms or greater, as the effect of X0 bushing on % winding difference is not significant.

Test Type	Test Current	X1-X0	X0-X2	X3-X0	Wdg. Diff %
Per Phase	10 A	13.84	13.87	13.94	0.72%
Two Phase (A&C)	10 A	13.77	13.87	13.85	0.57%

Table 8. Secondary winding resistance with two phase measurement and acceptable % winding difference

5.5 WINDING INDUCTANCE

Transformer configurations like single phase, large auto transformers and secondary delta windings, pose a great challenge in getting stable and accurate WR measurements. The stabilization time is dependent on the time constant L/R of the circuit. Large auto transformers and secondary delta windings, both have small R to measure and a high inductance to neutralize. A closed loop delta winding allows test current to flow in all three windings, thereby, taking time to neutralize all three winding inductances to achieve core saturation. Figure 17 below shows the results from a 345 kV/143 kV/23 kV, 800 MVA, wye auto transformer with a delta tertiary. With 50 A of test current, it took 15 mins to get a stable and accurate measurement. The test instrument should be capable of identifying the reading stability and automatically record the measurements upon stabilization.

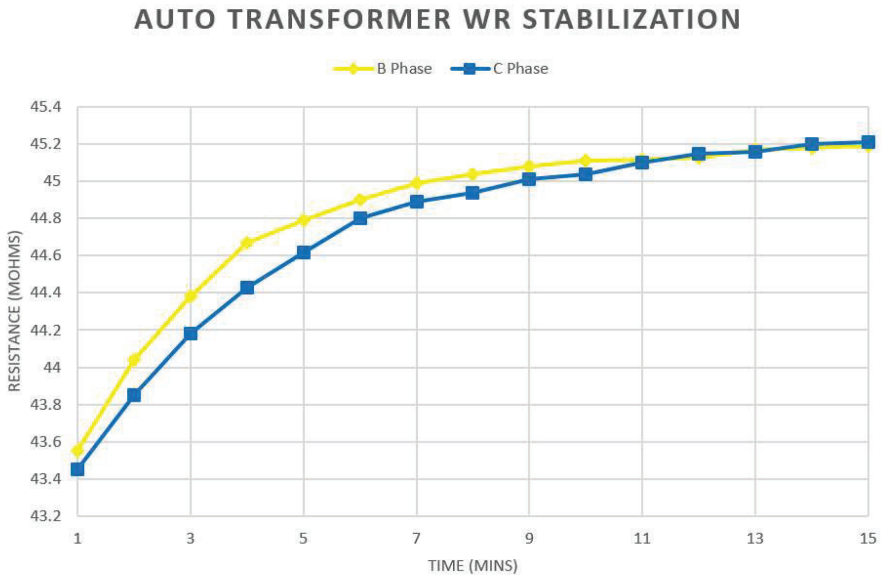


Figure 17. Stabilization time for WR measurement of B and C phase of an auto transformer

5.6 DEMAGNETIZATION

Table 9 below shows the comparative analysis of standard DC demagnetization technique and adaptive demagnetization method with time duration and residual magnetism (remanence) at the completion of the test. It can be observed that adaptive demagnetization is faster and more effective.

Transformer	DC Current (switching polarity)		Adaptive Demagnetization	
After WRM @ 16 A	Time	Remanence	Time	Remanence
10.4 kV / 400 V 500 kVA	2 min 10 s	~10-15%	15 s	<1%
80 kV / 6.6 kV 20 MVA	2 min 58 s	~1%	49 s	<1%

Table 9. Comparative analysis of DC polarity reversal demagnetization and adaptive demagnetization

It is recommended to perform the demagnetization on high voltage winding, B-phase (center leg), to reduce the residual magnetism to close to zero.

6. CONCLUSION

As pointed out in the introduction of this paper, the winding resistance measurements on a transformer might look trivial at first, but several factors play important roles for an individual to be able to perform the test both efficiently and accurately. These factors can be classified in three main categories. First, the technical specifications of the transformer, including its capacity and winding configuration. Second, the technical specifications of the instrument used to perform the measurements, including compliance voltage, test current, and source configuration, as well as the test leads configuration (single-phase vs three-phase). Lastly, the test methods used to perform the measurements.

It was outlined throughout the paper that the core saturation and current stabilization are the key elements to get an accurate measurement. Understanding how the transformer behaves during WR tests, along with the knowledge of the different techniques and methods available to perform these measurements, will give an individual the necessary tools not only to efficiently perform a WR test, but to use its results to troubleshoot possible issues with a transformer.

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