TRANSFORMER TURNS RATIO TEST:

SOME UNKNOWN FACTS

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ABSTRACT

Transformer Turns Ratio (TTR) is one of the most common test used to assess the condition of the transformer's windings and core. It is performed as a part of acceptance and maintenance test procedure to determine any problems due to poor design, assembly, handling, overloading, fault conditions or poor maintenance. TTR results are compared against the nameplate ratings to determine any possible insulation deterioration, shorted turns, core heating or any other winding or core abnormalities. TTR is a simple and easy test to perform that is often taken for granted without fully understanding the principle and basis of the test. In cases when measurements are not within expected limits, it becomes a challenging task to determine the root cause and resolve the problem. This paper will focus on some of the unknown facts associated with the TTR test. The paper covers in detail the effect of applied test voltage, comparative analysis of step up vs step down excitation, different vector configurations, differences between nameplate ratio, voltage ratio and turns ratio, sources of ratio and phase angle errors, comparison of per phase testing vs true three phase testing, extreme tap ratios being out of tolerance for On Load Tap Changers (OLTC), and TTR test correlation with other electrical tests. The paper also provides field test results and case examples to explain the above-mentioned unknown facts.

1. BASICS OF TTR TESTING

By definition, a transformer is a "static electric device consisting of a winding, or two or more coupled windings, with or without a magnetic core, for introducing mutual coupling between electric circuits [1]." This device is used from start to end in the electrical power system, extending across transmission, distribution and utilization of electrical energy. While the range of applications for a transformer is very wide, in most of the cases, the application will involve a basic function consisting on transferring power by electromagnetic induction between circuits, at different levels of voltage and current. This basic function is achieved with a relationship between the number of turns of specific pair of windings in the transformer. Given the importance of this particular quantity that, among others, define the performance of the transformer, a *transformer turns ratio test* (commonly referred as to *TTR test*) is performed several times throughout the life of the unit, starting early in the manufacturing process, then acceptance, routine maintenance as well as diagnostic testing. There are several concepts involved in this simple test. Knowledge of principles and terminology allow better understanding and interpretation of the results. The *transformer turns ratio (TTR)*, as implied by its name, is defined solely by the relationship between the physical number of turns of a pair of windings and we can calculate it with equation (A).

$$TTR = \frac{N_p}{N_s} \tag{A}$$

Where, N_p is the number of turns in the primary winding and, N_s is the number of turns in the secondary winding. Both Np and Ns are defined early in the design process of a transformer, and in general, these are quantities not known by the transformer owner or the individuals running the maintenance tests. When preforming the TTR test, the values used to calculate the *transformer nameplate ratio (TNR)* are taken from the transformer nameplate, and the numbers used are the *line-to-line voltages* for each of the windings pertaining the measurement. Using these two quantities then, the *TNR* can be calculated as shown in equation *(B)*.

$$TNR = \frac{V_{LLp}}{V_{LLs}} \tag{B}$$

Where V_{LLp} is the line-to-line voltage of the primary winding and, V_{LLs} is the line-to-line voltage of the secondary winding, both taken from the nameplate of the transformer. Modern TTR instruments will perform the test by applying a voltage on one side of the transformer *(V_p)*, measuring the resulting voltage on the other side of the transformer *(V_s)* and then, calculate the *transformer voltage ratio (TVR)* using equation *(C)*. For three phase transformers, a correction factor should be included in the equation depending on the vector configuration of the windings in the transformer. Vector configurations are reviewed in section 2 of this paper.

$$TVR = \frac{V_p}{V_s} \tag{C}$$

Given that the TTR measurements are made in an open circuit configuration, i.e., under no load conditions, the impedance will have negligible effects on the results (as the excitation impedance is much larger than the short circuit impedance) and thus, the *TVR* (the actual, measured value) will be approximately equal to the *TTR*, as expressed by equation (D).

$$TTR = \frac{N_p}{N_s} \approx \frac{V_p}{V_s} \tag{D}$$

For this reason, it is an industry standard practice to validate a transformer turns ratio (TTR) by means of an instrument that measures *TVR*.

2. VECTOR CONFIGURATIONS

When testing single-phase, and three-phase transformers that are Yy or Dd, the nameplate ratio will be the same as the voltage ratio, however, when dealing with Yd, Dy, or the less common, zig-zag winding configurations, a recalculation factor is necessary to obtain the voltage ratio based on the nameplate values, per equation (E).

$$TVR = k * TNR \tag{E}$$

Where *k* is the correction factor corresponding to the winding configuration under test. TTR instrument manufacturers generally include tables describing these correction factors; Table 1 below is an example [2].

Transformer configurations/ vector groups	TVR recalculation factor (k), TVR=k*TNR
Dd	1
Dy	√3
Dyn	√3
Dz	1.5
Dzn	1.5
Yd	√3/2
YNd	1/√3
Yy	1
YNy	1
Yyn	1
YNyn	1

Transformer configurations/ vector groups	TVR recalculation factor (k), TVR=k*TNR
Yz	√3/2
YNz	√3/2
Yzn	√3
YNzn	√3
Zd	1
ZNd	2/3
Zy	√3/2
ZNy	1/√3
Zyn	1
ZNyn	1

Table 1. Nameplate ratio to voltage ratio recalculation

3. UNDERSTANDING THE RESULTS

When performing a TTR test, the instrument will present three quantities per each measurement: ratio, excitation current and phase deviation. As discussed above, the number presented as the ratio is the *TVR*, as it is calculated using both the voltage applied to one side of the transformer and the induced voltage on the other side of the transformer. Having the measured *TVR* then, a percentage deviation from the calculated TVR (per Table 1 above) can be calculated, either manually or automatically by the instrument being used. The percentage deviation between measured and calculated TVR should be within a ±0.5% tolerance as per IEEE [3].

The excitation current test is a routine measurement that can be used to detect major problems in the magnetic core structure and winding defects, like shorted turns. This measurement can be performed individually using a power factor test set, as it is normally made at rated frequency and voltages up to 10 kV. The results are voltage dependent and due to the fact that the measurements evaluation relies heavily on pattern recognition, the numbers obtained during TTR testing –even when ran at considerably lower voltages– can be used as a good tool to diagnose the issues mentioned above, especially when having previous data from tests performed at the same voltage.

The phase deviation is defined primarily by the core construction material quality, involving both its permeability characteristics and its insulation quality (between each laminated core strip). Building a transformer core with high permeability, low loss material and with no defects between laminations – in other words, no shorts between adjacent layers in the core – will help minimize the eddy currents and thus reduce the phase deviation. One can therefore state that any significant phase deviation reflects a core which is not efficient. If a transformer exhibits higher losses than expected, the core is the probable cause and phase deviation a visible result.

As documented by IEEE [3], there are special cases involving a transformer with a load tap changer in the LV side with an overall low number of turns that will cause some of the steps not having the same number of turns and thus, the variation per tap is not uniform and might be outside the 0.5% tolerance of deviation from nameplate values. In these cases, there are two criteria used to evaluate the results. First, both extreme ends of the tap changer (highest and lowest) should be within the 0.5% tolerance from nameplate values, and second, for any given tap, all three phases of the transformer should have the same voltage ratios.

4. CORRELATION WITH OTHER TESTS

Performing the *TTR* test involves both the electric and magnetic circuits of a transformer, and as discussed in previous sections, certain parameters of the transformer and their present state at the time of the measurements will directly affect the readings. When a problem is found, it is useful to know how the *TTR* readings are related to others tests that can be performed in the field.

The *excitation current* of the transformer is the current flowing in the winding being energized, while all other windings of the transformer are open-circuited; this current establishes a magnetic field in the core and thus, a voltage will be induced in the corresponding, non-energized windings of the transformer. This test can help identify major problems in the core structure, issues with tap changers, turn to turn faults and grounded windings. The *winding resistance* measurements will also be affected if there is an insulation issue in the windings causing turn to turn shorts, and by problems in tap changers that, in extreme cases, will also affect the *TTR measurements*. Among the several measurement types when performing *sweep frequency response analysis (SFRA)*, the inductive inter-winding test can be used to obtain a good approximation of the voltage ratio of a transformer, using the flat magnitude response (lower frequencies, less than 60 Hz) that is typical in this specific measurement; the *TTR* can be obtained by calculating the reciprocal of the magnitude in the aforementioned flat section of the response [4].

5. SOURCES OF ERROR

The IEEE C57.152 standard defines the turns ratio of a transformer as the ratio of the number of turns in a HV winding to that in a LV winding. The voltage ratio of a transformer is the ratio of the root mean square (rms) terminal voltage of an HV winding to the rms terminal voltage of an LV winding under specified conditions of no load [3]. As mentioned before, the assumption is made that under open circuit or no-load condition, the voltage ratio of a transformer would be equal to the turns ratio of a transformer.

Another assumption made is all the flux produced by one winding links with the second winding and there is no leakage of flux. It is a well-known fact that there is always a flux leakage and the induced voltage in the secondary winding will always be less than the proportional induced voltage because of applied primary voltage. The coupling between the windings is not always 100% as all the flux generated by the primary winding does not completely couple with the secondary winding. The coefficient of coupling is always less than one. These factors, along with core losses (eddy current and hysteresis losses), excitation losses, effect of applied excitation voltage and core permeability, can contribute to the error in the measured turns ratio and true turns ratio.

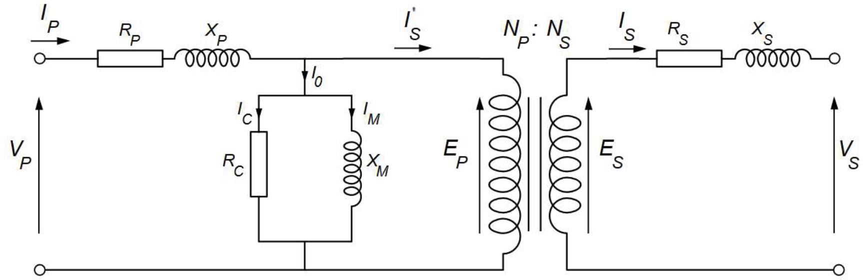

Figure 1. Transformer equivalent circuit

From transformer equivalent circuit in the Figure 1, under ideal case, VP (primary terminal voltage) should be equal to E_P (primary EMF) and V_S (secondary terminal voltage) should be equal to E_S (secondary EMF) which means that in a loss free system,

$$\frac{N_p}{N_s} = \frac{E_p}{E_s} = \frac{V_p}{V_s} \tag{F}$$

However, as the linkage between the windings is not ideal, the ratio of terminal voltages would introduce error in the true measurement of turns ratio using voltage ratio method. Additionally, under open circuit condition I_P (primary current) will be equal to I_0 (excitation current), which will be the vector summation of I_C (core loss component) and I_M (magnetizing component), currents representing the core losses and excitation, respectively. The core loss R_C represents the energy lost in hysteresis and eddy current losses. Similarly, the winding resistance and leakage flux components are represented by R_P and X_P on the primary side and R_S and X_S on the secondary side. These components represent copper losses and loss in flux linkages between primary and secondary winding.

Other external factors that can influence the measurements include the type of test specimen (two winding, three winding, autotransformer with tertiary etc.), test specimen configuration (Dy, Yd, Yy, Dd etc.), connections made to the specimen from test instrument (HV winding excitation or LV winding excitation), single phase vs. three phase excitation, loading of delta windings (when present on the measuring side), magnitude of excitation voltage, and the value of the turns ratio itself. These factors will be explained in detail in section 6.

6. FACTORS IMPACTING THE TURNS RATIO RESULTS

6.1. TEST VOLTAGE

The TTR test is generally performed by energizing the high voltage (HV) winding and measuring the voltage on the low voltage (LV) winding of the transformer. This is also known as step down method of testing. The test voltage used to excite the winding can affect the measurements. This can be explained with the Figure 2 below.

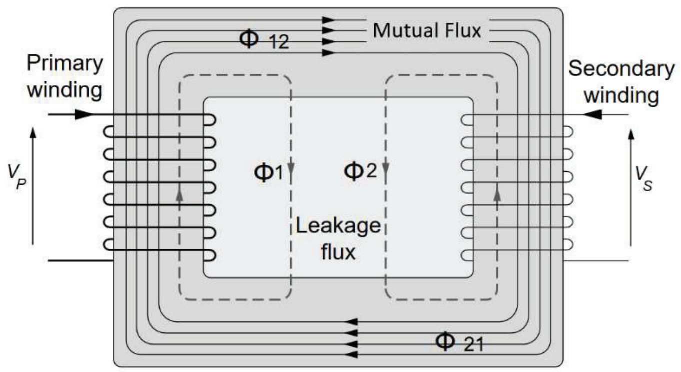

Figure 2. Flux distribution in a two-winding transformer

When an ac voltage is applied to the winding, flux is induced in the core due to the excitation current passing through the winding. The amount of flux is directly proportional to volts/turn. Ideally, the magnetic lines of flux are intended to follow the path of the magnetic core but in reality, there is always a certain amount of flux that does not follow that path and leaks through the non-magnetic circuit. This leakage flux does not link with the secondary winding. The flux produced by primary winding that links with the secondary winding to induce a voltage in the secondary winding is called a *mutual flux*. The mutual flux depends on winding inductances, core design, construction and permeability of the core. Tightly coupled windings will have higher flux linkage from primary to secondary winding. Since the flux in the core is a function of volts/turn, based upon the voltage ratings and number of turns of a winding, a higher excitation voltage may be required to obtain higher mutual flux linkage and overcome errors from losses due to leakage flux, excitation losses and core losses. As the permeability of the core increases with an increase in excitation voltage, there is a tendency to use a higher test voltage for determining the turns ratio from the voltage ratio [5].

Figure 3 below shows the ratio test results at different voltages when energized from HV side for a Dyn1, 138 kV to 4.365 kV transformer.

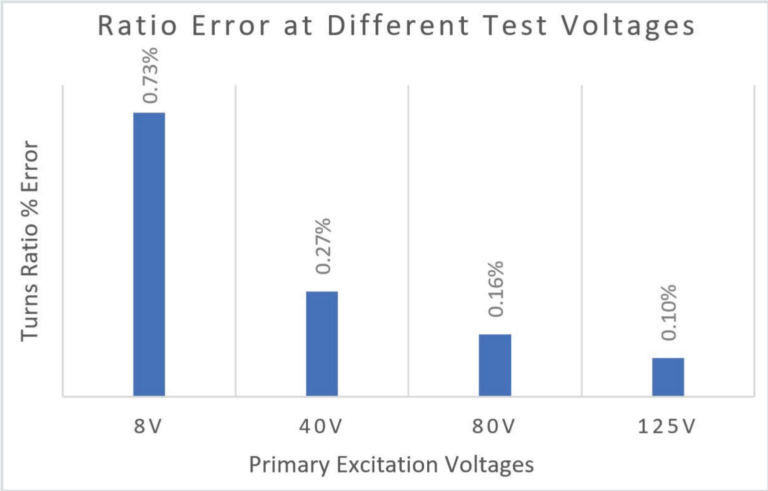

Figure 3. Turns Ratio percent error at different test voltages (per phase energization from HV side)

Similar observations can be made by energizing the LV winding and inducing voltage on the HV winding. Figure 4 below shows the ratio test results of a two winding YNyn0, 13.2 kV to 480 V transformer with three phase LV winding excitation (figure shows different induced HV winding voltages and respective ratio errors for each phase)

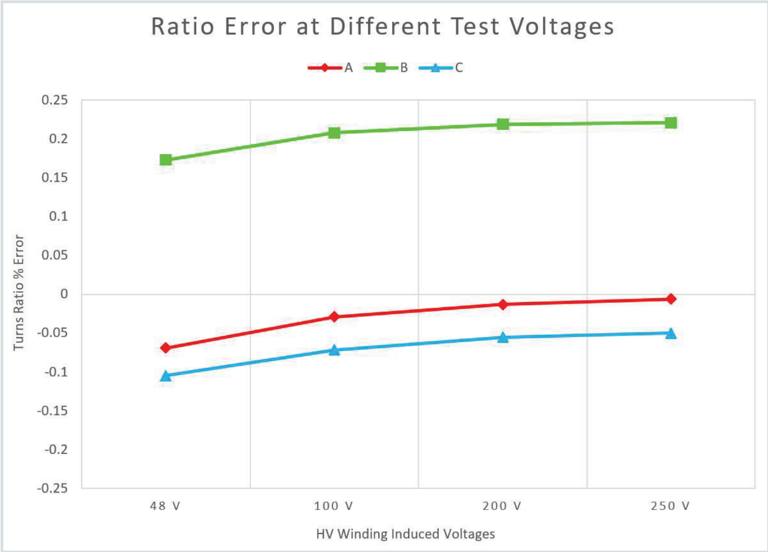

Figure 4. Turns Ratio percent error at different test voltages (three phase energization from LV side)

For each transformer, there is an excitation voltage level beyond which the voltage dependence of the transformer reduces, and the ratio results are consistent at any voltage above that threshold. In Figure 4, any voltage above 200 V reduces the voltage dependence of the transformer for TTR measurements.

6.2. TRANSFORMER CONFIGURATIONS

Three phase transformers can be designed in different configurations based upon the application and use of the transformer. Delta-Wye transformer configuration is the most common one in North America. Additionally, based upon the requirements, one can have a two-winding, three-winding or autotransformer with or without tertiary winding.

As discussed earlier, the single-phase excitation from HV side can present voltage dependency and thus, influence the turns ratio measurements. It is more difficult to test accurately if the LV winding is a delta configuration. The ratio test using voltage method makes the assumption that the secondary is an open circuit and no load is connected to the winding. With a delta LV winding, because of closed loop delta system that assumption doesn't hold true as the winding under test gets loaded internally through the other two windings. The delta loop circulating current leads to internal losses and impacts the ratio accuracy. In such cases, it is recommended to either energize the HV winding line to line or perform three-phase excitation to offset any delta loading challenge. Exciting more than one phase reduces the delta loading and dependence on the applied voltage. An even better recommendation is to perform the test exciting LV winding (step up mode) and measuring the induced voltage on HV winding. This eliminates any delta loading concern and provides additional benefits of step up excitation.

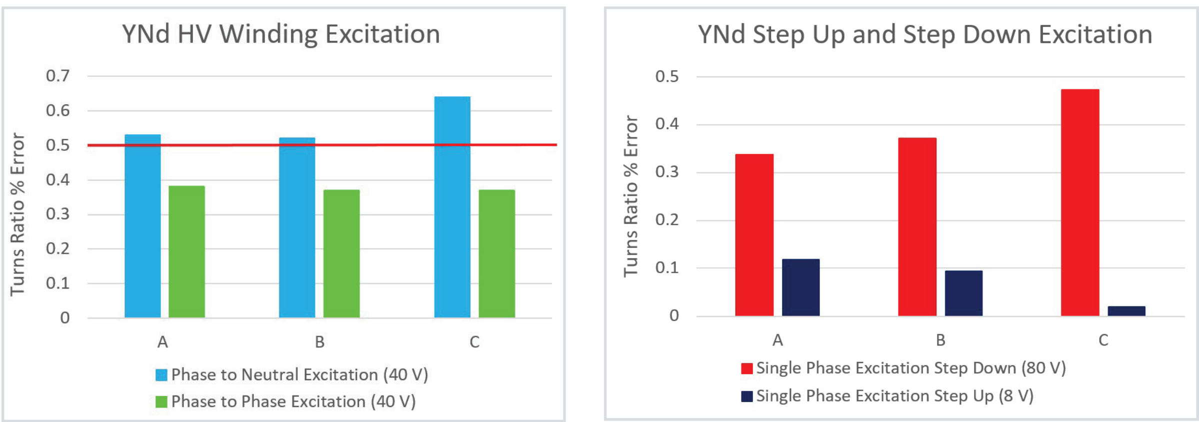

Figure 5. Comparison of Turns Ratio % Error for a YNd transformer through different excitation techniques

The Figure 5 above shows two comparative results for a YNd transformer. In the first case, the turns ratio test was performed from HV side. Test was performed in phase-to-neutral and phase-to-phase excitation mode. One should note when testing phase-to-neutral, it results in higher ratio errors in the positive direction, and when energizing phase-to-phase (two phases) percent ratio error is comparatively less. The results that were outside the IEEE limits fell within the tolerance with phase-to-phase excitation mode. The second case shows a comparison of single-phase excitation from HV and LV side. It can be noted that even an 8 V signal from LV side produced much accurate measurement compared to 80 V excitation signal from HV side in step down mode.

When working with three winding transformers or autotransformers with a tertiary winding, it becomes difficult to get a good ratio measurement from HV to tertiary. Tertiary winding is usually closest to the core with the HV winding being the outermost winding in the design. There are number of reasons for this type of construction that includes lower cost in insulating HV winding, reduced core losses, suppression of harmonics etc. With this design, when TTR test is performed from the HV side, the coupling coefficient between HV and tertiary winding is not as great as in the construction of a two-winding transformer. Furthermore, the problem compounds when the nameplate turns ratio is high. Based upon field experience, any ratio greater than 20:1 for a HV to tertiary ratio measurement would be a challenge when measuring in a step-down mode. With HV winding being the outermost winding with reference to the core, the coupling or linkage reduces for HV rating windings (or high ratio transformers) because of allowed space for insulation and cooling. In most cases, the tertiary winding is a delta configuration and the winding is typically

10–20% of the VA rating of the other windings. This type of delta winding is an additional challenge to measuring ratio properly, as discussed above.

To overcome this challenge, it is recommended to perform the measurement in step up mode from tertiary side. It is important to keep the LV excitation voltage in check so as not to induce dangerously high voltage on the HV side. Usually, the step-up excitation test voltage is selected based on the voltage the test instrument being used can measure in the HV winding, both safely and accurately.

Figure 6 shows the HV to tertiary turns ratio measurements for a 288.7 kV /95.2 kV/26.4 kV autotransformer with tertiary. Test was performed from HV side and tertiary side for a comparative analysis. As observed, the HV winding excitation test failed the first half of the taps as results were outside the IEEE 0.5% limit. The tertiary winding energization gave more accurate measurements and results for all the taps were within the tolerance. Tertiary winding being closest to the core results in less leakage flux and higher flux linkage to the HV winding and therefore more accurate TTR results are obtained when step up mode is used.

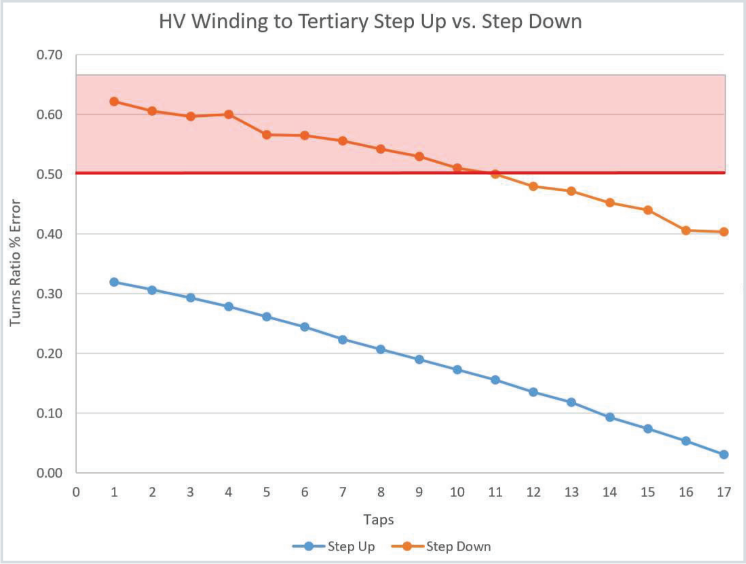

Figure 6. Comparison of TTR percent error for an autotransformer with tertiary in step up vs step down mode

6.3. HV WINDING VS. LV WINDING EXCITATION

Based upon Figure 1, and assuming a transformer with a turns ratio of unity, if a voltage V_P is applied, the induced voltage E_P would always be less than V_P because of reasons discussed in section 5. This would mean that V_S would also be less than V_P as per the equivalent circuit of a transformer.

The turns ratio measurement using a HV winding excitation voltage ratio method would then yield a number greater than one resulting in a positive ratio error. This would be the case even when the rated voltage is applied to the HV winding for the measurement.

As discussed earlier, the flux linking from HV winding to LV winding (mutual flux) defines how efficient the transformation ratio would be. The mutual coupling between the windings is dependent upon the geometry of the windings, number of winding turns and permeability of the core.

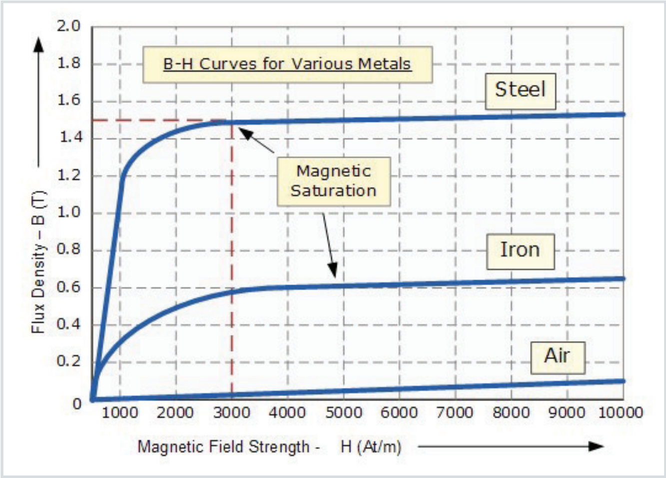

Figure 7: B-H curve for different magnetic materials [6]

The permeability of the core can be understood by looking at the relation between magnetic flux density (B) and Magnetic field strength (H) on a B-H curve as shown in Figure 7.

$$B = \mu H \qquad (G)$$

Where μ = μ0 * μr

In equation G, μ is the magnetic permeability of a specific medium, μ_0 is the magnetic permeability of the free space and μ_r is the relative permeability.

The permeability of the core is not a constant function. The slope of the curve (μ) is different for different material. For steel (typically used for construction of the transformer core) the magnetic permeability increases rapidly with increase in H (Ampere Turns/Meter). By applying higher excitation voltage, the magnetic field strength can be increased and hence the magnetic permeability of the core, resulting in more effective coupling between the windings (coupling coefficient). With better coupling, more flux can be linked to LV winding (mutual flux) when HV winding is being energized and more accurate transformation ratio can be achieved.

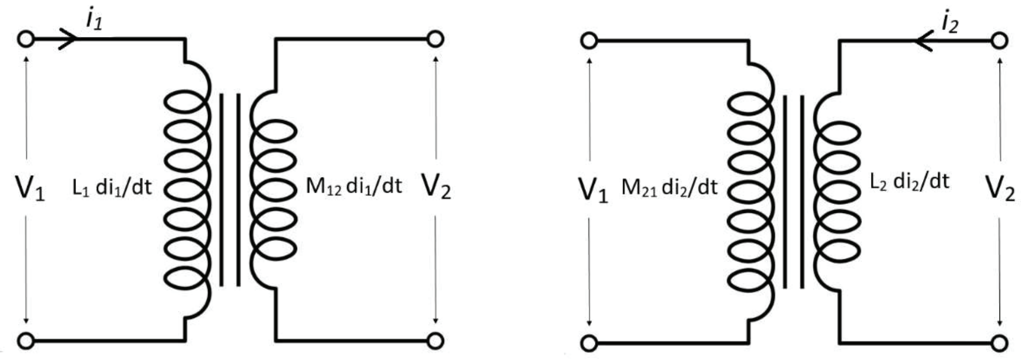

Figure 8: Induced voltages for excitation from HV and LV side respectively

From Figure 8, assuming a system with no excitation losses, when turns ratio is measured by HV winding excitation method, the self-induced voltage in the HV winding is defined by equation H,

$$V_1 = L_1 * \frac{di_1}{dt} \tag{H}$$

Likewise, the induced voltage in the LV winding based on Faraday's law of electromagnetic induction is defined by equation I,

$$V_2 = M_{12} * \frac{di_1}{dt} \tag{I}$$

M_{12} is the mutual inductance because of current i1 in the HV winding.

The turns ratio for this transformer from voltage ratio method will be as shown in equation J:

$$\frac{V_1}{V_2} = \frac{L_1}{M_{12}} \tag{J}$$

This shows that HV winding excitation voltage test would result in a positive ratio error.

If the ratio test is performed from LV side, the voltage ratio method would cause a negative ratio error as shown in equation K below.

$$\frac{V_1}{V_2} = \frac{M_{21}}{L_2} \tag{K}$$

As mentioned earlier, a transformer would typically produce a positive ratio error because of excitation losses and coupling coefficient of less than one, performing a test from HV side would add additional positive ratio error. When test is performed from LV winding it results in a negative ratio error.

It is to be noted that positive ratio error from HV side and negative ratio error from LV side are not the same because the excitation losses are different from high side and low side [5]. Additionally, the coupling between the windings from HV to LV winding is not the same as from LV to HV winding. The LV winding being closer to the core is more tightly wrapped around the core and results in higher coefficient of coupling (although still less than 1) when compared to HV winding where spacing is left for insulation and cooling purposes resulting in lower coupling coefficient.

In the Figure 8 above, $M_{12} < M_{21}$ however for many applications to keep things simple for analysis they are assumed to be equal (which is not really the case).

Increasing the test voltage would help in increasing the core permeability and reduce the positive ratio error when tested from HV side. Figure 9 shows that when HV winding excitation test voltage is increased the percent ratio error moves in the negative direction from a positive ratio error towards the zero.

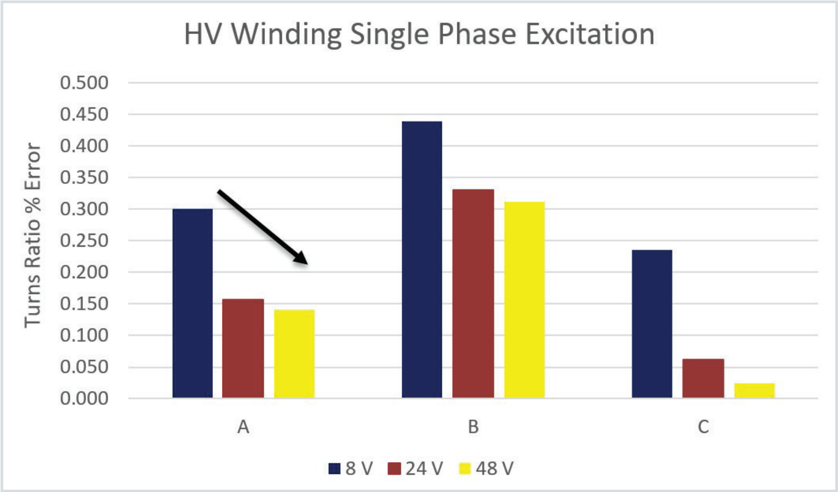

Figure 9. HV winding single-phase excitation at different voltages

The step up mode of testing where the transformer is energized from the LV side provides numerous advantages. Since flux is a function of volts/turn, at same excitation test voltage more flux is generated if energized from LV side. There is a better coupling between the windings from LV to HV as discussed earlier. Better coupling and more flux results in more accurate turns ratio measurement with LV winding excitation (step up mode). Figure 10 shows that step-up mode would produce comparatively negative ratio error with respect to step down mode.

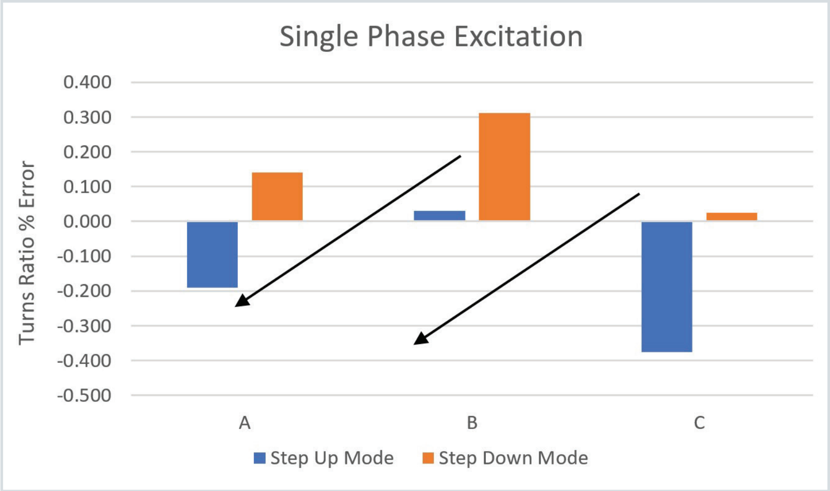

Figure 10. Single-phase excitation, step-up vs. step-down

As shown in Figure 11 as the test voltage is increased for LV winding excitation, the ratio error moves in the positive direction from negative ratio error at lower voltages.

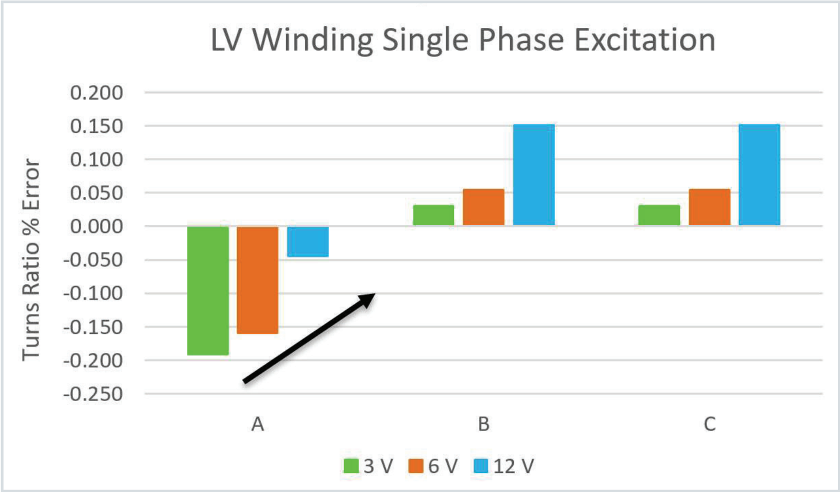

Figure 11. LV winding single-phase excitation at different voltages

It is to be noted that one should be cautious of applying too high of a voltage to the LV winding as that would induce a very high voltage on the HV side when testing in a step-up mode.

Step up mode of testing allows increased accuracy under extreme interference conditions with measurement of HV winding induced voltage (because of its magnitude). With LV winding excitation, today's available measurement and signal processing techniques allow reliable and repeatable measurements of applied and measured voltages in a field environment.

6.4. COEFFICIENT OF COUPLING

Mutual inductances M_{12} and M_{21} can be defined as shown in equation L and M,

$$M_{12} = k_{12} * \sqrt{(L_1 * L_2)} \qquad (L)$$

$$M_{21} = k_{21} * \sqrt{(L_1 * L_2)} \qquad (M)$$

Where k_{12} is the coefficient of coupling from HV to LV winding
k_{21} is the coefficient of coupling from LV to HV winding

Both k_{12} and k_{21} are less than one. From Figure 8 and equation J and K, HV winding excitation turns ratio and LV winding excitation turns ratio can be written as shown in equation N and O,

$$(Turns\ Ratio)_{HV} = \left(\frac{1}{k_{12}}\right) * \sqrt{\left(\frac{L_1}{L_2}\right)} \qquad (N)$$

$$(Turns\ Ratio)_{LV} = (k_{21}) * \sqrt{\left(\frac{L_1}{L_2}\right)} \qquad (O)$$

It can be observed that with the increase in core permeability or coefficient of coupling (k_{12} and k_{21}), the HV winding excitation turns ratio would decrease and LV winding excitation turns ratio would increase.

6.5. PER PHASE VS. THREE-PHASE EXCITATION

It is very common to test three phase power transformers with a single-phase source that results in performing measurements on a per phase basis. This requires switching of power supply through relays from one phase to another for the measurement. Per phase measurements can present its own challenges as discussed above like results being sensitive to the excitation voltage, loading of the delta winding, excitation losses provided by only one source winding, reduced coupling between the winding etc. To overcome these challenges, it is recommended to use a higher excitation test voltage, use step up test mode or energize two phases by testing phase to phase. With two windings energized, the coupling between the windings is improved and turns ratio dependency on the excitation voltage can be reduced.

On the same principle, even better results are obtained by utilizing a three-phase source and testing all the three phases simultaneously. It offers many distinct advantages. More uniform flux distribution is achieved that leads to higher coupling between all the windings of the transformer. The results are then less sensitive to excitation voltage. Excitation losses during the test are shared by all the three sources and provide much accurate measurement when compared to single phase or two-phase excitation. Simultaneous measurement of all three phases provide increased efficiency when testing in the field and more safe and reliable operation. This eliminates the need for swapping leads during the test and less trips up and down the ladder. The switching of relays with one phase source instrument for testing three-phase transformer is eliminated, resulting in better reliability and improved life of the test instrument.

Figure 12 shows comparative analysis of three phase simultaneous TTR percent error results against per phase results of a three-phase transformer for five HV winding tap positions. Same excitation test voltage was used for all the measurement. As observed, the ratio error decreases with three-phase excitation.

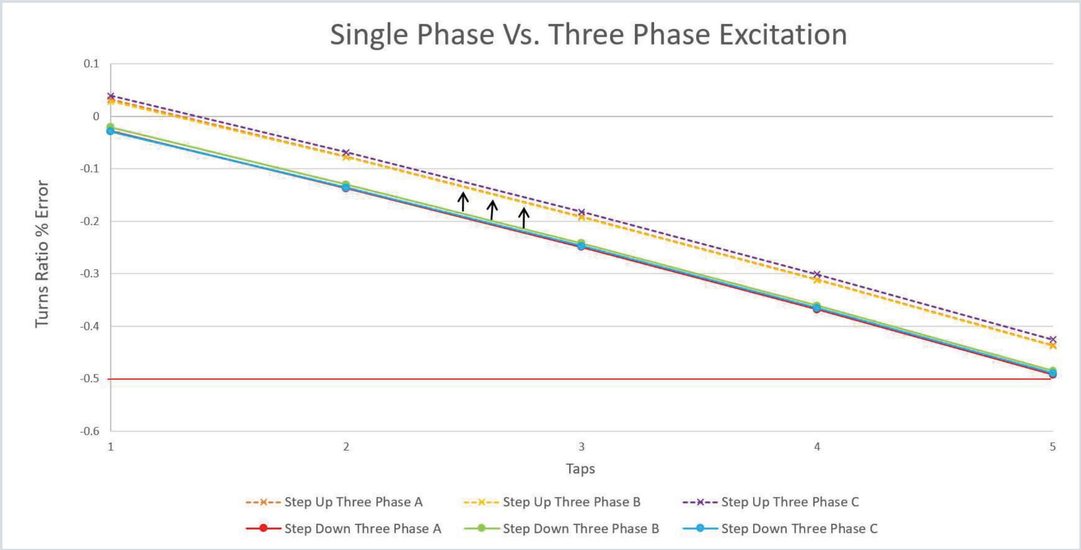

Figure 12. Single phase vs. Three phase excitation TTR percent error results of a three-phase transformer at 5 taps

Figure 13 shows the single-phase vs. three-phase excitation results at different voltages in step up mode. It is observed that percent error reduces with three phase excitation voltages for all the four test voltages selected.

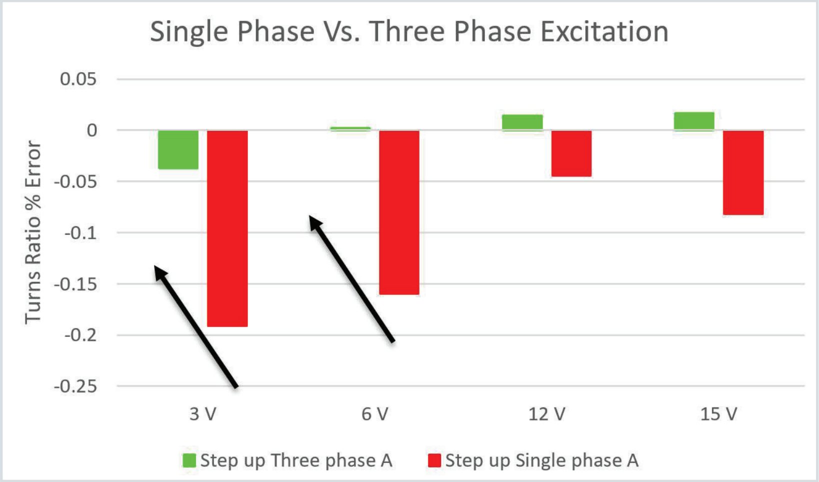

Figure 13. Single phase Step up vs. Three phase Step up excitation TTR percent error results of A phase

With all the measurements of three phases obtained simultaneously, the results between the phases are compared more effectively and allows additional advantages such as testing ratio and polarity of phase shifting transformers, increased accuracy in phase deviation measurements and implementation of vector recognition technique for old transformers with limited nameplate information.

An even better set up is performing three phase source turns ratio measurements in step up mode. This provides unique advantages of both the features as discussed above.

Figure 14 shows the three-phase step down excitation results of a HV side OLTC of Dyn1 138 kV/4.365 kV three-phase transformer. It can be seen that results are not consistent with ratio percent error varying all over the place. Additionally, there are no. of taps on all three phases that exceed the ±0.5% IEEE tolerance limit.

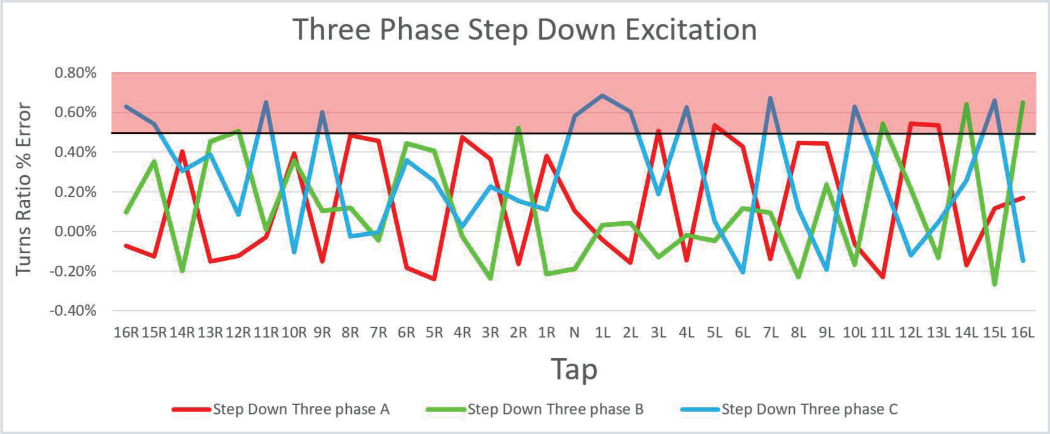

Figure 14. Three phase step-down excitation TTR percent error results of an OLTC of a three-phase transformer

Figure 15 shows the three phase excitation test results of the same OLTC and it can be seen that results are consistent between the phases and all the taps are well within the IEEE tolerance limit.

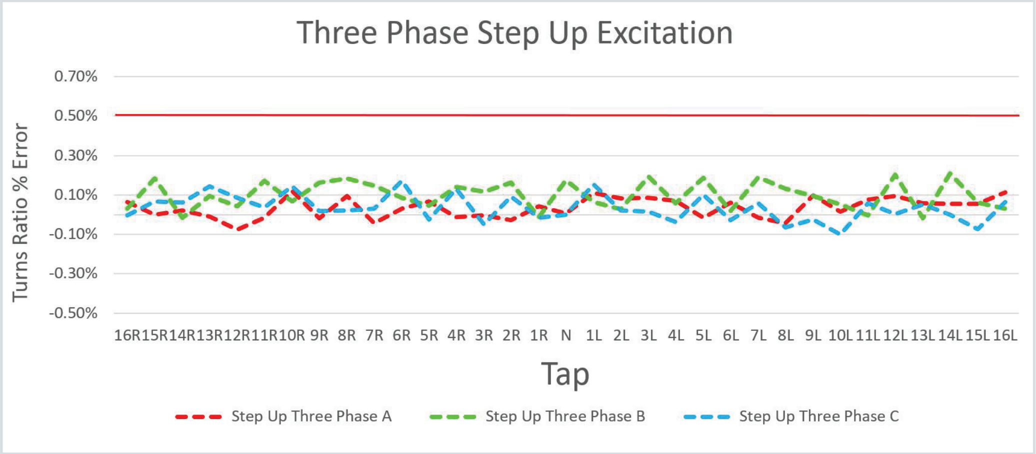

Figure 15. Three-phase step up excitation TTR percent error results of an OLTC of a three-phase transformer

7. SUMMARY AND CONCLUSION

TTR test is an important test to assess the transformer's winding, core and insulation condition. Although the test is very simple, many factors can affect the measurements. The core permeability, mutual and leakage flux, excitation losses, and winding configuration are some of those factors based upon the design, construction and applications of transformers. Additionally, the method and principle employed to perform the field-testing could also significantly influence the measurement accuracy that can lead to noticeable differences between measured and nameplate ratio.

As a test operator, even though some of those factors are not in your control but measures can be taken to improve the accuracy and repeatability of the measurements. Based upon the test specimen and available test instrument, best practices can be employed to select the appropriate winding to be energized (step up or step down mode), correct excitation voltage to overcome voltage dependence and energization of multiple windings (line to line or three phase excitation) to mitigate the effect of excitation losses and winding configuration challenges on the ratio accuracies.

Field test results show that the simultaneous three-phase excitation and step up mode of testing greatly improves the TTR results accuracy. In cases where three-phase excitation is not available line-to-line voltage helps reduce the excitation losses to improve the accuracy. Step up mode of testing allows better coupling, generates more flux and reduces voltage dependence when compared against step down mode.

With these best practices, transformers that are sensitive to applied excitation voltage, auto transformers with tertiary windings and transformers with delta LV windings can be tested accurately and obtain ratio errors that can be compared with IEEE limits to truly assess the condition of the windings and insulation of the transformers under test.

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REFERENCES

[1] *IEEE Standard Terminology for Power and Distribution Transformers*, IEEE Std C57.12.80, 2002.

[2] M. Ohlen, P. Werelius, *A Guide to Transformer Ratio Measurements*, Megger, 2010.

[3] *IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors*, IEEE Std C57.152, 2013.

[4] V. Naranjo, *Sweep Frequency Response for Power Transformer Diagnostics*: TechCon North America, 2013, Charlotte, N.C.

[5] O. Iwanusiw, *The Art and Science of Transformer Ratio Measurement*: Electrical Insulation Conference, 2018, San Antonio, Texas.

[6] https://www.electronics-tutorials.ws/electromagnetism/magnetic-hysteresis.html