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A Systematic Approach to Analyzing Exciting Current Measurements on Power Transformers

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1 Abstract

The exciting current test has long been accepted as a powerful tool for identifying power transformer faults, such as insulation, core, and tap-changer failures. The exciting current measurement produces unique test results, which differ based on the transformer's core construction, winding configuration, and tap-changer design, and are often not fully understood.

A systematic approach will be presented for analyzing exciting current measurements on power transformers. This will help the audience easily identify incipient failure modes within a power transformer when performing the exciting current test. Failure modes associated with the insulation system, magnetic core, winding assembly, and tap-changer components will be discussed.

Case studies will be presented focusing on the importance of the exciting current measurement, and in general, a thorough electrical diagnostic testing plan.

2 Exciting Current Introduction

A transformer's "exciting current" is essentially the minimum current required to operate the transformer under no-load conditions. Historically, the exciting current test is performed by applying an AC Voltage on the primary winding of the transformer, while the secondary windings of the transformer are open-circuited. The current flowing through the primary winding of the transformer is then measured, and is the main focus of the exciting current measurement.

The high-voltage exciting current test is a single-phase test, so a series of three measurements are performed to measure the exciting current for each phase, which are then compared and analyzed. Note, even though the secondary windings of the transformer are not measured directly, failures involving the secondary windings (e.g. a turn-to-turn short-circuit on the secondary winding) can be detected using the exciting current test.

3 Exciting Current Fault Modes

The purpose of any electrical diagnostic test is to detect a failure within the test specimen. The exciting current test is used to detect the following power transformer failure modes,

- Compromised Insulation (e.g. turn-to-turn, inter-winding, and/or winding-to-ground insulation)

- Core Failures

- Tap-Changer Failures (e.g. failures involving the regulating winding, preventative autotransformer, reversing switch, tap selectors, stationary contacts, etc.)

- Severe Discontinuities, Poor Connections, and/or Open-Circuits

Note, a magnetized core may contaminate the exciting current measurement and prevent an accurate assessment of the results. The most common cause of an excessively magnetized core is the DC winding resistance test. Therefore, it is highly recommended that the DC winding resistance test is performed after the exciting current test (and, in general, is the last electrical measurement performed on a power transformer).

4 Test Equipment and Applied Voltage

The instrumentation requirements for the exciting current test are,

- The test instrument must output AC voltage (preferably up to 10kV)

- The test instrument must measure AC current (in the mA range)

- The test instrument must be equipped with a guard circuit, which is used to isolate and test individual phase-windings when the exciting current measurement is performed

The three requirements listed above are fulfilled by a "Power Factor Test Set". A test set that has the ability to perform the power factor measurement has the ability to perform the exciting current measurement.

The test voltage should be carefully considered when performing the exciting current test. The test voltage should be as high as possible without exceeding the line-to-ground voltage rating of the primary winding. In general, the higher the test voltage, the more the insulation system is stressed, which will provide the best opportunity to detect a failure within the transformer.

However, it is possible (and not uncommon) that the maximum allowed test voltage cannot be applied when performing the exciting current test. Users may encounter a scenario where the test instrument "trips" when the test voltage is applied to the primary winding of the transformer. The test set can "trip" as a result of exceeding the output volt-amps (VA) power limitation of the test instrument. If the test set "trips" when the exciting current measurement is performed, the user must troubleshoot the measurement to determine if the cause of the "overcurrent" is due to,

- User error (e.g. incorrect test connection)

- The transformer construction

- Distribution transformers (< 5MVA) have been known to produce higher than normal exciting currents

- Power transformers with reactive-type load tap-changers have been known to produce higher than normal exciting currents when tested in a "bridging position" (see section 7.3 for more information)

- A failure within the transformer – Case study #2 demonstrates when the exciting current measurement could not be performed on a transformer due to an insulation failure

Special care should be taken to determine which of the three scenarios above caused the test set to "trip". The following list is a collection of general guidelines for diagnosing a situation that causes the test instrument to "trip",

- If the transformer under test has a Delta primary winding and the test instrument "trips" when all three phase-measurements are performed, then it is unlikely (although still possible) that a fault within the transformer is the culprit (assuming the recommended test connections have been made). In this case, to successfully complete the exciting current measurement, the test voltage must be decreased. Due note, however, that all three phase-measurements and all tap-changer positions must be repeated at the new, lower test voltage to properly assess the results.

- If the transformer under test has a Delta primary winding and only the Phase-C measurement "trips", then it is unlikely (although still possible) that a fault within the transformer is the culprit (assuming the recommended test connections have been made). In this case, to successfully complete the exciting current measurement, the test voltage must be decreased. Due note, however, that all three phase-measurements and all tap-changer positions must be repeated at the new, lower test voltage to properly assess the results.

- If the transformer under test has a Delta primary winding and two of the three phase-measurements "trip", then a fault within the transformer is possible (assuming the recommended test connections have been made). In this case, the transformer should be investigated immediately.

- If the transformer under test has a Wye primary winding and any combination of the three phase-measurements "trip", then the user must troubleshoot to determine whether the cause of the "tripping" is due to a failure, user error, or due to the construction of the transformer.

Note, when a power transformer has a Delta primary winding, the Phase-C exciting current measurement should be performed first (i.e. before the Phase-A and Phase-B measurements). If the recommended test connections (outlined in Table 1) are used, the Phase-C measurement will require the largest output power (VA) from the test instrument, which may cause the test set to "trip". In general, for a transformer with a Delta primary winding, if the Phase-C measurements can be completed without "tripping" the test instrument, then the Phase-A and Phase-B measurements can be completed without "tripping" the test instrument (assuming that a failure does not exist within the transformer).

5 Test Connections and Test Procedure

To properly understand, perform, and assess the exciting current measurement, it is important to become familiar with the recommended test connections for testing several different transformer winding configurations. This paper focuses on the following three transformer winding configurations,

- Delta
- Wye with an accessible neutral
- Wye without an accessible neutral

For each phase-measurement, two test leads are connected to two different bushing terminals on the primary side of the power transformer. The two test leads include,

1.) High-voltage injection lead (up to 10kV)

2.) Low-voltage measurement lead (at ground potential)

Three-successive single-phase measurements are performed by changing the test connections on the primary side of the power transformer.

Note, the Delta winding requires an additional ground lead, which is used to isolate and measure each individual phase of the transformer. This concept is discussed thoroughly in the following section.

5.1 Delta Primary Winding

Understanding, performing, and analyzing the exciting current measurement for a transformer that has a Delta primary winding can be difficult, due to the test procedure required to isolate and measure each individual phase-winding of the transformer. The Delta-wye transformer is the most common two-winding power transformer in the United States, so it is important that the industry, as a whole, understands the recommended test procedure for this tricky winding configuration. The recommended test procedure for testing a transformer with a Delta primary winding is discussed thoroughly in this section.

The Delta-wye (Dyn1) vector diagram is provided in Figure 1. Each phase vector of the Delta primary winding has been labeled a particular phase. The recommended test connections for performing the three exciting current phase-measurements on a Dyn1 transformer are provided in Table 1.

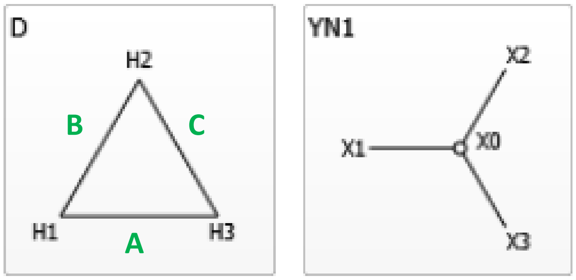

Figure 1: Delta-wye Vector Diagram

Table 1: Exciting Current Test Connections for Dyn1 Transformer

Phase	High-Voltage Lead (HV)	Low-Voltage Lead (LV)	Ground	Float	Test Mode
A	H1	H3	H2, X0	X1,X2,X3	UST
B	H2	H1	H3, X0	X1,X2,X3	UST
C	H3	H2	H1, X0	X1,X2,X3	UST

To begin the discussion, consider the Phase-A measurement outlined in Table 1. Since the exciting current test is an open-circuit test, the three phase bushing terminals on the secondary (i.e. X1, X2, and X3) are open-circuited when the three exciting current measurements are performed. The high-voltage (HV) test lead is placed on the H1 bushing terminal and the low-voltage (LV) test lead is placed on the H3 bushing terminal. In addition, the H2 bushing terminal (the third bushing terminal of the Delta winding) is grounded. The ground lead connected to the H2 bushing terminal is critical for isolating and measuring the exciting current of Phase-A. To grasp the functionality of the ground connection made on H2, the Dyn1 vector diagram should first be analyzed for when the H2 bushing terminal is left open-circuited, as shown in Figure 2.

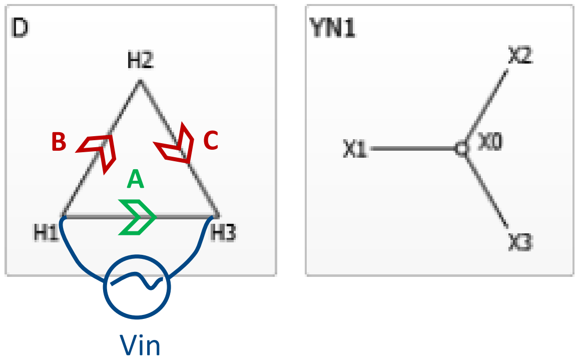

Figure 2: Phase-A Measurement - H2 Floating

As can be seen in Figure 2, when the test voltage is applied across the Phase-A winding (H1-H3), a current is induced in the Phase-A winding (indicated by the green arrow); additionally, due to the Delta winding configuration, a voltage is also applied across the Phase-B and Phase-C windings, which induces a current in these two phase-windings (as indicated by the red arrows). The Phase-B and Phase-C current converges at the H3 bushing terminal, which is then included in the Phase-A exciting current measurement. In short, by leaving the H2 bushing terminal floating during the Phase-A exciting current measurement, the measured current will be comprised of all three phases.

In general, the goal of any electrical diagnostic test is to isolate the test specimen into as many components as possible, so that a failure is not masked or overlooked by the healthy majority. For a transformer with a Delta primary winding, to isolate each individual phase, a ground lead must be placed on the third, unused Delta bushing terminal. The ground connection will help remove the parallel phase-currents for the single phase-measurement.

To elaborate further, consider the current distribution through the Delta primary winding when the H2 bushing terminal is grounded, as shown in Figure 3.

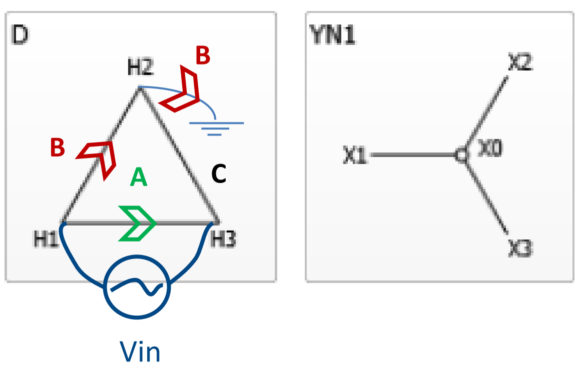

Figure 3: Phase-A Measurement - H2 Grounded

As can be seen in Figure 3, when the test voltage is applied across the Phase-A winding (H1-H3), a current is induced in the Phase-A winding (indicated by the green arrow); additionally, the test voltage is applied across the Phase-B winding, which induces a current in Phase-B (as indicated by the red arrows). However, the Phase-B winding current is directed to ground via the H2 ground connection. Since the exciting current measurement is an Ungrounded Specimen Test (UST), any current flowing to ground is "guarded" and removed from the measurement. Therefore, the Phase-B winding current is guarded and does not contribute to the Phase-A exciting current measurement.

The influence of the Phase-C winding should also be considered. Because the LV test lead (located on the H3 bushing terminal) is at ground potential, both ends of the Phase-C winding are at the same potential, which effectively short-circuits the Phase-C winding. Thus, there is zero potential applied across the Phase-C winding, which results in a negligible current flow through the winding. In short, the Phase-C winding does not contribute to the Phase-A exciting current measurement.

Table 2 provides a summary of the phase-windings that are "excited" and measured when the exciting current test is performed on a transformer with a Delta primary winding. Although two phase-windings are "excited" simultaneously, only one phase-winding is measured at a time (assuming the correct test connections are made).

Table 2: Delta Primary Winding – Measurement Summary

	Test Connection	**Ground**	**"Excited" Phases**	**Measured Phase**
Phase A	H1-H3	H2	Phase A and Phase B	Phase A
Phase B	H2-H1	H3	Phase B and Phase C	Phase B
Phase C	H3-H2	H1	Phase C and Phase A	Phase C

5.2 Wye Primary Winding *with* Accessible Neutral

The recommended test connections for testing a transformer with a Wye primary winding *with* an accessible neutral (H0) are discussed in this section. Fortunately, when the transformer under test has this particular winding configuration, the exciting current measurement is relatively simple to understand and perform.

To begin the discussion, the vector diagram for a Ynd1 transformer is provided in Figure 4.

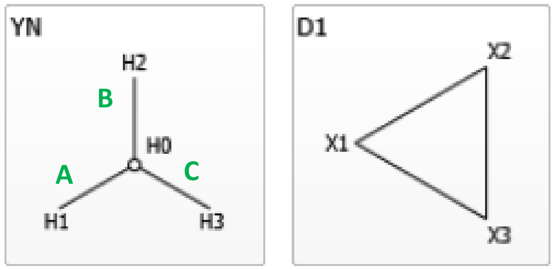

Figure 4: Ynd1 Vector Diagram

The recommended test connections for performing the exciting current measurement on a Ynd1 transformer are provided in Table 3. Since the exciting current measurement is an open-circuit test, the three phase bushing terminals on the secondary (i.e. X1, X2, and X3) are open-circuited for the entirety of the test. For all three phase-measurements, the LV measurement lead is placed on the primary neutral bushing terminal (H0). Additionally, the HV injection lead is placed on one of the three primary phase bushing terminals (i.e. H1, H2, or H3) for each phase-measurement.

Table 3: Ynd1 - Exciting Current Test Connections

Phase	High-Voltage Lead (HV)	Low-Voltage Lead (LV)	Ground	Float	Mode
A	H1	H0	-	X1,X2,X3, H2, H3	UST
B	H2	H0	-	X1,X2,X3, H1, H3	UST
C	H3	H0	-	X1,X2,X3, H1, H2	UST

For example, consider the Phase-A exciting current measurement, which is depicted in Figure 5. The output current of the test instrument enters the Phase-A winding through the H1 bushing terminal, and returns via the H0 bushing terminal. As can be seen, when the primary winding of the transformer is Wye connected with an accessible neutral, each phase-winding can easily be isolated and tested.

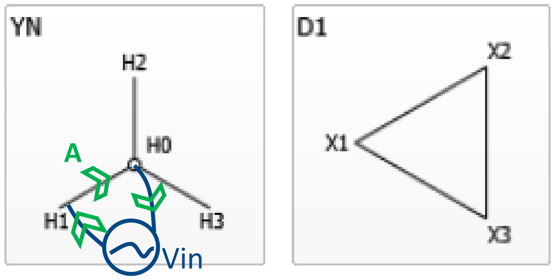

Figure 5: Ynd1 - Phase-A Exciting Current Measurement

5.3 Wye Primary Winding *without* Accessible Neutral

The recommended test connections for testing a transformer with a Wye primary winding *without* an accessible neutral (H0) are discussed in this section. Unfortunately, when the transformer under test has this particular winding configuration, the analysis of the exciting current measurement is somewhat complex.

To begin the discussion, the vector diagram for a Yd1 transformer is provided in Figure 6.

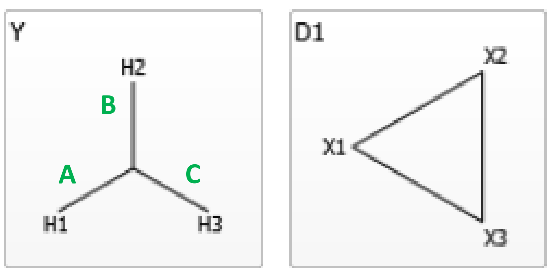

Figure 6: Yd1 Vector Diagram

The recommended test connections for performing the exciting current measurement on a Yd1 transformer are provided in Table 4. When the Wye primary winding has no accessible neutral, there is no reasonable way to isolate and measure each phase-winding individually. Unfortunately, the LV measurement lead must be placed on one of the three phase bushing terminals, which results in "exciting" and measuring two phase-windings simultaneously.

Table 4: Yd1 Exciting Current Test Connections

Phase	High-Voltage Lead (HV)	Low-Voltage Lead (LV)	Ground	Float	Mode
"A"	H1	H3	-	X1,X2,X3, H2	UST
"B"	H2	H1	-	X1,X2,X3, H3	UST
"C"	H3	H2	-	X1,X2,X3, H1	UST

Consider the "Phase-A" measurement, which is depicted in Figure 7. The HV injection lead is placed on the H1 bushing terminal and the LV measurement lead is placed on the H3 bushing terminal. As a result, the measured current for "Phase A" is actually the sum of the Phase-A (indicated by the green arrow) and Phase-C (indicated by the red arrow) winding currents. In other words, the Phase-A and Phase-C windings are tested in series. A summary of the "excited" and measured phases for the three exciting current measurements is provided in Table 5.

The analysis of the results for a transformer that has a wye primary winding without an accessible neutral is discussed thoroughly in Section 6.2.

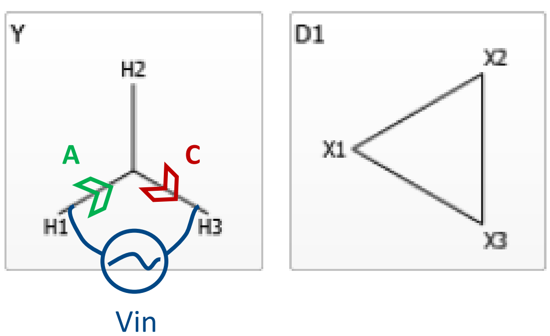

Figure 7: Yd1 "Phase-A" Exciting Current Measurement

Table 5: Wye Primary Winding with No Accessible Neutral - Measurement Summary

	Test Connection	"Excited" Phases	Measured Phases
"Phase A"	H1-H3	Phase A and Phase C	Phase A and Phase C
"Phase B"	H2-H1	Phase B and Phase A	Phase B and Phase A
"Phase C"	H3-H2	Phase C and Phase B	Phase C and Phase B

6 Exciting Current Phase Patterns

The analysis of the exciting current measurement involves identifying **phase patterns** and **tap-changer patterns**. There are several phase patterns that can be encountered in the field, which are typically influenced by the transformer's core construction and primary winding configuration (i.e. delta, wye, etc.) The three most common exciting current phase patterns are,

1.) **High-Low-High** Phase Pattern

2.) **High-Low-Low** Phase Pattern

3.) **Low-High-Low** Phase Pattern

Figure 8 provides an example of each of these three phase patterns, which will be discussed in detail in this section.

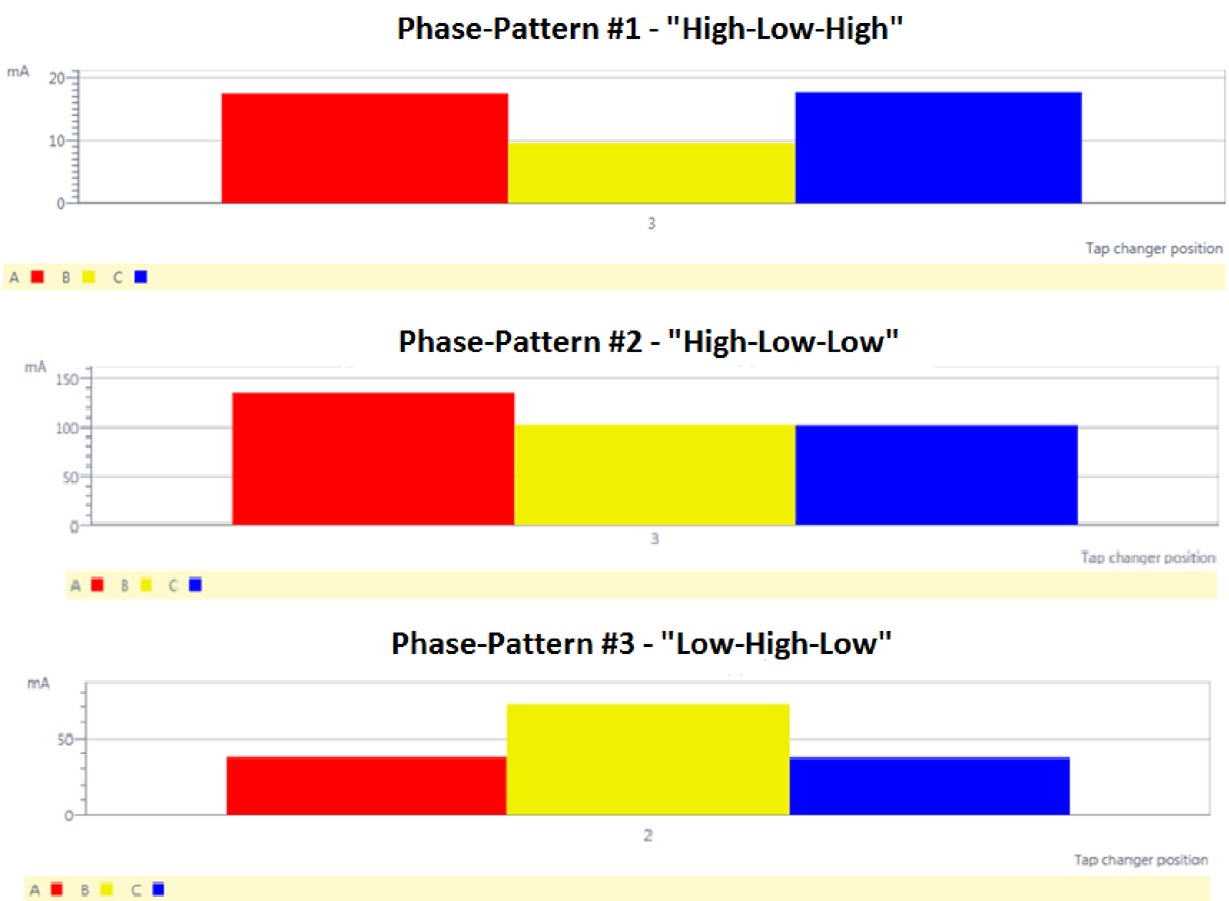

Figure 8: Typical Exciting Current Phase Patterns

6.1 High-Low-High Phase Pattern

The most common exciting current phase pattern is the **high-low-high** pattern, which is characteristic of most transformers in the field. A high-low-high pattern is typically obtained when testing a transformer with a 3-limb magnetic core and having either of the following primary winding configurations,

- Delta
- Wye winding with accessible neutral

A high-low-high pattern describes the magnitude of the measured current when comparing the three phase-measurements, where Phase-A and Phase-C produce a current that is higher in magnitude than Phase-B. An example of the high-low-high phase pattern is provided in Figure 9.

	Phase A	Phase B	Phase C
Measured Exciting Current	17.5mA	9.5mA	17.6mA

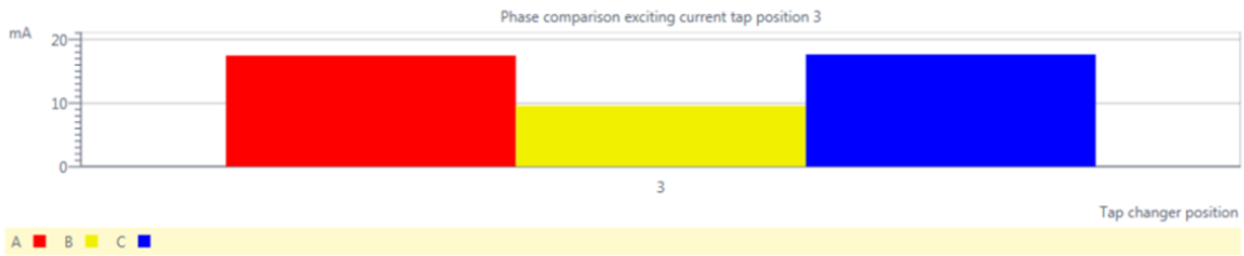

Figure 9: High-Low-High Phase-Pattern Example

It is interesting that the measured current for Phase-B differs in magnitude relative to the other two phases, which, from an electrical perspective, is identical to the Phase-A and Phase-C windings. However, for an inductive exciting current measurement, the phase pattern is heavily influenced by the magnetic circuit of the transformer, and more specifically, the construction of the transformer core.

The most common core construction used for field power transformers is a 3-limb (or 3-legged) core, which is depicted in Figure 10. For a 3-limb core-form transformer, each phase-winding rests on a separate limb of the core. In most cases (but certainly not all), the Phase-B winding is located on the center limb of the core.

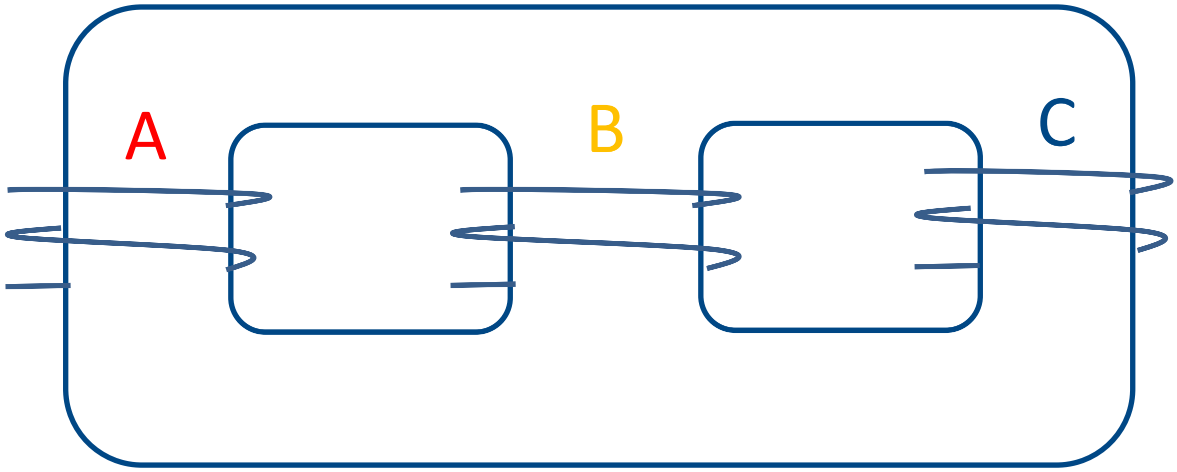

Figure 10: Transformer 3-Limb Core Construction

Consider applying an AC voltage to the Phase-A winding of the transformer, as shown in Figure 11. When an AC voltage is applied across the winding, magnetic flux is generated throughout the core.

The magnetic flux is often referred to as “magnetic current” flowing through the core. In reality, more than two flux paths are generated through the core, but for simplicity, the flux paths are lumped or averaged together as two paths. For the Phase-A injection, the first flux path flows through the center limb of the core (shown in red) and the second flows through the opposite outer limb of the core (shown in green).

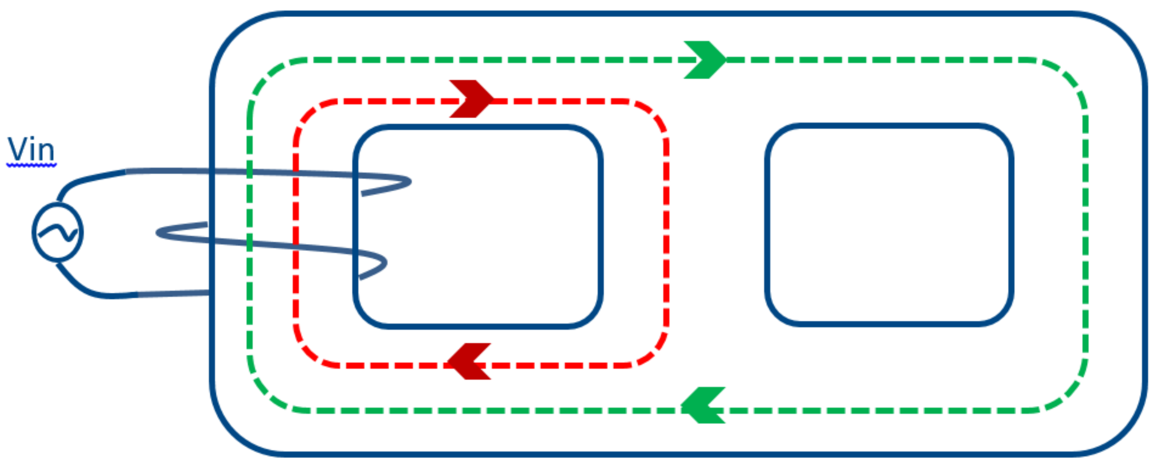

Figure 11: Phase-A Injection and Flux Distribution

Now, consider applying an AC voltage across the Phase-C winding of the transformer, as shown in Figure 12. The Phase-C injection also induces a flux path through the center-limb of the core (shown in red) and a flux path through the opposite outer limb of the core (shown in green).

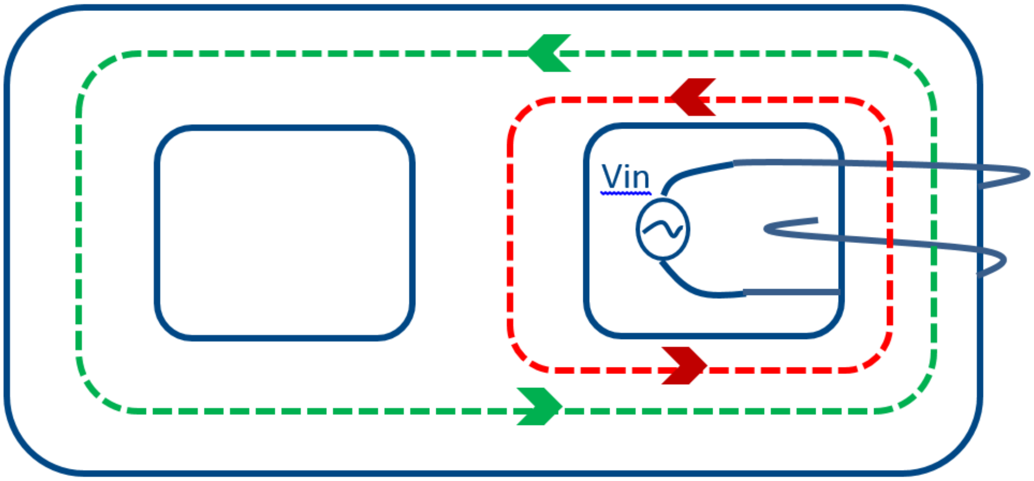

Figure 12: Phase-C Injection and Flux Distribution

By comparing Figures 11 and 12, it is clear that the Phase-A and Phase-C injections produce nearly identical flux distributions throughout the core.

Finally, the core flux distribution should be considered for the Phase-B injection, which is depicted in Figure 13. For the Phase-B Injection, two similar flux paths flow from the center limb to the outer limbs of the core (shown in red).

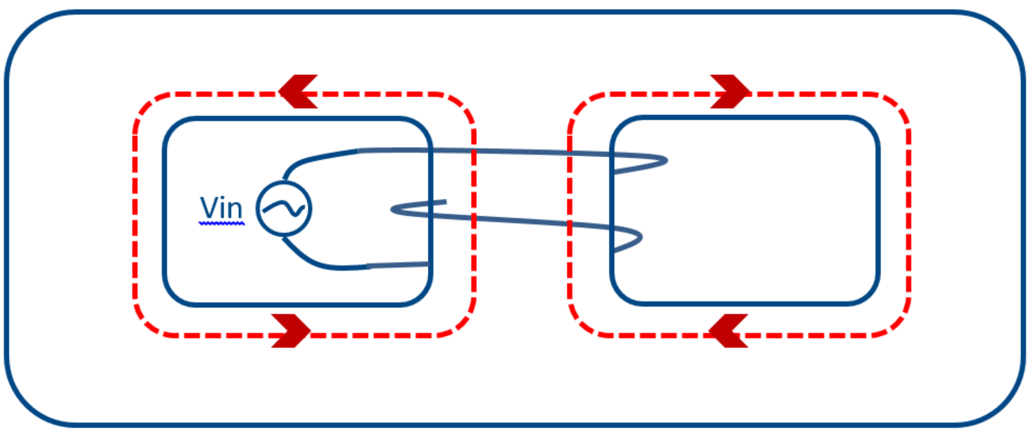

Figure 13: Phase-B Injection and Flux Distribution

The *length* of these flux paths significantly influences the measured exciting current. For an inductive exciting current measurement, the current is proportional to the sum of the length of the two flux paths generated through the core. The sum of the length of the two flux paths produced by the Phase-B injection is less than the sum of the length of the two flux paths produced by the Phase-A and Phase-C injections. Therefore, the exciting current for Phase-B is lower relative to Phase-A and Phase-C, which results in the high-low-high phase pattern.

For nearly all field transformers, regardless of the phase pattern, two of the three phase-measurements produce a similar exciting current. It is recommended that the two similar measurements compare to within 5-10%, in order for the transformer to "pass" the exciting current test. In some cases, a deviation of more than 10% is allowed.

For the high-low-high phase pattern, the Phase-A and Phase-C measurements should be compared. If these two measurements are dissimilar by more than 10%, then the exciting current measurement is questionable and should be investigated. A dissimilarity between the two measurements may be caused by one of the following,

- A fault within the transformer

- Residual magnetism - It is recommended that the transformer core is demagnetized and the exciting current test is repeated (for more information regarding residual magnetism, please see Section 8)

- The physical construction of the transformer (e.g. due to a unique core, winding, and/or insulation construction)

6.1.1 High-Low-High Phase Pattern in Sweep Frequency Response Analysis (SFRA)

The high-low-high phase pattern also makes an appearance during the Sweep Frequency Response Analysis (SFRA) test. Consider the three low-voltage open-circuit traces in Figure 14, which were obtained from testing a Wye winding with an accessible neutral. For an open-circuit SFRA trace, the low frequency range (i.e. frequencies <10 kHz) is heavily influenced by the core of the transformer. By analyzing the three traces in the "core region", it can be seen that the Phase-A (X1-X0) and Phase-C (X3-X0) traces are similar and overlap well, whereas the Phase-B (X2-X0) trace is slightly offset and lower in magnitude. This is the same high-low-high phase pattern that is obtained when performing the exciting current test.

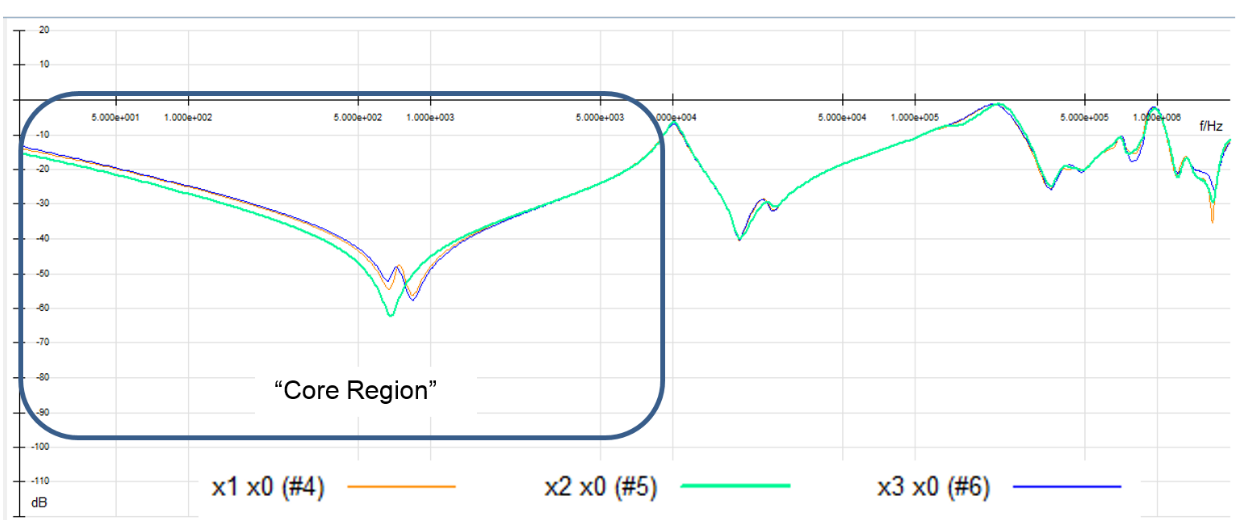

Figure 14: High-Low-High Pattern in SFRA

Also, the Phase-A (X1-X0) and Phase-C (X3-X0) traces produce two distinct resonance "valleys" in the core region, whereas the Phase-B trace only produces one resonance valley. The two resonance valleys produced by Phase-A and Phase-C are attributed to the two *different* flux paths that are generated when exciting their respective windings (see Figures 11 and 12). However, when exciting the Phase-B winding, the two flux paths are *similar* (see Figure 13), which results in a single resonance valley in the core region.

The exciting current and SFRA tests complement each other well, especially for assessing the integrity of the magnetic core circuit of a power transformer. The SFRA test is often a useful tool for investigating a questionable exciting current measurement. Do note that, like the exciting current test, the SFRA test is sensitive to residual magnetism within the core and, therefore, should be performed before the DC Winding Resistance test.

6.2 High-Low-Low Phase Pattern

Up to this point, only the high-low-high phase pattern has been discussed. A second, common phase pattern that may be encountered in the field is the **high-low-low** pattern, which is the expected phase pattern for a power transformer that has a Wye primary winding with no accessible neutral (H0).

Unfortunately, when the Wye primary winding has no accessible neutral, there is no reasonable way to isolate and measure each individual phase. Instead, two phase-windings of the transformer are tested in series and measured simultaneously, which results in the high-low-low phase pattern. To rationalize the high-low-low pattern, consider the Yd1 vector diagram shown in Figure 15. Each phase-vector of the primary winding has been labeled a particular phase and relative magnitude of exciting current.

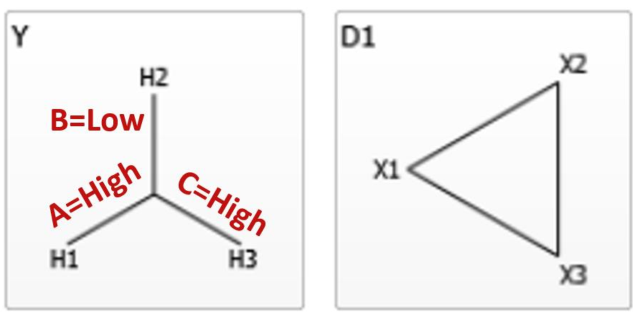

Figure 15: Yd1 Vector Diagram

The expected magnitude of exciting current for each phase-pair can be summed to derive the high-low-low pattern. For example, consider placing the HV injection lead on the H1 bushing terminal and the LV measurement lead on the H3 bushing terminal. This test connection (H1-H3) results in the excitation of the Phase-A and Phase-C windings, which produces the current flow depicted in Figure 16.

By summing the relative magnitude of exciting current for Phase-A ("high") and Phase-C ("high"), the resulting exciting current is "high+high". As can be seen in Table 6, the "Phase-B" (H2-H1) and "Phase-C" (H3-H2) measurements result in a relative magnitude of "high+low", which is a lower magnitude relative to the "Phase-A" measurement.

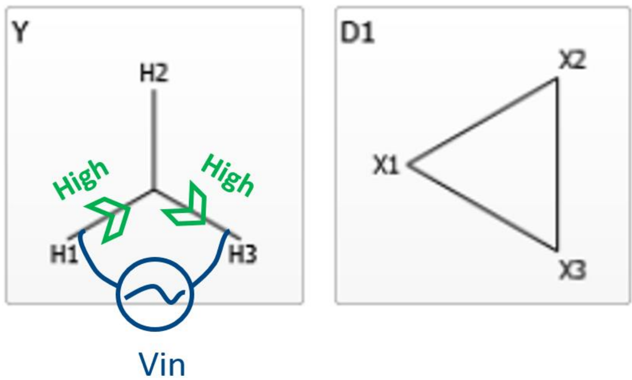

Figure 16: Yd1 – H1-H3 Measurement

Table 6: Wye Winding with No Accessible Neutral – Test Connections

Measurement	Test Connection	Measured Phases	Relative Current Magnitude for Both Phases	Total Relative Current Magnitude
"Phase A"	H1-H3	Phase A and Phase C	High+High	High
"Phase B"	H2-H1	Phase B and Phase A	Low+High	Low
"Phase C"	H3-H2	Phase C and Phase B	High+Low	Low

As an example, the exciting current test was performed on the following transformer,

Two-Winding Transformer – Yd1

4.160kV-0.380kV – 1MVA

The test connections provided in Table 6 were used to complete the exciting current measurement, and the test results are summarized in Figure 17. As can be seen, the transformer produced the expected High-Low-Low phase pattern.

	Phase A	Phase B	Phase C
Measured Current	135mA	102mA	102mA

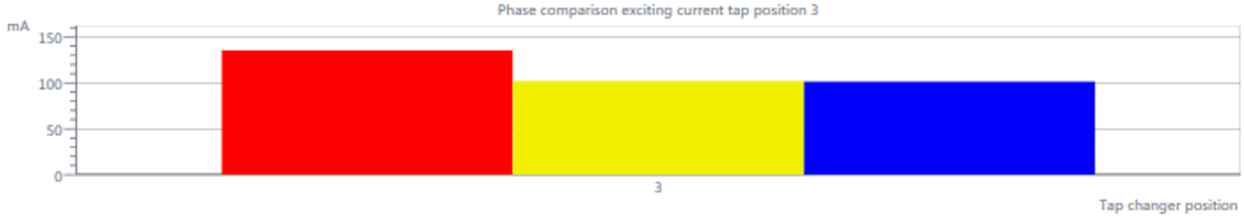

Figure 17: High-Low-Low Phase-Pattern Example

Note, depending on the test connections and lead rotation, the "high" current measurement could be obtained for either of the three exciting current measurements.

Therefore, to generalize, if the transformer under test has a wye winding with no accessible neutral, the expected phase-pattern is "one-high and two-lows".

For the high-low-low phase pattern, the two "low" measurements should be compared. If these two measurements are dissimilar by more than 10%, then the exciting current measurement is questionable and should be investigated. A dissimilarity between the two measurements may be caused by one of the following,

- A fault within the transformer
- Residual magnetism - It is recommended that the transformer core is demagnetized and the exciting current test is repeated (for more information regarding residual magnetism, please see Section 8)
- The physical construction of the transformer (e.g. due to a unique core, winding, and/or insulation construction)

6.2.1 High-Low-Low Phase Pattern in Sweep Frequency Response Analysis (SFRA)

The high-low-low phase pattern also makes an appearance in the Sweep Frequency Response Analysis (SFRA) test. For example, consider the three high-voltage open-circuit traces in Figure 18, which were obtained from testing a wye winding with no accessible neutral. For an open-circuit SFRA trace, the low frequency range (i.e. frequencies <10 kHz) is significantly influenced by the core of the transformer. By analyzing the "core region" of the three SFRA traces, it can be seen that the H1-H3 trace is higher in magnitude relative to the H2-H1 and H3-H2 traces. The H2-H1 and H3-H2 traces are similar and overlap well. This is the same high-low-low phase pattern that is obtained when performing the exciting current test.

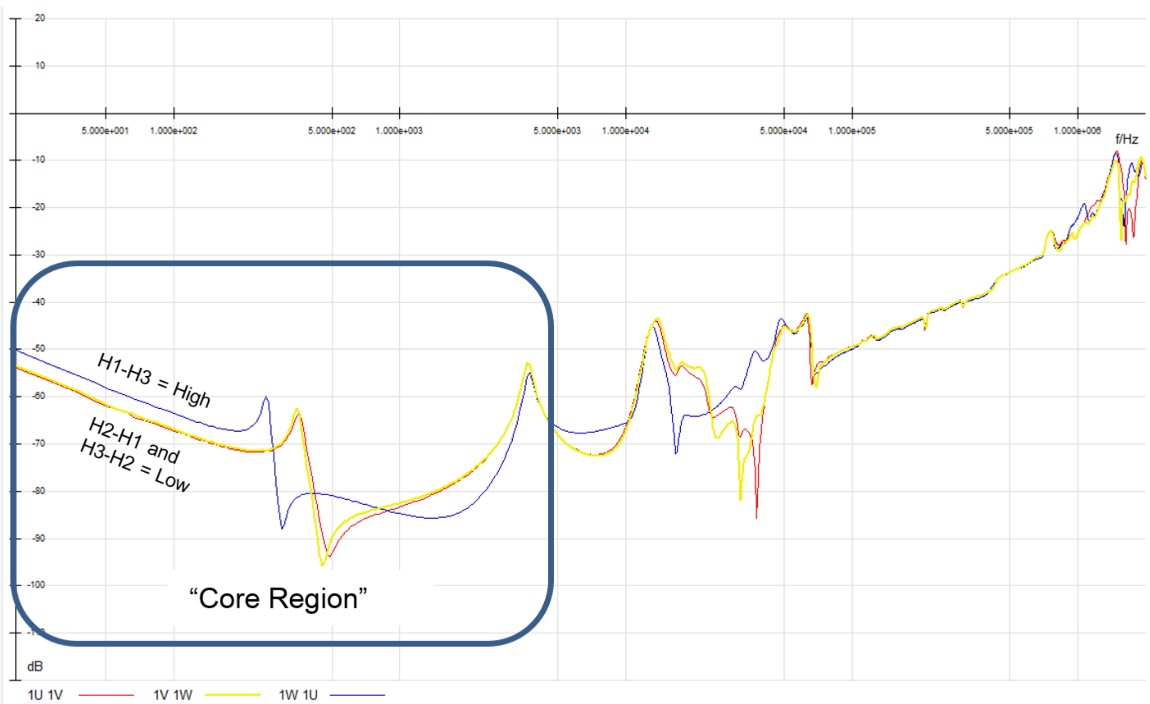

Figure 18: High-Low-Low Phase Pattern in SFRA

Again, the exciting current and SFRA tests complement each other well, especially for assessing the integrity of the magnetic core circuit of a power transformer. The SFRA test is often a useful tool for investigating a questionable exciting current measurement. Do note that, like the exciting current test, the SFRA test is sensitive to residual magnetism within the core and, therefore, should be performed before the DC Winding Resistance test.

6.3 Low-High-Low Phase Pattern

The **low-high-low** phase pattern that will be discussed in this section is *typically* only produced by distribution transformers. Although differentiating between a power transformer and a distribution transformer is not cut and dried, for this discussion, the two will be differentiated by using the following criteria,

- Power Transformer > 3MVA
- Distribution Transformer < 3MVA

Again, the criteria above is not cut and dried, but its intention is to give the reader an idea of the size of transformer that may produce the low-high-low exciting current phase pattern.

In most cases, a power transformer will produce one of the two phase patterns previously discussed in this document. Although a distribution transformer can also produce either of the two aforementioned phase patterns, it is not uncommon that a distribution transformer produces a low-high-low phase pattern. For the low-high-low phase pattern, the measured exciting current for Phase-A and Phase-C are similar, but lower in magnitude relative to Phase-B.

Unfortunately, there is no simple way (e.g. by looking at the transformer nameplate) of predicting whether a distribution transformer will produce a low-high-low phase pattern or not; however, it is important to know that it is not uncommon that a healthy, faultless distribution transformer produces the low-high-low phase pattern (conceivably due to its physical construction). When testing a distribution transformer, if the exciting current measurement produces the low-high-low phase pattern, and all of the other diagnostic tests performed on the transformer are acceptable, then the exciting current results are probably acceptable. The exciting current results and phase pattern should then be documented and used as a reference when performing future exciting current tests.

However, if the low-high-low pattern was obtained when testing a power transformer, it is more likely that the power transformer has a fault, relative to a distribution transformer that produces this same pattern. This very case is demonstrated in Section 9 (Case Study #1) and in Section 11 (Case Study #3). Again, in most cases, a power transformer will produce one of the first two patterns discussed in this paper.

Three examples of the low-high-low phase pattern are provided in Figures 19, 20, and 21, which were obtained when testing distribution transformers.

Summarizing, without previous test results, it is difficult to predict when the low-high-low phase pattern will be produced when testing a distribution transformer; however, whenever the exciting current measurement is performed on a distribution transformer, it is important to keep in mind that the low-high-low phase pattern is not uncommon, and is, in most cases, not indicative of a failure within the transformer.

Example #1 – Low-High-Low Phase Pattern

Two-Winding Transformer (Oil-Filled) – Ynyn0

24.9kV (14.376kV) - 0.480kV (0.277kV) – 1.5MVA

	Phase A	Phase B	Phase C
Measured Exciting Current	32.8mA	34.8mA	32.9mA

Figure 19: Low-High-Low Example #1

Example #2 - Low-High-Low Phase Pattern

Two-Winding Transformer (Oil-Filled) – Ynyn0

24.9kV (14.376kV) - 0.480kV (0.277kV) – 1.5MVA

	Phase A	Phase B	Phase C
Measured Exciting Current	35.1mA	37.6mA	35.4mA

Figure 20: Low-High-Low Example #2

Example #3 - Low-High-Low Phase Pattern

Two-Winding Transformer (Oil-Filled) – Ynyn0

24.9kV (14.376kV) - 0.208kV (0.120kV) – 150kVA

	Phase A	Phase B	Phase C
Measured Exciting Current	10mA	14mA	10mA

Figure 21: Low-High-Low Example #3

7 Exciting Current Tap-Changer Patterns

The transformer exciting current measurement can be performed on various de-energized tap-changer (DETC) and load tap-changer (LTC) positions to verify the integrity of the tap-changer and its associated components. To properly identify tap-changer failures using the exciting current measurement, it is important to understand the **tap-changer patterns** that can be obtained when performing the exciting current measurement on various tap-positions, which include,

1.) **De-Energized Tap Changer (aka No-Load Tap-Changer) Patterns**

2.) **Resistive-Type Load Tap Changer Patterns**

3.) **Reactive-Type Load Tap Changer Patterns**

The following sections summarize the expected exciting current **tap-changer patterns** for the tap-changer configurations outlined above. Emphasis is placed on the analysis of the reactive-type LTC patterns, which are unique, and often not fully understood.

Note, regardless of the tap-changer configuration, the expected **phase-pattern** should not change versus tap-position, and should be consistent with the **phase-patterns** discussed in the previous sections.

7.1 De-Energized Tap-Changer (aka No-Load Tap-Changer) Patterns

De-energized tap-changers (DETCs) are commonly located on the primary side of a power transformer, and typically have five tap-positions (although any number of tap-positions is possible). For routine maintenance, a power transformer is typically only tested on the "as-found" DETC position; however, for commissioning and acceptance testing, a power transformer may be tested on all DETC positions.

A power transformer with a DETC should have a predictable, simple exciting current tap-changer pattern. As the DETC is varied from extreme position to extreme position (e.g. from 1-5 or A-E), the measured exciting current is expected to increase or decrease linearly (depending on which direction the DETC is tested and which winding the DETC is located on). A typical DETC tap-changer pattern is shown in Figure 22. As the DETC is varied from positions A-E, the measured current increases linearly, as expected.

As a DETC is varied from extreme position to extreme position (e.g. from 1-5 or A-E), the number of winding turns included in the test circuit is either increased or decreased, which causes the impedance of the test circuit to either increase or decrease. By applying ohm's law, as the impedance of the test circuit changes, the magnitude of exciting current changes (assuming a fixed applied voltage).

If the measured exciting current does not increase or decrease linearly versus the DETC position, then the exciting current results are questionable and should be investigated.

	Phase A					Phase B					Phase C				
Tap	V out	I out	I phase	Watt losses	Reactance	V out	I out	I phase	Watt losses	Reactance	V out	I out	I phase	Watt losses	Reactance
A	7.00 kV	33.707 mA	-22.35 °	218.168 W	78.935 kΩ	7.00 kV	17.665 mA	-6.21 °	122.963 W	42.876 kΩ	7.01 kV	33.550 mA	-16.90 °	224.867 W	60.703 kΩ
B	7.00 kV	35.308 mA	-22.24 °	228.701 W	75.016 kΩ	7.00 kV	18.599 mA	-7.10 °	129.211 W	46.543 kΩ	7.00 kV	35.339 mA	-17.40 °	236.116 W	59.261 kΩ
C	7.00 kV	37.005 mA	-22.04 °	240.075 W	70.966 kΩ	7.00 kV	19.620 mA	-7.89 °	136.094 W	49.028 kΩ	7.00 kV	37.306 mA	-17.90 °	248.605 W	57.706 kΩ
D	7.00 kV	38.817 mA	-21.75 °	252.375 W	66.825 kΩ	7.00 kV	20.728 mA	-8.62 °	143.535 W	50.655 kΩ	7.01 kV	39.456 mA	-18.42 °	262.236 W	56.081 kΩ
E	7.00 kV	40.739 mA	-21.39 °	265.495 W	62.651 kΩ	7.00 kV	21.939 mA	-9.27 °	151.655 W	51.447 kΩ	7.00 kV	41.796 mA	-18.91 °	276.894 W	54.313 kΩ

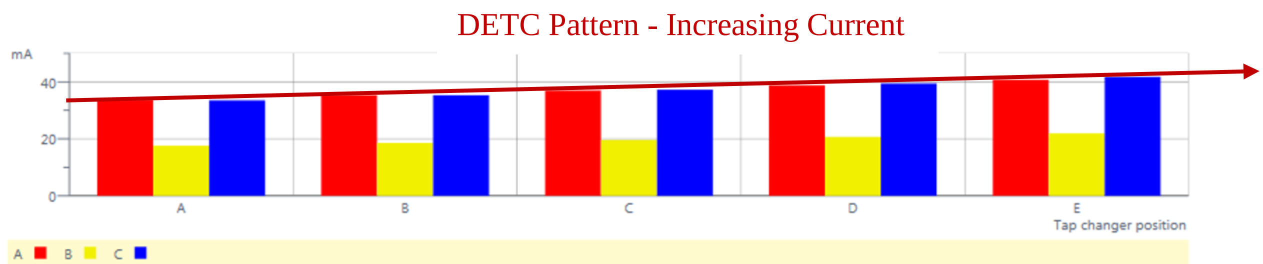

Figure 22: Typical DETC Tap-Changer Pattern

7.2 Resistive Load Tap-Changer (LTC) Patterns

Load tap changers (LTCs) are commonly located on the secondary side of a power transformer and typically have 33 tap-positions (e.g. 16R-16L or 1-33). A resistive-type LTC has resistors which are used to limit the current flow through the LTC and its components when the LTC changes positions. Although the resistors themselves are not directly tested when the exciting current measurement is performed, it is important to be able to identify when an LTC is a resistive-type, so that the exciting current results can be analyzed properly.

A resistive-type LTC can be identified by reviewing the nameplate information (specifically, the wiring diagram) of the transformer. For example, consider the wiring diagram shown in Figure 23, which was extracted from a transformer nameplate. Emphasis should be placed on the regulating winding and tap-changer components shown in the wiring diagram. A resistive-type LTC can be identified by the number of stationary contacts that the regulating winding possesses. A resistive-type LTC will have a regulating winding that possesses sixteen stationary contacts (seventeen including the neutral contact).

Figure 24 provides a second example of resistive-type LTC wiring diagram.

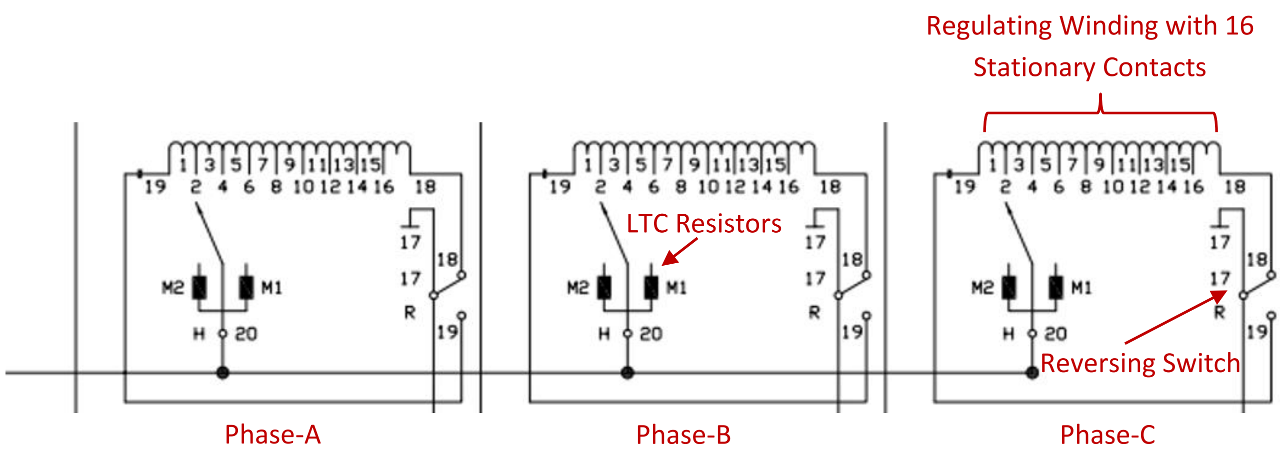

Figure 23: Typical Wiring Diagram of a Resistive-Type LTC

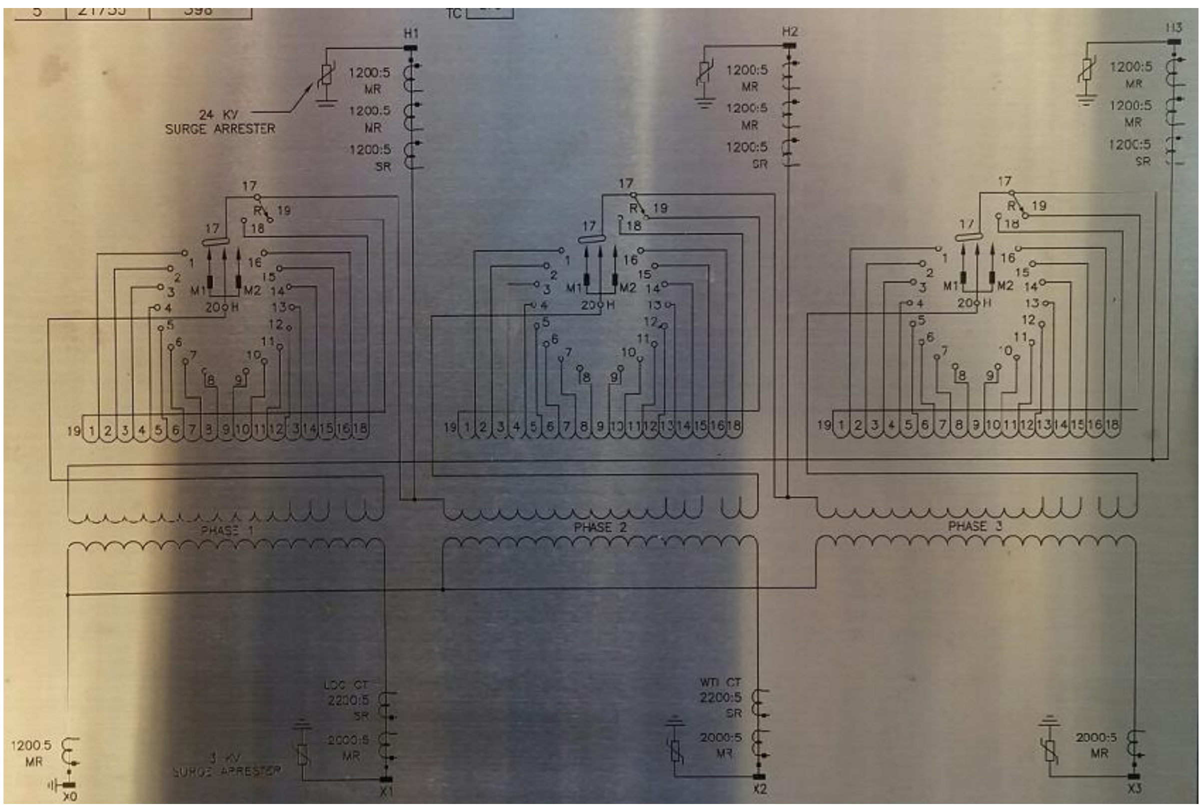

Figure 24: Typical Wiring Diagram of a Resistive-Type LTC

A power transformer with a resistive-type LTC typically produces a predictable, simple tap-changer pattern. As a resistive LTC is varied from position to position, the measured exciting current is expected to increase or decrease linearly.

If the resistive LTC is located on the secondary side (i.e. on the load side) of the power transformer, the measured current, if plotted versus tap-position, creates a "V" shaped pattern, as shown in Figure 25. In this scenario, the extreme tap-positions (e.g. 16R and 16L or 1 and 33) produce the highest current. In either extreme tap-position, all (or most) of the regulating winding turns are included in the test circuit. The more winding turns that are included in the test circuit, the larger the "load", which results in a larger exciting current. As the tap-changer is moved from either extreme position towards the neutral position, the number of winding turns in the test circuit is reduced, and therefore, the "load" and exciting current decreases. When the transformer is tested in the neutral position, the regulating winding is excluded from the test circuit. Therefore, the number of winding turns included in the test circuit is at a minimum, which results in the lowest measured current relative to the other tap-positions.

If the transformer under test has a resistive-type LTC that is located on the secondary side and the measured tap-changer pattern deviates from the expected "V" shaped pattern, then the exciting current results are questionable and should be investigated.

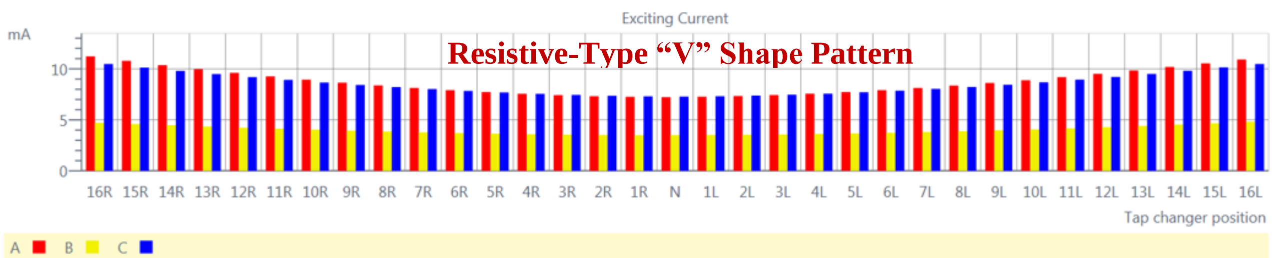

Figure 25: Typical Tap-Changer Pattern when Resistive LTC is Located on Secondary Side

If the resistive-type LTC is located on the primary side of the transformer under test, typically, the measured current increases (or decreases) linearly from one extreme position to the other, as shown in Figure 26. If the measured tap-changer pattern deviates from the expected pattern, then the exciting current results are questionable and should be investigated.

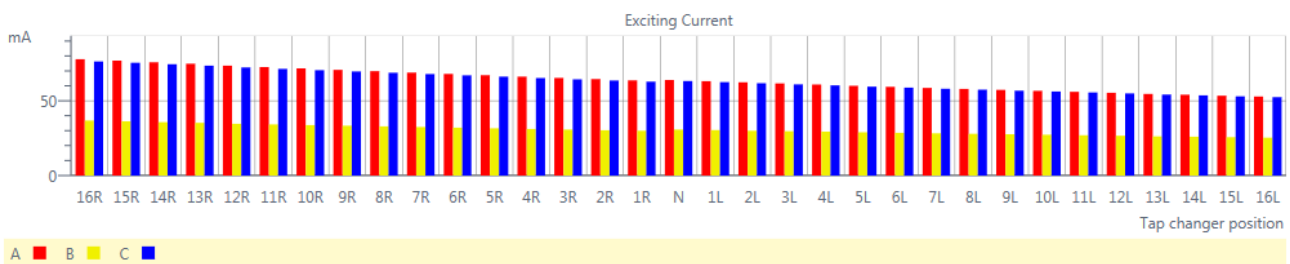

Figure 26: Typical Tap-Changer Pattern when Resistive LTC is Located on Primary Side

7.3 Reactive Load Tap Changer (LTC) Patterns

Analyzing the exciting current results for transformers with reactive-type LTCs is undoubtedly more complex than analyzing the results for transformers with resistive-type LTCs. The following sections serve to teach the reader how to identify a reactive-type LTC, and how to properly analyze the exciting current results for a transformer with a reactive-type LTC.

7.3.1 Reactive-Type LTC Basics

A power transformer that has a reactive-type LTC has a preventative autotransformer (PA), which is a 3-phase transformer associated with the operation of the LTC. The PA is a standalone 3-phase transformer that is typically located inside the main tank, which has its own core and windings. Therefore, if a power transformer has a reactive-type LTC, the main tank will typically house two separate 3-phase transformers: the first core and winding assembly will include the primary, secondary, and regulating windings. The second core and winding assembly will include the preventative autotransformer.

Each phase of the PA is comprised of two reactor (or inductor) windings, which significantly influence the exciting current test results. Therefore, it is important to be able to identify a power transformer that has a reactive-type LTC, so that the exciting current results can be properly analyzed.

A reactive-type LTC can be identified by reviewing the number of stationary contacts that the regulating winding of the transformer possesses. A reactive-type LTC will have a regulating winding that possesses eight stationary contacts (nine including the neutral contact), like the example provided in Figure 27. The regulating winding in Figure 27 possesses eight stationary contacts (C, D, E, F, G, H, K, and L), which is half the number of stationary contacts that a resistive-type regulating winding will possess. As can be surmised, the user can easily distinguish between a reactive-type and resistive-type LTC by identifying the number of stationary contacts that the regulating winding possesses. Then, by knowing the LTC type (resistive or reactive), the user can properly assess the exciting current results.

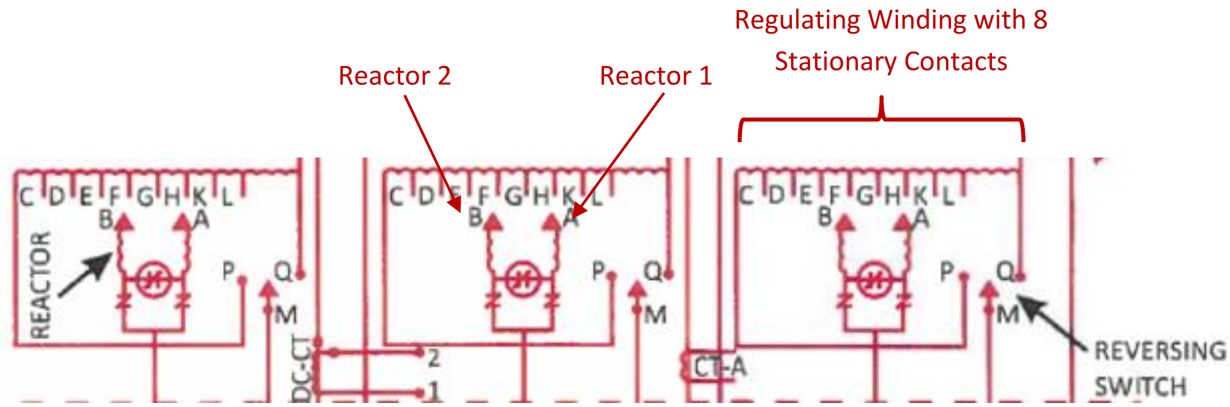

Figure 27: Typical Wiring Diagram of a Reactive-Type LTC

Understanding the operation of the PA is critical to understanding the exciting current test results for a transformer that has a reactive-type LTC. The PA has two distinct positions as the tap-changer position is varied, which includes,

- **<u>"Non-Bridging" Tap-Positions:</u>** In a non-bridging position, the two tap-selectors of the PA are connected to the same stationary contact of the regulating winding. Figure 28 depicts a PA that is in a non-bridging position. Both tap-selectors of the PA are connected to the stationary contact "F". When the PA is in a non-bridging position, the PA windings are short-circuited, and therefore, there is zero voltage potential applied across the PA windings. Since there is no voltage potential applied across the PA windings, the PA is not "excited". In a non-bridging position, the measured exciting current is not influenced by the PA.

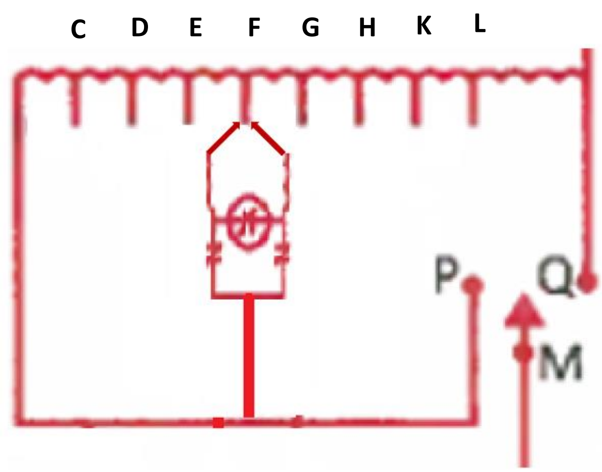

Figure 28: Non-Bridging Position Example

- **<u>"Bridging" Tap-Positions:</u>** In a bridging tap-position, the two tap-selectors of the PA are connected to two adjacent stationary contacts of the regulating winding. Figure 29 depicts a PA that is in a bridging position. The first tap-selector is connected to contact "E" and the second tap-selector is connected to contact "F", thus "bridging" the "E" and "F" contacts. When the PA is in a bridging position, a voltage potential is applied across the PA windings, which "excites" the PA. The voltage applied across the PA windings causes a circulating current to flow through the PA windings. In a bridging position, the measured exciting current is significantly influenced by the circulating current through the PA.

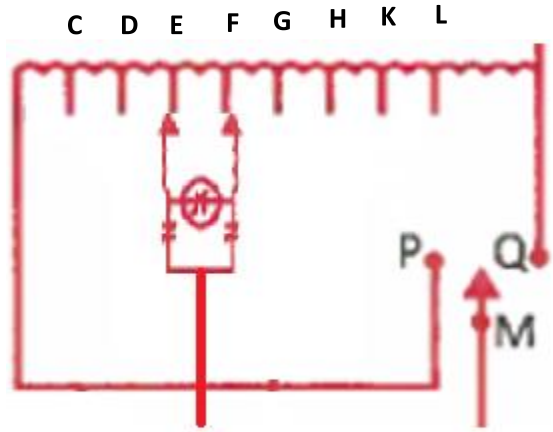

Figure 29: Bridging Position Example

A tap-position can be identified as bridging or non-bridging by reviewing the LTC voltage table located on the nameplate of the transformer. The voltage table shown in Figure 30 was extracted from the nameplate of a power transformer that has a reactive-type LTC.

Again, the PA is in a non-bridging position when the two tap-selectors (i.e. “A” and “B” in Figure 27) are connected to the same stationary contact of the regulating winding. Based on the voltage table shown in Figure 30, the non-bridging positions for this particular transformer are 16R, 14R, 12R, and all other even positions (including the Neutral position).

The PA is in the bridging position when the two tap-selectors (i.e. “A” and “B” in Figure 27) are connected to two adjacent stationary contacts of the regulating winding. Based on the voltage table shown in Figure 30, the bridging positions for this particular transformer are 15R, 13R, 11R, and all other odd positions.

As can be seen by the LTC voltage table in Figure 30, a reactive-type LTC alternates between the bridging and non-bridging positions. Due note, however, it cannot be assumed that the non-bridging positions are always the “even” positions and that the bridging positions are always the “odd” positions. If a reactive-type LTC has a naming convention of 1-33 (as opposed to 16R-16L), then the non-bridging positions would now be the “odd” positions, and the bridging positions would now be the “even” positions.

LV WINDING CONNECTIONS						
VOLTS	AMP 10500 KVA	MECHANISM				REVERSING SWITCH CONNECTS
			DIAL POS	CONNECTS		
				A TO	B TO	
4576	1325		16	L	L	Non-Bridging
4550	1335		15	L	K	Bridging
4524	1340		14	K	K	Non-Bridging
4498	1350		13	K	H	Bridging
4472	1355		12	H	H	Non-Bridging
4446	1365		11	H	G	Bridging
4420	1375		10	G	G	Non-Bridging
4394	1380		9	G	F	M TO P
4368	1390	RAISE	8	F	F	
4342	1395		7	F	E	
4316	1405		6	E	E	
4290	1415		5	E	D	
4264	1425		4	D	D	
4238	1430		3	D	C	
4212	1440		2	C	C	
4186	1450		1	C	M	
4160			N	M	M	
4134			1	M	L	
4108			2	L	L	
4082			3	L	K	
4056			4	K	K	
4030			5	K	H	
4004			6	H	H	
3978			7	H	G	
3952	1460	LOWER	8	G	G	M TO Q
3926			9	G	F	
3900			10	F	F	
3874			11	F	E	
3848			12	E	E	
3822			13	E	D	
3796			14	D	D	
3770			15	D	C	
3744			16	C	C	

Figure 30: Reactive-Type LTC Voltage Table Example

7.3.2 Reactive-Type LTC Patterns

To better understand the effect of the PA on the exciting current measurement, it is worth considering an example of the exciting current results. The exciting current test was performed on a power transformer with a reactive-type LTC and a graph of the results for all three phases, versus tap-position, is provided in Figure 31.

For this particular transformer, the even positions are non-bridging positions and the odd positions are bridging positions. Notice that the exciting current for the bridging positions is significantly higher relative to the non-bridging positions, which is expected for a reactive-type LTC. When the PA is in the bridging position, a voltage potential is applied across the PA windings, which causes a circulating current to flow through the PA windings. This circulating current through the PA causes the total exciting current to increase relative to a non-bridging position, where there is no circulating current flowing through the PA.

Therefore, the expected tap-changer pattern for a reactive-type LTC is an "up-down-up-down, etc…" or "saw-tooth" pattern as the transformer is tested on consecutive LTC positions. Due note, however, that the expected phase pattern should not change versus tap-position, and should be consistent with the phase patterns previously discussed in this paper.

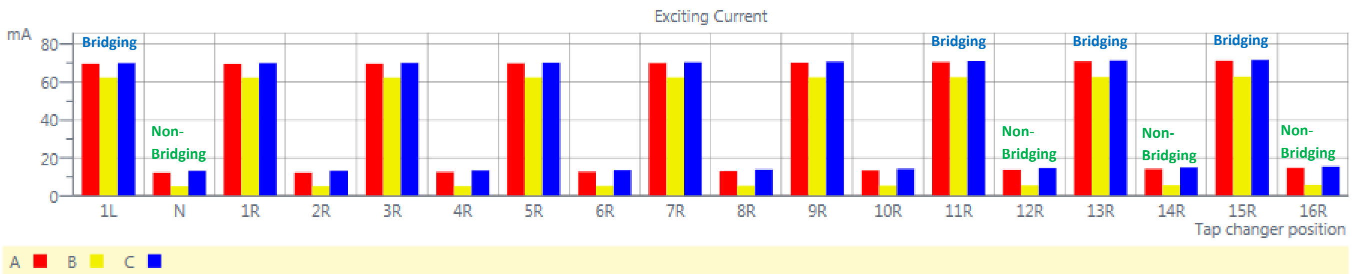

Figure 31: Reactive-Type LTC Pattern Example

7.3.3 Reactive-Type LTC "Bridging Patterns"

Not only does the exciting current vary significantly when comparing the non-bridging and bridging positions, but also the exciting current may vary significantly when comparing the bridging tap-positions to each other. In short, the bridging positions themselves may produce a "bridging pattern", which is difficult to predict, but must be identified for proper test result analysis.

Consider the exciting current results provided in Figure 32, which was obtained from testing a transformer with a Delta primary winding and a reactive-type LTC. For this particular transformer, the even positions are non-bridging positions and the odd positions are bridging positions.

Figure 32: Reactive-Type LTC "Bridging Pattern" Example #1

Based on the results in Figure 32, the transformer produced the expected high-low-high phase pattern. Also, as expected, the measured exciting current for all bridging positions is higher than the measured current for all non-bridging positions. However, notice that the magnitude of current is not consistent when comparing most of the consecutive bridging (odd) positions, which creates a “bridging pattern”. In most cases (but not all), if a “bridging pattern” exists, there are two different magnitudes of current for the bridging positions, which will be referred to as “bridging high” and “bridging low”. For example, in Figure 32, the 15R, 11R, and 15L positions are “bridging high” positions, whereas the 13R, 9R, and 13L positions are “bridging low” positions.

There are several different “bridging patterns” that exist for power transformers with reactive-type LTCs. Unfortunately, these bridging patterns are not easy (if not impossible) to predict without referring to previous exciting current test results. Therefore, for analysis purposes, it is important to be aware of the possible bridging patterns that may be encountered in the field.

Figure 33 provides several examples of different bridging patterns that may be encountered in the field. Note, however, that Figure 33 is not an all-inclusive collection of the possible exciting current bridging patterns, and that other bridging patterns may be obtained in the field.

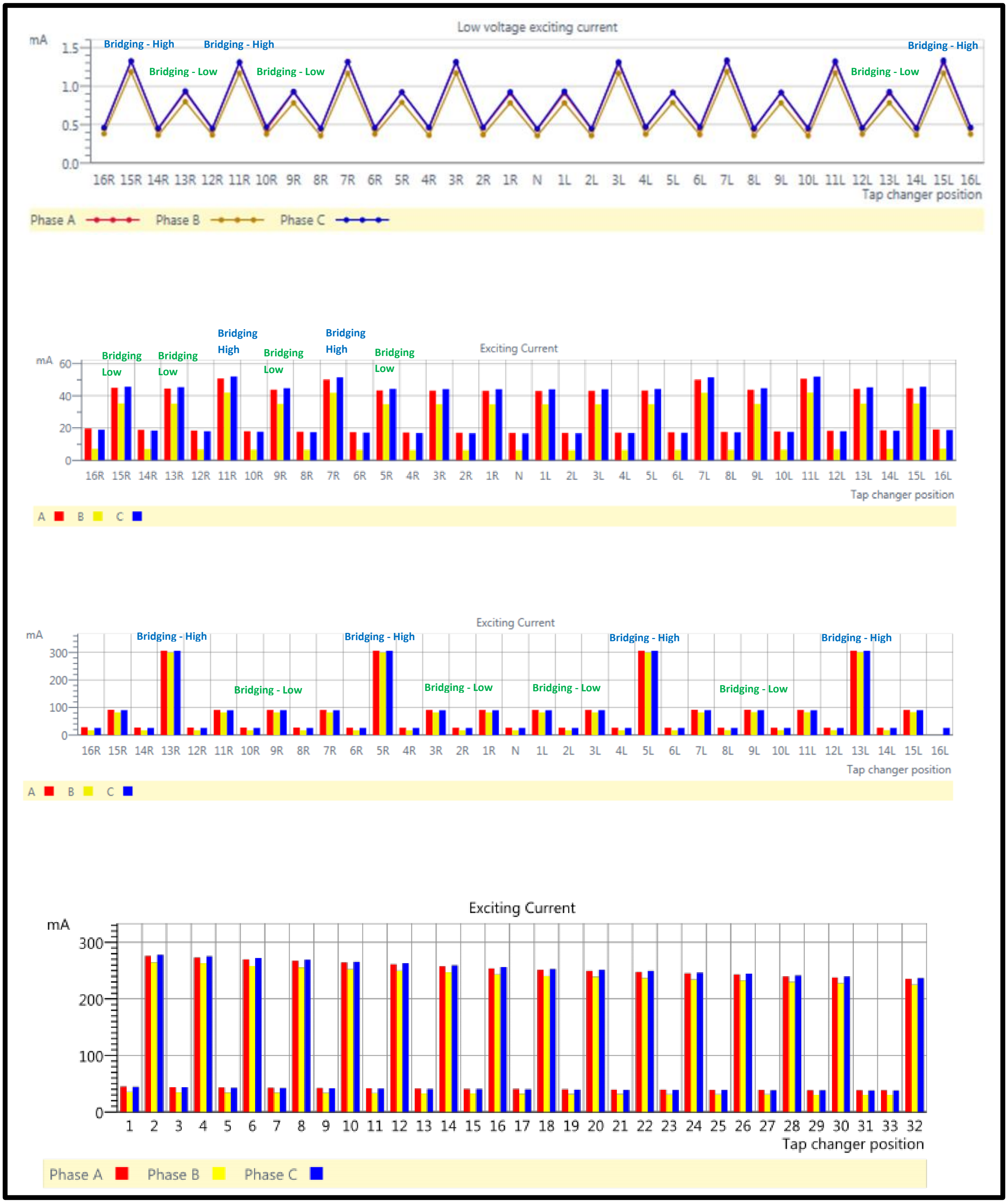

Figure 33: Reactive-Type LTC "Bridging Pattern" Examples

A “bridging pattern” is dictated by the number of winding turns between each pair of adjacent stationary contacts of the regulating winding. Surprisingly, the number of winding turns may not be consistent between each pair of stationary contacts of the regulating winding. This inconsistency causes the exciting current for the bridging positions to vary in magnitude. The more winding turns that exist between two adjacent stationary contacts, the higher the applied voltage across the PA, which results in a larger circulating current through the PA.

Consider the wiring diagram of a reactive-type LTC provided in Figure 34. Since the regulating winding has eight stationary contacts, this particular power transformer has a reactive-type LTC. Now, as a theoretical exercise, let’s assume that the exciting current results shown in Figure 35 were obtained from testing this particular transformer.

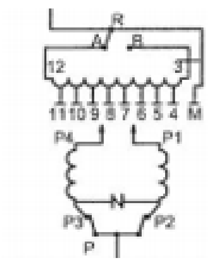

Figure 34: Reactive-Type LTC Wiring Diagram Example

Based on the measured current versus tap-position in Figure 35, the bridging positions can be categorized as follows,

- Bridging-High Positions: 15R, 11R, 7R, 3R, 3L, 7L, 11L, and 15L
- Bridging-Low Positions: 13R, 9R, 5R, 1R, 1L, 5L, 9L, and 13L

Since the exciting current in the “bridging high” positions is larger relative to the “bridging low” positions, it is conceivable that there are more winding turns between the two adjacent stationary contacts that are bridged in a “bridging high” position. To elaborate, a theoretical construction of the regulating winding shown in Figure 34 has been superimposed on the test results provided in Figure 35. In this theoretical example, the number of winding turns between two adjacent stationary contacts in a “bridging-high” position is two, while the number of winding turns between two adjacent stationary contacts in a “bridging-low” position is one. Again, the more winding turns that exist between two adjacent stationary contacts, the higher the applied voltage across the PA, which results in a larger circulating current through the PA.

Finally, referring back to the results provided in Figure 31, it can be seen that this particular transformer does not produce a “bridging pattern”, which is not uncommon. It can be assumed that the regulating winding of this particular power transformer has a consistent number of winding turns between each pair of adjacent stationary contacts.

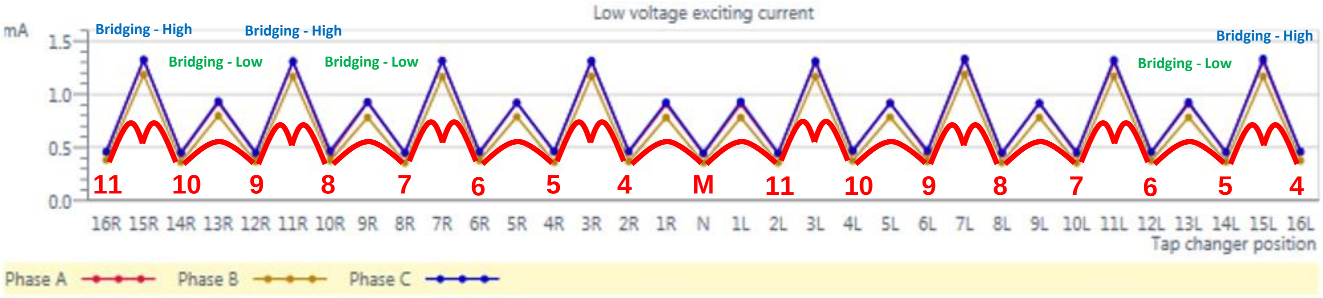

Figure 35: Reactive-Type LTC “Bridging Pattern” Versus Regulating Winding Construction

8 Residual Magnetism

It has been well documented that the exciting current test results can be contaminated by residual flux within the transformer core. When a transformer is de-energized and removed from service, there always exists some degree of residual flux within the core. In most cases (but not all), the residual flux is benign and will not influence the exciting current test results.

The most common cause of excessive residual flux that plagues the exciting current test results is the DC winding resistance test. When the DC winding resistance test is performed on a power transformer, a DC current is injected into a transformer winding until the transformer core becomes saturated, which allows the user to isolate and measure the DC resistance of the winding. Unfortunately, when the DC winding resistance test is complete, there still may exist excessive residual flux in the core, which may contaminate the exciting current test results.

Therefore, it is always recommended that the DC Winding Resistance is performed after the exciting current test, and in general, is the final diagnostic test performed on a power transformer.

Residual flux in the core can contaminate any diagnostic test that is significantly influenced by the transformer core circuit; namely, the exciting current test, the sweep frequency response analysis (SFRA) Test, and the turns-ratio (TTR) test. Regarding the exciting current test results, residual flux in the core may create unusual phase patterns and/or dissimilarities between two measurements that are supposed to be similar. The latter is demonstrated by the results shown in Figure 36.

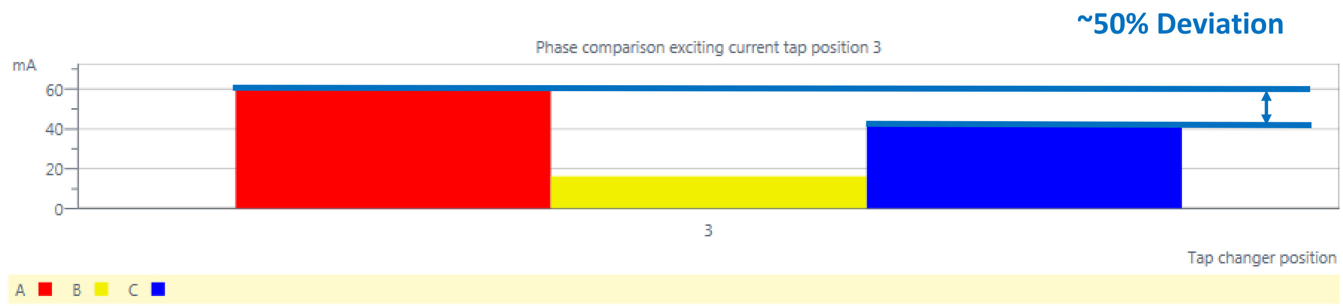

Figure 36: Exciting Current Results with Magnetized Core

In Figure 36, the Phase-A current is approximately 50% higher than the Phase-C current, which exceeds the 10% recommendation when comparing two similar measurements. It is possible that a fault within the transformer could cause this dissimilarity between Phase-A and Phase-C. However, before condemning the transformer, the influence of residual flux should be considered.

For electrical diagnostic testing of power transformers, it is advantageous to possess an instrument that can demagnetize the core of the transformer. If questionable exciting current measurements are obtained when testing a power transformer, then the demagnetization test should be performed, and then the exciting current test should be repeated. Hopefully, after demagnetizing the core and repeating the exciting current test, the expected phase pattern can be measured. If the repeated exciting current results are acceptable, then it is conceivable that residual flux in the core was the cause of the original, questionable exciting current measurements.

For example, the transformer with the questionable exciting current results shown in Figure 36 was demagnetized, and then the exciting current test was repeated on all three phases. The repeated exciting current results are shown in Figure 37. After the transformer's core was demagnetized, the exciting current test produced the expected high-low-high pattern, and the Phase-A and Phase-C measurements compare within 1%. Thus, it is conceivable that residual flux in the core was the cause of the original, questionable results shown in Figure 36.

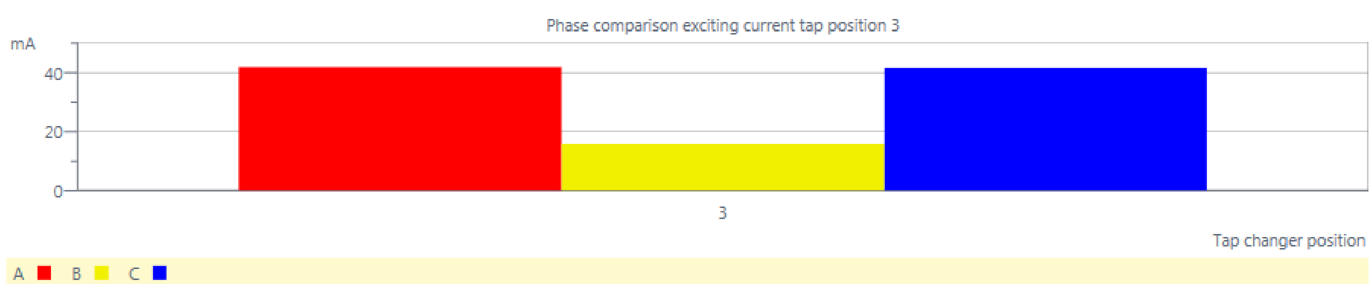

Figure 37: Exciting Current Results after Core was Demagnetized

9 Case Study #1

Two-Winding Transformer (Oil-Filled) – Dyn1

90.2kV-34.5kV – 50MVA

The power transformer outlined above experienced a fault event and “tripped” out of service. After the transformer experienced the fault event, a battery of diagnostic tests were performed, which included the Dissolved Gas Analysis (DGA), power factor, and exciting current measurements.

9.1 Dissolved Gas Analysis (DGA) Results

One of the most valuable diagnostic tests that can be performed on a transformer after it experiences an event is the Dissolved Gas Analysis (DGA) test. Fortunately, this particular transformer had a well-documented DGA history dating back nearly 20 years, so a quality trend could be established for the key DGA combustible gases. The DGA results dating back to 2009 are provided in Figure 38.

Post-Fault Sample

Pre-Fault Samples

Gas Analysis	07/09/2014	ppm/day	03/11/2014	04/24/2012	10/20/2010	08/12/2009	Limits
Sample No	**3212**		3068	3179	2314	2916	
Fluid Temp C	**42**		30	35	23	38	
Hydrogen (H2)	**221**	1.84 Abnormal +	<5	<5	14	<5	< 100
Methane (CH4)	**60**	0.50 +	<1	<1	2	3	< 75
Ethane (C2H6)	**605**	5.04 High +	<1	<1	<1	<1	< 75
Ethylene (C2H4)	**3**	0.03	<1	9	10	11	< 75
Acetylene (C2H2)	**136**	1.13 Very High ++	<1	<1	<1	<1	< 3
Carbon Monoxide (CO)	**144**	0.93	33	84	57	68	< 700
Carbon Dioxide (CO2)	**103**	-12.06	1550	3348	3183	3278	< 7000
Oxygen (O2)	**55201**		221047	11121			
Nitrogen (N2)	**205176**		909014	56413			
TDCG (ppm)	**1169**	9.47 Abnormal +	33	93	83	82	< 1000
Equivalent TCG (%)	**0.23**		0.00	0.10			
CO2/CO	**0.72**		46.97	39.86	55.84	48.21	
O2/N2	**0.27**		0.24	0.20			
Equipment Condition	**4**		1	1	1	1	

Figure 38: Dissolved Gas Analysis (DGA) History

When comparing the pre-fault and post-fault samples, it can be seen that several of the DGA combustible gases, such as hydrogen, methane, ethane, and acetylene increased significantly in magnitude (ppm), conceivably due to the fault event. The increase in combustible gases warrants immediate concern and further investigation.

9.2 Overall Power Factor Results

The overall power factor measurement was performed on the two-winding transformer to assess the integrity of the insulation system. For the overall power factor test on a two-winding transformer, there are three insulation components that can be isolated and tested, which includes,

1.) CH: High-voltage winding-to-ground insulation, including the high-voltage bushing insulation

2.) CL: Low-voltage winding-to-ground insulation, including the low-voltage bushing insulation

3.) CHL: High-voltage to low-voltage (inter-winding) insulation, which does not include the bushing insulation

The overall power factor results are summarized in Figure 39.

Insulation Component	Power Factor (%)
CH Insulation (10kV)	0.30
CL Insulation (7kV)	47.4
CHL/CLH Insulation (10kV)	0.38

Figure 39: Overall Power Factor Results

The CH and CHL insulation components tested below 0.5%, which is typically indicative of healthy insulation (assuming an oil-filled power transformer); however, the CL insulation component tested with an alarmingly high power factor value of 47.4%, which suggests there exists an insulation failure involving the low-voltage winding-to-ground insulation system. It is conceivable that the elevated combustible gases are linked to the insulation failure.

It is important to note that the C1 insulation of the low-voltage bushings influences the CL power factor measurement; therefore, the C1 power factor test was performed on all of the low-voltage bushings, to determine if the elevated CL power factor was caused by a defective bushing(s). All four low-voltage bushings (i.e. X1, X2, X3, and X0) tested with a C1 power factor value below 0.7%. Therefore, we can conclude that the abnormally high CL power factor was probably not caused by a defective bushing, but by an insulation failure within the main tank of the transformer.

9.3 Exciting Current Results

The exciting current test was performed on the "as-found" tap position(s) only. Since the primary winding of the transformer was Delta connected, and since the unit is a power transformer (50MVA), the expected exciting current phase pattern is **high-low-high**. The exciting current results, post-fault, are provided in Figure 40.

	Phase A	Phase B	Phase C
Measured Exciting Current	37.5mA	71.9mA	37.2mA

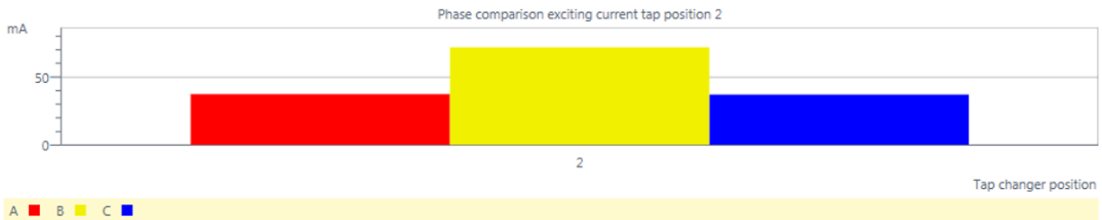

Figure 40: Exciting Current Results - Post-Fault

The expected phase pattern for this transformer was **high-low-high**; however, the measured Phase-B current was significantly *higher* than Phase-A and Phase-C, resulting in a **low-high-low** phase pattern, which was not expected. Although a discrepancy between the expected and measured phase pattern does not necessarily confirm that the transformer has failed, whenever a transformer produces an unexpected phase pattern, it should be investigated further.

A fault typically causes the magnitude of exciting current to increase (i.e. the exciting current will be higher than expected). Therefore, due to the unusually high Phase-B exciting current, and based on the "failed" DGA and overall power factor results, the customer concluded that the failure involved the low-voltage winding-to-ground insulation system of Phase-B. The customer immediately removed the transformer from service and replaced the unit.

10 Case Study #2

Two-Winding Transformer (Dry-Type) – Dyn1

13.8kV-0.208kV – 3MVA

The transformer outlined above experienced a fault event and "tripped" out of service. Since this particular unit is a dry-type transformer, there are no DGA results to review. Therefore, the transformer was investigated by performing a battery of offline electrical diagnostic tests, which included the power factor and exciting current measurements.

10.1 Overall Power Factor Results

The overall power factor measurement was performed on the two-winding transformer to assess the integrity of the insulation system. The overall power factor results are provided in Figure 41.

Insulation Component	Power Factor (%)
CH Insulation (7kV)	6.1
CL Insulation (0.1kV)	17.1
CHL Insulation (7kV)	0.46

Figure 41: Overall Power Factor Results

The CHL insulation system tested below 0.5%, which is typically indicative of healthy insulation for a dry-type transformer; however, the CH and CL insulation components tested with values of 6.1% and 17.1%, respectively. Unfortunately, without previous test results, it is difficult to condemn the CH measurement, since higher than normal power factor values are not uncommon for dry-type transformers. However, the CL measurement is excessively high and indicates that a failure involving the low-voltage winding-to-ground insulation system may exist.

Unfortunately, since the bushings on the secondary of the transformer did not have test taps (which is often the case for distribution transformers), the C1 bushing power factor test could not be performed to determine if a bushing failure contributed to the excessively high CL power factor value.

10.2 Exciting Current Results

The exciting current test was performed on the "as-found" tap position to investigate the suspected insulation failure involving the low-voltage winding-to-ground insulation system. Since the transformer under test had a Delta primary winding, the expected exciting current phase pattern is **high-low-high**. When the exciting current test was performed on Phase-A and Phase-B at 5kV, the test set "tripped" (due to an overcurrent); however, the Phase-C measurement could be completed without "tripping" the test set. The post-fault exciting current results are summarized in Figure 42.

	Phase A					Phase B					Phase C				
Tap	V out	I out	I phase	Watt losses	Reactance	V out	I out	I phase	Watt losses	Reactance	V out	I out	I phase	Watt losses	Reactance
n/a	V	Overcurrent – Test Set Tripped		W	kΩ	V	Overcurrent – Test Set Tripped		W	kΩ	4.98 kV	19.673 mA	-35.85 °	79.347 W	148.148 kΩ

Figure 42: Exciting Current Results

As stated in Section 4, if the transformer under test has a Delta primary winding, and two of the three phase-measurements "trip", then a fault within the transformer is probable. To elaborate, it is important to understand the exciting current test connections for testing a Delta primary winding, which are thoroughly discussed in Section 5.1, and summarized in Table 7.

Table 7: Delta Primary Winding Measurement Summary

	Test Connection	Ground	"Excited" Phases	Measured Phase
Phase A	H1-H3	H2	Phase A and Phase B	Phase A
Phase B	H2-H1	H3	Phase B and Phase C	Phase B
Phase C	H3-H2	H1	Phase C and Phase A	Phase C

When testing a Delta primary winding, although only a single-phase winding is measured, two phase-windings are "excited" simultaneously (assuming the recommended test connections are made). Notice that the Phase-C measurement, which requires the higher output power (VA) from the test instrument, was completed successfully. In general, if no fault exists, and the Phase-C can be completed, then the other two phase-measurements should be able to be completed without "tripping" the test instrument. Based on this reasoning, it is conceivable that the test instrument "tripped" during the Phase-A and Phase-B measurements due to a fault.

Furthermore, since the measurement was successfully completed on Phase-C, it is conceivable that the fault is not located on either Phase-C or Phase-A, since both phase-windings are “excited” during the Phase-C measurement. However, notice that the Phase-B winding is “excited” when both the Phase-A and Phase-B measurements are performed. This leads to the conclusion that the failure is located on Phase-B and involves the low-voltage winding-to-ground insulation system.

In general, if the transformer under test has a Delta primary winding, and two of the three phase-measurements “trip”, the fault is most likely located on the phase that is “excited” during both of the measurements that “trip”.

10.3 Exciting Current Voltage Tip-Up Test

A technique that can be used to investigate a questionable exciting current measurement is the “exciting current voltage tip-up test”. For this test, the exciting current measurement is performed on all three phases at increasing test voltages. The exciting current voltage tip-up test helps identify a voltage sensitive failure within the transformer, which is only “triggered” past a certain test voltage (typically at higher voltages). If a voltage sensitive failure exists, then the expected phase pattern may be obtained when testing at a relatively low voltage. However, when the test voltage is relatively high, the phase pattern may deviate from the expected pattern and/or the test instrument may “trip”, which can help provide more evidence that the transformer has failed.

The exciting current test was performed on the transformer under test at 500V, and the results are provided in Figure 43.

	Phase A					Phase B					Phase C				
Tap	V out	I out	I phase	Watt losses	Reactance	V out	I out	I phase	Watt losses	Reactance	V out	I out	I phase	Watt losses	Reactance
n/a	488.00 V	5.088 mA	-50.77 °	1.570 W	74.241 kΩ	489.00 V	2.498 mA	-49.90 °	0.787 W	149.744 kΩ	475.00 V	5.152 mA	-51.50 °	1.523 W	71.966 kΩ

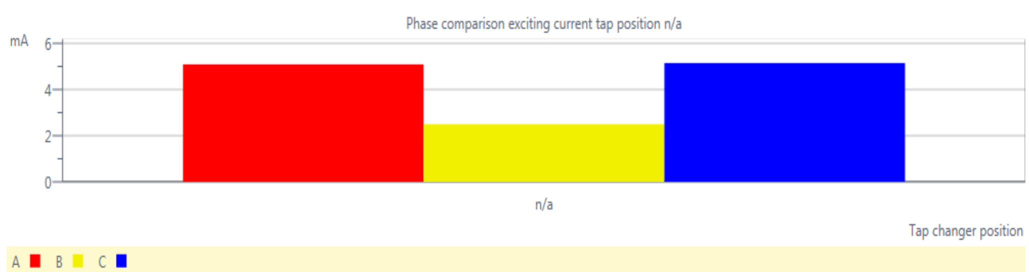

Figure 43: Exciting Current Results at 500V

With a test voltage of 500V, the exciting current measurement produced the expected high-low-high pattern; however, at higher test voltages (e.g. 5kV), the exciting current test failed. Therefore, based on the 500V and 5kV exciting current results, there appears to be a voltage sensitive insulation failure, which is only “triggered” when the test voltage exceeds a certain threshold (somewhere between 500V and 5kV).

Case Study #3 also demonstrates the value of performing the exciting current voltage tip-up test, when a transformer under test is suspect.

11 Case Study #3

The following case study demonstrates the exciting current test’s ability to detect a fault involving the LTC of a power transformer. During routine maintenance, a battery of offline electrical diagnostic tests were performed on a power transformer, which included the power factor, exciting current, turns-ratio, leakage reactance, and DC winding resistance measurements. The transformer’s nameplate information is provided in Figure 45.

By reviewing the wiring diagram of the transformer, it can be seen that the regulating winding possesses eight stationary contacts, which indicates that this particular transformer has a reactive-type LTC with a preventative autotransformer.

11.1 Overall Power Factor Results

The overall power factor measurement was performed on the two-winding transformer to assess the integrity of the insulation system. The overall power factor results are provided in Figure 44.

Insulation Component	Power Factor (%)
CH Insulation (10kV)	0.20
CL Insulation (10kV)	0.38
CHL Insulation (10kV)	0.24

Figure 44: Overall Power Factor Results

All three insulation components tested with a power factor value well below 0.5%, which is typically indicative of healthy insulation (assuming an oil-filled power transformer).

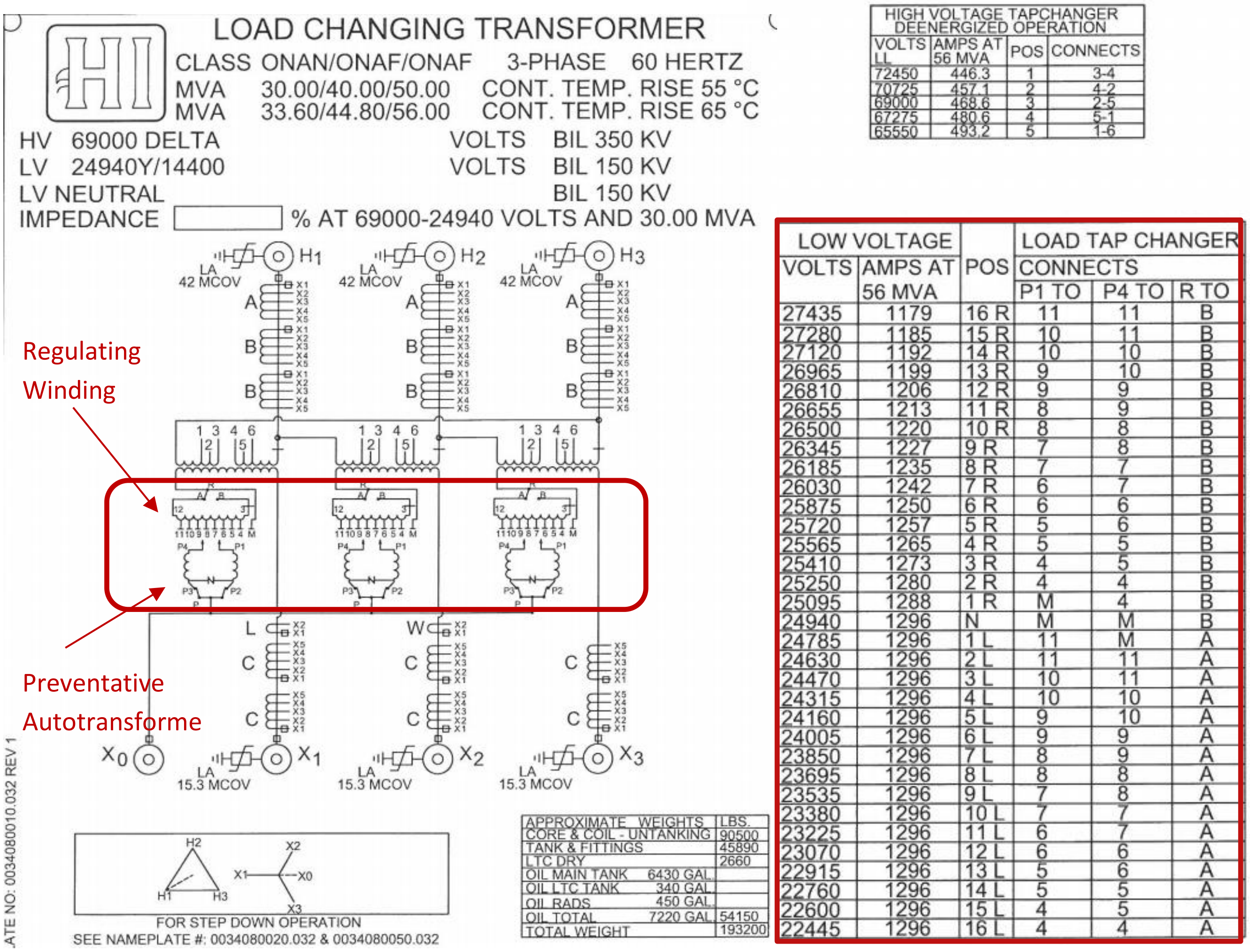

Figure 45: Case Study #3 - Transformer Nameplate

11.2 Exciting Current Results

The exciting current measurement was performed on the following LTC positions,

- 1L, N, 1R, 2R, 8R, 9R, 15R, and 16R

As can be seen by reviewing the LTC voltage table in Figure 45, these tap-positions include several non-bridging positions, several bridging positions, and the neutral position. For this particular LTC, the even positions are non-bridging positions and the odd positions are bridging positions. It is expected that the exciting current for the non-bridging positions is lower than the exciting current for the bridging positions. Also, since the power transformer under test has a Delta primary winding, the expected phase pattern is **high-low-high**.

The exciting current results are provided in Figure 46 and a summary of the analysis is provided below.

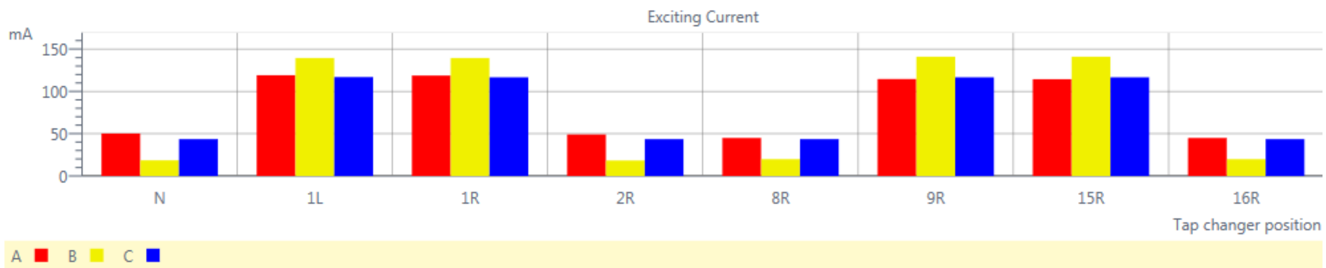

Figure 46: Exciting Current Results

- <u>Neutral Tap-Position (N):</u> The neutral tap-position is technically a non-bridging position, so the measured current should be lower relative to the bridging positions, which is the case. Also, the transformer produced the expected **High-Low-High** phase pattern in the neutral position. Therefore, the results for the neutral position are acceptable.

- <u>Non-Bridging Tap-Positions (2R, 8R, and 16R):</u> For the non-bridging positions, the measured current should be lower relative to the bridging positions, which is the case. Also, the transformer produced the expected **High-Low-High** phase pattern in all non-bridging positions. Therefore, the results for the non-bridging positions are acceptable.

- <u>Bridging Tap-Positions (1L, 1R, 9R, 15R):</u> For the bridging positions, the measured current should be higher relative to the non-bridging and neutral positions, which is the case. However, the transformer produced a **Low-High-Low** phase pattern in all bridging positions, which is not the expected phase pattern. Since the measured phase pattern deviates from the expected phase pattern, the exciting current measurements for the bridging positions are questionable. The exciting current for Phase-B is higher than expected, so a fault involving Phase-B should first be investigated.

Based on the results, the failure within the transformer is most likely associated with the preventative autotransformer. A defect involving the preventative autotransformer can typically only be detected when testing a reactive-type LTC in a bridging position, since a voltage potential is applied across the PA in the bridging positions. Typically, a fault involving the PA does not show itself when testing the transformer on the neutral and non-bridging positions, since there is zero potential applied across the PA windings in these positions.

Since the exciting current results for the neutral and non-bridging positions are acceptable, the fault is probably not associated with the main core, primary winding, secondary winding, and regulating winding of the power transformer. If the fault involved one or more of these components, then the issue would most likely also appear when testing in the non-bridging and/or neutral positions.

11.3 Exciting Current Voltage Tip-Up Test Results

To investigate the questionable exciting current results, the "exciting current voltage tip-up test" was performed on the 15R position to determine if the suspected failure was voltage sensitive. Note, since the exciting current results were questionable for all of the bridging positions, the voltage tip-up test could have been performed on any of the bridging positions. The exciting current voltage tip-up test was performed on Phase-A and Phase-B, where Phase-B is the phase under investigation, and Phase-A is the "reference". It was deemed unnecessary to perform the voltage tip-up test on Phase-C, since the Phase-C current should be approximately equal to the Phase-A current (as demonstrated by the results in Figure 46).

The exciting current voltage tip-up test was performed at 500V, 1kV, 2kV, and 10kV, and the results are provided in Figure 47. When the measurement is performed at 500V, the Phase-B current is lower than the Phase-A current, as expected; however, notice that, as the applied voltage increases, the Phase-B current increases relative to Phase-A. At voltages exceeding 1kV, the measured Phase-B current exceeds the Phase-A current, which is unexpected.

In general, the measured exciting current phase pattern should not change versus the applied voltage. The fact that the measured phase pattern changed versus the applied voltage provides further evidence that the transformer under test has a fault. Again, the fault probably involves the Phase-B preventative autotransformer.

Concluding, the offline electrical diagnostic tests outlined below were performed on the power transformer under test. All of the measurements, with the exception of the exciting current test, produced acceptable test results. In other words, the exciting current test was the only diagnostic test that detected the fault within the transformer. Thus, Case Study #3 demonstrates the importance of performing the exciting current test on a routine basis.

- Overall Power Factor – Pass
- Exciting Current – Fail
- Turns-Ratio Test – Pass
- Leakage Reactance – Pass
- DC Winding Resistance - Pass

Figure 47: Exciting Current Voltage Tip-Up Results (Phase-A and Phase-B Only)

12 References

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

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