ABSTRACT

In Part I of the article, the Indian practice (magnetic balance test) of detecting defects in the windings and in the core of a transformer in field conditions was considered. This Part II is devoted to IEEE practices.

KEYWORDS:

distribution transformer, excitation current test, IEEE, IEEMA, magnetic balance test, no-load loss at reduced voltage test, power transformer

The excitation current test consists of a simple open-circuit measurement of the current magnitude and loss, typically on the HV side of the transformer, with the terminals of the other windings are left to float

Simple ageless methods for field testing power transformers of no-load condition at the low induced voltage

(Analytical review with the aid of transformer field service technicians) – Part II

3. IEEE practice (excitation current test)

3.1. Historical aspect

According to the C57.93-2019 standard [13], the measure of transformer excitation current is one of 15 proposed tests during commissioning, the scope / list of which is determined depending on the equipment available and the importance of the particular transformer.

This test is often referred to simply as the Doble Test. As reported by Mark Lachman [14], the single-phase exciting-current test was introduced as a diagnostic tool in 1967 in Doble Engineering Company. In subsequent years, this test became more widespread, and in 1995 the test was the first included in the IEEE-1995 standard [15] (however, it had not yet been included in the IEEE-1978 standard). Note that the IEEE-1995 clause "6.1.3 Exciting Current" is only two pages long. Further development of American practice, especially after the works of Lachman [14, 16, etc.], led to a greater detail of the testing process. This detail was reflected in works Doble 72A-2244 Rev. A, 2000 [17] and repeated in 72A-2244-03 Rev. A, 2006. In the updated 2013 standard, clause "7.2.11 Excitation current" already contains six pages of text [1]. It is important to note that in the 2013 standard, in addition to measuring current, a loss measurement was also added.

In the years after 2013, Lachman and Shafir continue to theoretically and practically improve the diagnostic properties of this test. The inductive, capacitive, and resistive components of the current, the influence of the core / coil configuration on the measured current and losses are investigated, and the hardware implementation of new knowledge is carried out [18, 19, 20, 21, etc.].

3.2. The essence of excitation current test

The excitation current test consists of a simple open-circuit measurement of the current magnitude and loss, typically on the HV side of the transformer, with the terminals of the other windings are left to float (with the exception of a grounded neutral). The excitation current is measured at rated frequency and usually at voltages up to 10 kV, which is more than an order of magnitude more than in the

The uniqueness of each individual transformer, even of one type, is explained by the influence on excitation current of numerous parameters of transformer manufacturing: core and winding design

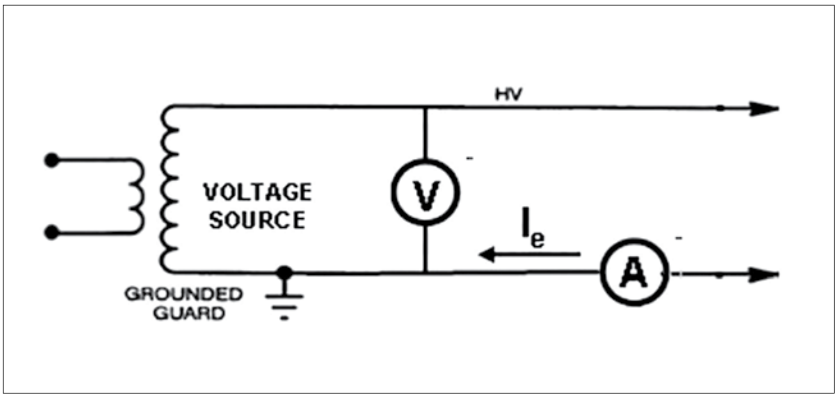
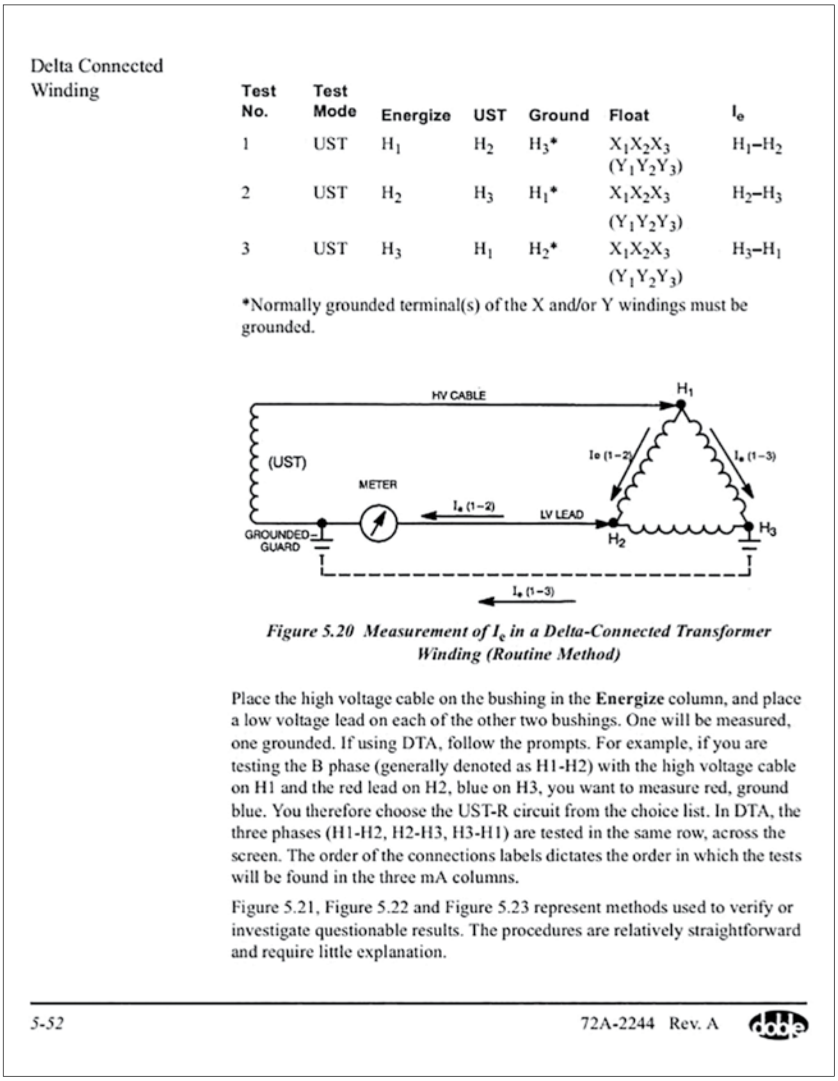


Figure 6. Basic measurement excitation circuit [1, 17]



Delta Connected Winding

Test No.	Test Mode	Energize	UST	Ground	Float	I_e
1	UST	H_1	H_2	H_3*	$X_1X_2X_3$ ($Y_1Y_2Y_3$)	H_1–H_2
2	UST	H_2	H_3	H_1*	$X_1X_2X_3$ ($Y_1Y_2Y_3$)	H_2–H_3
3	UST	H_3	H_1	H_2*	$X_1X_2X_3$ ($Y_1Y_2Y_3$)	H_3–H_1

*Normally grounded terminal(s) of the X and/or Y windings must be grounded.

Figure 5.20 Measurement of I_e in a Delta-Connected Transformer Winding (Routine Method)

Place the high voltage cable on the bushing in the **Energize** column, and place a low voltage lead on each of the other two bushings. One will be measured, one grounded. If using DTA, follow the prompts. For example, if you are testing the B phase (generally denoted as H1-H2) with the high voltage cable on H1 and the red lead on H2, blue on H3, you want to measure red, ground blue. You therefore choose the UST-R circuit from the choice list. In DTA, the three phases (H1-H2, H2-H3, H3-H1) are tested in the same row, across the screen. The order of the connections labels dictates the order in which the tests will be found in the three mA columns.

Figure 5.21, Figure 5.22 and Figure 5.23 represent methods used to verify or investigate questionable results. The procedures are relatively straightforward and require little explanation.

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Figure 7. Excitation current test Doble for delta connected winding transformer (scan from [18])

methods of MBT, GOST, FRA, and SFRA. This is an important advantage of the practice of IEEE since it makes it possible to detect defects in the active part of the transformer at an earlier stage of its development. Three-phase transformers are tested by applying a single-phase test voltage to one phase at a time.

The basic measurement scheme is shown in Fig. 6.

The excitation current magnitude depends on the transformer design (3 limb / 5 limb or triplex, star or delta, etc.) and is unique for each unit.

NOTE: The uniqueness of each individual transformer, even of one type, is explained by the influence on Excitation Current of numerous parameters of transformer manufacturing: core and winding design (stacking techniques, overlap distance, laminations per layer, magnetic flux density, lamination width for the wound-core, number of turns of low voltage) and natural vibrations annealing process (geometry of the core pile during annealing, thermal cycle, atmosphere of the furnace), mechanical process (liquid to lubricate cores before cutting, slitting process of lamination, handling of the electrical steel), operating conditions (impulse test, frequency, residual magnetism), magnetic material (lamination thickness, amorphous versus conventional material), assembly process (length of the air gap, core dimensions). Interested readers can read about it in more detail in article [22].

Reference [17] details the measurement circuit and test procedure for: single-phase transformer, single-phase autotransformer, three-phase wye connected winding, three-phase wye connected winding with no accessible neutral, delta connected winding (Fig.7), wye connected winding with the reverse method, delta connected winding with the reverse method, delta winding with the alternate method. As an

The IEEE practice, in contrast to the MBT and GOST methods, attaches great importance to the influence of tap-changer

example, Fig. 7 illustrates the test procedure for one of these options. The reader can find other options in those available in the public domain [17].

It is generally desirable to make all excitation current measurements on a given transformer at the same potential; however, there may be certain exceptions in the case of units equipped with a tap-changer. The IEEE practice, in contrast to the MBT and GOST methods, attaches great importance to the influence of tap-changer. When doing the test, it is useful to remember that the circuit breaker on the test set may trip if the impedance of the transformer is greater than the test set can handle, or it is a problem with the HV device's cable or it is caused by a fault in the transformer. When in doubt, the test is usually repeated, then repeated at a lower voltage and if the instrument / cables confirmed OK, the transformer has a problem.

Doble is constantly improving devices for its Doble Test Procedures, including the excitation current test. Thirty years ago, instead of the classic set of tools (voltmeter-ammeter-wattmeter), the Doble Test Set M2H was developed, then the more advanced M4000 Insulation Analyzer (http://userequip.com/files/specs/5380/Doble-M4000-User-Guide.pdf).

NOTE. It is emphasized that the M4000 performs PF measurements where interference may be an issue at frequencies of 47.5 and 52.5 Hz (Eastern Hemisphere), that is, slightly below and above the industrial frequency. The use of active filters can significantly reduce the level of interference (seven times at a frequency of 47.5 compared to 50 Hz). The arithmetic mean of two measurements is taken as the result, which quite well corresponds to the value that would be measured at a frequency of 50 Hz.

Currently, the M 4100 High Voltage Apparatus Tester is used with an increased test voltage up to 12 kV. The M4100 device is integrated with Doble Test Assistant Software to collect, analyse and manage test results (https://www.doble.com/product/dta-software/#).

Other devices can be used for excitation current test (TTRU3 and DELTA 4000 MEGGER, CPC 100 and TESTRANO 600 OMICRON, TRT30B DV Power, Vanguard EZCT-2000C, etc.).

In modern EHV transformers, inductive current can be comparable to capacitive current, and in some units it can be even lower

3.3. Evaluation criteria of excitation current test

According to the standard [1], the usual approach to the analysis of the excitation current test results is to compare the results with previous tests or with similar single-phase transformers, or with phases of a given three-phase transformer. For the great majority of three-phase transformers, the pattern is two similar high readings on the outer phases and one lower reading on the center phase (Fig. 8).

Two more patterns are described in [1] ("Low-High-Low" and "All three similar patterns"), but more recent studies by Doble ([18, 19, 20] and other) show the need for a more careful approach to these two, and to any other phase patterns. In modern EHV transformers, inductive current can be comparable to capacitive current, and in some units it can be even lower. The consequences can be unexpected current patterns.

In the early 1990s, Lachman investigated the effect of a tap-changer on the excitation current test and identified twelve patterns for tap-changer transformers [14, 16]. His work is the basis of Doble and IEEE's practice in evaluating the test results of transformers with DETC and LTC. The recommended initial tests include measurements at half of the LTC positions, the neutral position and one step in the opposite direction. The excitation current test allows you to assess the health of the unit as a whole (both the transformer and the tap-changer). The analysis of test results according to Doble depends on the presence of an LTC and on whether the test is an initial or a subsequent one. When an LTC is present, both the LTC pattern and the absolute value of the reading are evaluated. When an LTC is not present, only the absolute value of the reading is evaluated. The understanding of how the LTC affects the current magnitude of individual phases has also refined in ongoing Doble studies.

NOTE: Since the literature contains a lot of different, often contradictory opinions and interpretations about phase patterns, the author is forced to warn the reader about this, referring him to Supplement 2.

It is important to emphasize that in [1, 17] only qualitative indicators are given for evaluating the test results, but there are no specific figures. This corresponds to modern ideas about the assessment of this test.

Quantification is inevitable when comparing the measured current with the previous test. In the author's practice, a difference of 50 % or more has occurred with a clear defect in the transformer. But even much smaller differences can be evidence of damage. The reader will benefit from concrete examples. The ageless saying is true: "There is no substitute for experience" - see section 3.4 below.

3.4. Cases of faults in transformers

3.4.1. Missing turn [14]

The test results for the subject transformer are shown in Table 11. Comparison of results between phases and comparison of different tap positions in phase show a typical pattern 1 (two high equal values and one lower value) with the exception of position **1L** on phase **HI-H2**. In this position, the measured current is **18 mA**,

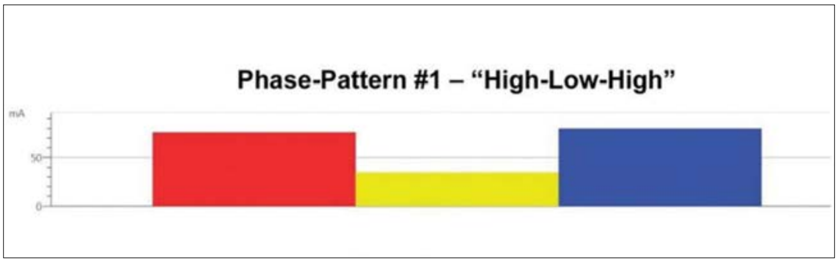

Figure 8. Example of an excitation current phase pattern

Excitation current pattern analysis can be helpful in the detection of the short-circuit turns of the three-phase transformer

Excitation current pattern analysis has also been used as an aid in the detection of the improper wiring of the preventative autotransformer 10 MVA, 69/23 kV

Excitation current pattern analysis is a simple method that can be used for the detection of a wide range of transformer faults

3.4.6. Damage with a scattering of copper and burnt insulation [14]

This transformer was taken out of service for LTC maintenance. The exciting current test results obtained after the maintenance are shown in Table 16. The expected pattern of two similar high readings and one lower reading was obtained in all the non-bridging positions. In the bridging positions, three dissimilar readings were obtained, with the highest reading in phase H2–H3. In all positions, the results were four times higher than the results for a similar transformer.

The internal inspection in the station showed a failed phase (H2-H3) on the preventative autotransformer with copper and burned insulation scattered around.

Table 15. The improper wiring of the preventative autotransformer 10 MVA, 69/23 kV [14]

Case II – Unit tested: 10 MVA, ∆/Y, 69/23 kV, 1991, DETC pos. 4

Before repair

LTC	TEST	MILLIAMPERES		
PSN	KV	H3-H1	H1-H2	H2-H3
1L	**10**	**195.0**	**48.3**	**55.2**
N	10	14.4	5.8	13.9
1R	10	196.4	48.2	55.3
2R	10	14.4	5.8	13.9
3R	10	196.6	48.3	55.3
4R	10	14.5	4.8	14.0
5R	10	197.0	48.3	55.3
6R	10	14.7	5.8	14.2
7R	10	197.2	48.4	55.4
8R	10	14.8	6.1	14.4
9R	10	197.4	48.7	55.7
10R	10	15.0	6.3	14.6
11R	10	198.0	49.0	55.9
12R	10	15.4	6.5	14.9
13R	10	198.8	49.0	56.4
14R	10	15.8	6.6	15.3
15R	10	199.0	49.1	56.6
16R	10	16.3	6.8	15.8

Power factor: C_H = 0.35 %, 2170 pF; C_L = 0.52 %, 12910 pF; C_{HL} = 0.24 %, 6590 pF;
TTR deviation from calculated value in bridging positions ranged: H_3-H_1 – 0.11–0.20 %, H_1-H_2 – 0.010–0.075 %, H_2-H_3 – 0.050–0.095 %,

After repair

LTC	TEST	MILLIAMPERES		
PSN	KV	H3-H1	H1-H2	H2-H3
1L	10	55.50	47.60	56.0
N	10	15.50	6.09	14.86
1R	10	55.50	47.40	55.60
2R	10	15.50	6.12	15.00
3R	10	55.70	47.50	55.60
4R	10	15.76	6.22	15.12
5R	10	55.90	47.80	55.90
6R	10	15.94	6.34	15.36
7R	10	56.10	48.00	56.30
8R	10	16.26	6.49	65.30
9R	10	56.40	40.01	56.30
10R	10	16.60	6.67	16.06
11R	10	57.0	48.20	56.50
12R	10	17.00	6.89	16.48
13R	10	57.20	48.40	57.30
14R	10	17.38	7.08	16.84
15R	10	57.40	48.60	57.50
16R	10	17.88	7.36	17.34

Power factor: C_H = 0.37 %, 2151 pF; C_L = 0.60 %, 12880 pF; C_{HL} = 0.29 %, 6570 pF;
TTR deviation from calculated value in bridging positions ranged: H_3-H_1 – 0.070–0.135 %, H_1-H_2 – 0.02–0.07 %, H_2-H_3 – 0.075–0.135 %,

When the transformer was untanked, it was obvious that copper and carbon from the failed autotransformer had spread throughout the entire unit. The failed phase in preventative autotransformer had shorted to the core steel causing an arc each time the LTC was in the bridging position. The main windings had no failures but were filled with copper beads from the failed autotransformer. A complete transformer rewind was authorized.

3.4.7. Excitation current after transformer failures in the field

Useful results excitation current tests after failures eight power rating 33.3–250 MVA, voltage rating 220–420 kV transformers in India are given in **Supplement 3.** The increase in this current after the damage is within very wide limits (from 1.3 to 580 times). Unfortunately, the source does not contain data on the design of the core and the group of connections of the windings.

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Table 16. Damage with a scattering of copper and burnt insulation in transformer 6.25 MVA, 34.4/5 kV [14]

Case III – Unit tested: 6.25 MVA, Δ/Y, 34.4/5 kV, 1960, DETC pos. 4				
Before repair				
LTC	**TEST**	**MILLIAMPERES**		
PSN	**KV**	**H3-H1**	**H1-H2**	**H2-H3**
1L	**4**	**347.0.0**	**360.0**	**408.0**
N	4	148.0	115.0	148.0
1R	4	344.0	360.0	409.0
2R	4	148.0	115.0	148.0
3R	4	344.0	360.0	408.0
4R	4	148.0	115.0	148.0
5R	4	344.0	360.0	408.0
6R	4	148.0	115.0	148.0
7R	4	594.0	698.0	755.0
8R	4	147.0	116.0	148.0
9R	4	345.0	361.0	405.0
10R	4	147.0	114.0	148.0
11R	4	347.0	361.0	406.0
12R	4	149.0	115.0	149.0
13R	4	347.0	361.0	406.0
14R	4	147.0	114.0	149.0
15R	4	347.0	361.0	406.0
16R	4	147.0	114.0	148.0

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Supplement 1. MBT transformers of Grempton Greaves Ltd. [10]

Voltage applied to	Voltage measured in Volts			The total voltage induced in the other two phases
	A - N	B - N	C - N	
Autotransformer 100 MVA 220/132/11 kV				
A - N	221 (100 %)	212 (95.9 %)	9 (4.1 %)	100 %
B - N	114 (51.8 %)	220 (100 %)	107 (48.6 %)	100.4 %
C - N	9.6 (%)	212 (95.5 %)	222 (100 %)	105.1 %
Autotransformer 100 MVA 220/132/11 kV				
A - N	230 (100 %)	224 (97.4 %)	8 (3.5 %)	100.9 %
B - N	118 (51.3 %)	230 (100 %)	108 (47.0 %)	98.3 %
C - N	8 (3.5 %)	224 (97.4 %)	230 (100 %)	100.9 %
Current, mA	1.87	0.81	1.63	
Autotransformer 150 MVA 220/132/11 kV				
A - N	237 (100 %)	227 (95.8 %)	10 (4.2 %)	100 %
B - N	118 (49.8 %)	237 (100 %)	116 (48.9 %)	98.7 %
C - N	12 (5.1 %)	225 (94.9 %)	237 (100 %)	100 %
Current, mA	2.63	2.01	2.55	
System transformer 60 MVA 220/34.6/11 kV				
A - N	229 (100 %)	219 (95.6 %)	9 (3.9 %)	99.5 %
B - N	124 (51.1 %)	225 (100 %)	99 (44.0 %)	95.1 %
C - N	10 (4.4 %)	213 (94.2 %)	226 (100 %)	98.6 %
System transformer 62.5 MVA 132/33/11 kV				
A - N	230 (100 %)	219 (95.2 %)	7 (3.0 %)	98.2 %
B - N	115 (49.8 %)	231 (100 %)	111 (48.1 %)	97.9 %
C - N	11 (4.8 %)	216 (93.5 %)	231 (100 %)	98.3 %
Current, mA	1.03	0,79	0,92	
Autotransformer 100 MVA 220/132/11 kV				
A - N	240 (100 %)	224 (93.3 %)	14 (5.8 %)	99.1 %
B - N	120 (49.8 %)	241 (100 %)	117 (48.5 %)	98.3 %
C - N	15 (6.2 %)	227 (93.8 %)	242 (100 %)	100 %
Current, mA	1.13	0.86	1.08	

Supplement 2. Obsolete but still widely accepted notions of an excitation current phase pattern

The author has attempted to briefly generalize these notions in this annex.

The most common phase pattern # 1 is "High-Low-High" because transformers with a 3-limb core-form design and HV winding connected in delta or wye (with neutral available) are the most common. This pattern is also characteristic of a transformer with a five-limb core-form (or shell) with a delta-connected secondary winding (Fig. 1). "High-Low-Low" phase pattern #2 is expected for transformers with a 3-limb core-form design and wye (without accessible neutral) HV winding and with. "Low-High-Low" phase pattern #3 is expected in the following cases: when the power transformer is damaged; when the third terminal on a delta-connected transformer has not been grounded (Fig. 2); is not uncommon for distribution transformers and for transformers that produce.

«All three similar» pattern expected for a five-limb core-form (or shell) transformer with a non-delta secondary winding. This pattern is also typical for three single-phase transformers connected as a three-phase transformer. The excitation current difference from this pattern in some single-phase transformer could be caused by a potential problem.

There are three most common types of tap-changers:

1. De-energized tap-changer (DETC) pattern: the measured exciting current typically increases or decreases linearly versus tap-position.
2. Resistive load tap-changer pattern: the measured exciting current typically increases or decreases linearly versus tap-position.
3. Reactive load-tap changer pattern: the measured exciting current typically fluctuates versus tap-position due to the excitation of the preventative autotransformer. It is expected that the bridging tap-positions produce higher currents for all three phases relative to the non-bridging tap-positions.

Fig. 3 provides an example of these three tap-changer patterns.

The literature often cites (and is contained in the document [29]) the obsolete Doble statement about quantifying test results for a three-phase transformer star / delta or delta / star (*Quote*): "Doble software only gives two indications on this test: "G" for good and "Q" for questionable. On a three-phase, wye / delta or delta / wye transformer test, the excitation current pattern will be two phases higher than the remaining phase. Compare the two high-

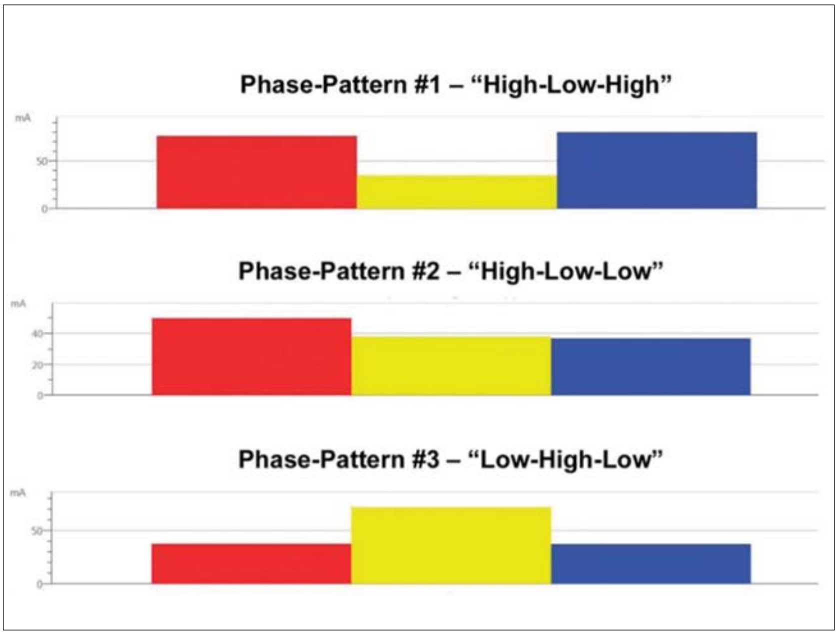
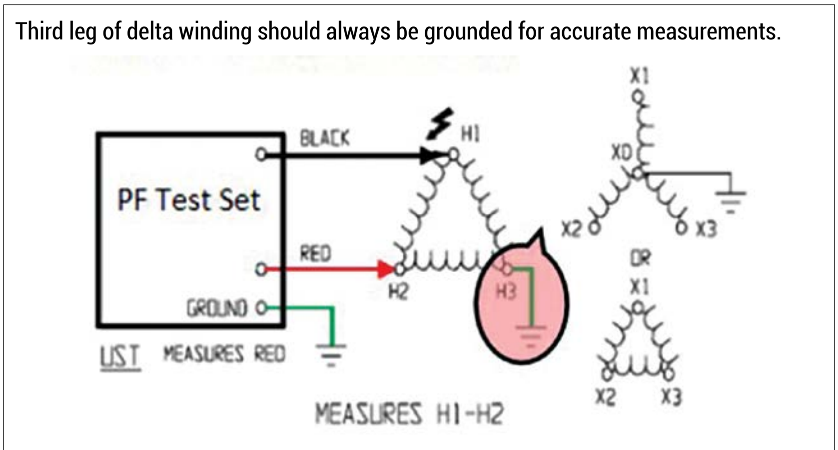


Figure 1. Example of an excitation current phase pattern (figure from OMICRON, explanations in the text)



Wdg H1-H2	With third leg grounded	Without third leg grounded
Voltage (kV)	Excitation current (mA)	Excitation current (mA)
6	82.35	114.46
7	94.49	132.06

Pending the inductance and resistance of each winding, if third leg is not grounded, the results would be approximately 30–50 % higher than true readings.

Figure 2. Ungrounded third leg of delta winding increases the excitation current by 30-50 % (figure from Megger)

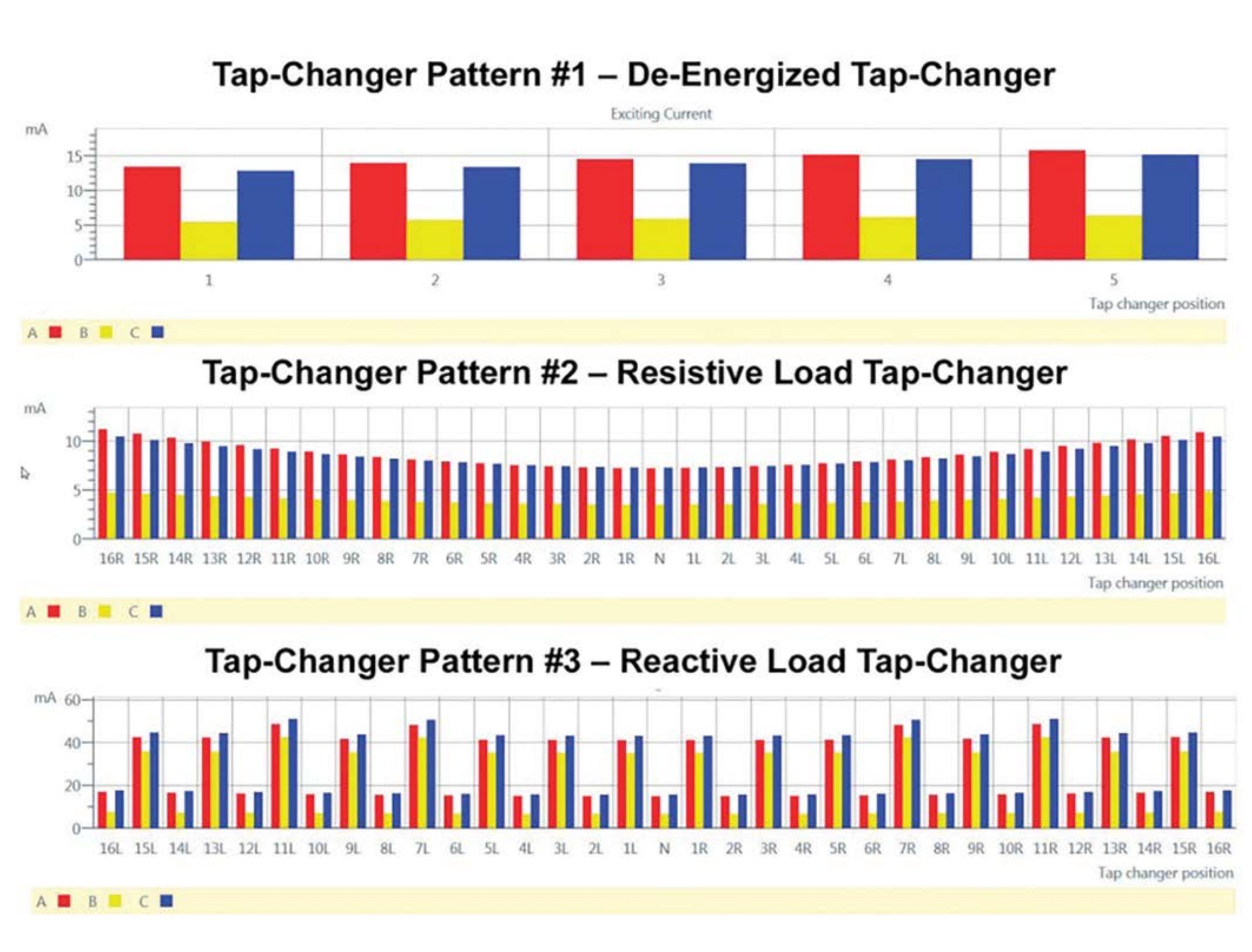


Figure 3. Example of the three tap-changer patterns (figure from OMICRON).

er currents only. If the excitation current is less than 50 milliamps (mA), the difference between the two higher currents should be less than 10 %. If the excitation current is more than 50 mA, the difference should be less than 5 %. In general, if there is an internal problem, these differences will be greater. When this happens, other tests should also show abnormalities, and an internal inspection should be considered. The results, as with all others, should be compared with factory and prior field tests." Doble has removed this requirement as out of date.

In the literature, there are useful, according to the author, tips for unclear results of the excitation current test: repeat the test when changing the polarity of the connection, carry out the test by applying voltage to the LV winding, repeat the test starting from a very low voltage (compared to 10 kV) and increase the voltage in steps 1–2 kV to the maximum allowable for the device or transformer.

Supplement 3. Details of tests after transformers failure in India

(https://cea.nic.in/old/reports/committee/failure_equipment/failure_03022017.pdf)

1. *Failure of 220/33 kV, 100 MVA.* Transformer tripped on differential relay, Buchholz relay, PRD, and SPRV. Magnetizing current in Y-phase was found to be 1.06 A which is very high as compared to 3.6 mA in R-ph and 3.5 mA in B-ph. The fault is most likely in Y-phase of the winding. A detailed investigation after the opening of the tank will provide the extent of the damage.
2. *Failure of 100 MVA, 220/66–33/11 kV.* The subject transformer tripped on the following indications: Buchholz (Trip), Differential (87 Ta & Tc). From the measurements of magnetizing currents:

HV side (1 Ph supply)		MV side (1 Ph supply)	
Magnetising current test		Magnetising current test	
I_{RN}	**9.1 mA**	I_{RN}	**310 mA**
I_{YN}	5.4 mA	I_{YN}	160 mA
I_{BN}	6.8 mA	I_{BN}	190 mA

It is observed that magnetizing current in R phase HV and MV winding is much higher than in the other two phases, which indicates that there might be inter-turn fault in R-phase winding.

3. *Failure of 100 MVA, 220/33/11 kV*. Details of last periodic maintenance are as follows:

Tap	HV			LV			TV		
	R-(mA)	Y-(mA)	B-(mA)	R-(mA)	Y-(mA)	B-(mA)	RY-(mA)	YB-(mA)	BR-(mA)
5	1.9	1.6	1.7	41.0	30.0	40.2	72.5	100.6	99.4

The transformer tripped on differential, REF, PRV, Buchholz and sudden pressure relay. Transformer oil spilled around the transformer. Details of tests done after failure indicate an inter-winding fault in the R-phase:

In mA

Tap	HV			LV			TV		
	R	Y	B	R	Y	B	RY	YB	BR
5	**590**	2.8	3.8	23800	43.5	44.7	106.7	107.4	47000

4. *Failure of 100 MVA, 220/66 kV.* Transformer was running on no-load after annual maintenance, tripped off, and oil spilled out from the main tank of the transformer. Magnetizing current test:

	R	Y	B
HV	430 mA	**890 mA**	430 mA
LV	4.2 A	8.5 A	4.28 A

Results of the test and physical inspection indicate faults involving Y-phase.

5. *Failure of 33.3 MVA, 220/√3//110/√3//11 kV, 1-phase transformer of 100 MVA transformer.* The transformer tripped on differential protection and on Buchholz alarm on B-phase unit. There was heavy lightning and rain during the time of failure. Excitation current test – HV-N exciting current is high with distorted waveform while on LV side could not be tested as the test kit was tripping on overcurrent. Fault in the windings near neutral end is possible. The transformer has been in service for about 38 years.
6. *Failure of 250 MVA, 15.75/220 kV.* Ground fault relay, differential relay, Buchholz relay, tap-changer overvoltage relay has tripped. The transformer caught fire. The LV tests on the faulty (magnetic balance, turns ratio test, magnetizing current measurement and insulation resistance were conducted. Y-phase of LV winding indicates shorted turns.
7. *Failure of 207 MVA, 21//400/√3 kV.* After overhaul, when energized / increased voltage electrical protection and Buchholz relay triggered. The side turret of the LV was deformed, oil spilled. During testing LV side magnetizing current was found **26.5 mA** as against the pre-commissioning value of **8 mA.**
8. *Failure of 250 MVA, 15/420 kV, 3-ph generator transformer.* During the synchronization, the unit tripped with sound. Sequence event recorder indicates that the GT PRD, overall differential relay, Buchholz stage-II had operated. Oil spillage was observed from PRD. Magnetising current test after failure:

HV side (applied voltage - 246.2 volts)

TAP 1	
RN	1.192 mA
YN	1.231 mA
BN	**1740 mA**

LV side (applied voltage – 30 volts)

TAP 1	
ry	29.09 mA
yb	29.05 mA
br	12.51 mA

Magnetizing current (**1740 mA** in B-phase which is very high) indicate that inter-turn fault might have taken place in phase B.