ABSTRACT

The low voltage supply to one transformer winding and measurement of voltage, current, and losses in different phases when other windings are open have long been used to assess the condition of the core and windings during commissioning, during periodic preventive maintenance (operational tests), during diagnostics, tests after an accident and after repair. These simple procedures are performed offline and are often critical in determining the health of the transformer and, in some cases, locating the fault in the transformer. These methods do not lose their importance in the 21st century. The article historically describes the practices of India, IEEE, and GOST, which differ from each other. For the convenience of technicians, numerous examples are given.

KEYWORDS:

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

Power transformers are key components of the electrical network and require special attention during commissioning and operation

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)

1. Introduction

Power transformers are key components of the electrical network and require special attention during commissioning and in operation. The importance of correctly assessing the condition of a transformer is becoming increasingly important. Already during transport of the transformer from the factory to the place of installation, the transformer may be subjected to mechanical shock exceeding the recommended "g" level. Increasing network complexity, increasing generating capacity, aging transformers reduce their ability to withstand external influences and increase costs in the event of transformer failure due to subsequent extensive outages. Insufficient attention to transformers maintenance can exacerbate the problem. Optimal maintenance means minimizing the cost and time of field tests while obtaining reliable information on the condition of the transformer.

Under external influences on the transformer, failure in the electromagnetic circuit or / and may occur in the insulation: displacement and / or deformation of the windings, damage to the insulation turn-to-turn, layer-to-layer, disk-to-disk, loosening of the compaction of the windings and / or core, displacement and / or deformation of the core, the occurrence of closed loops in the core (core lamination shorts, insulated bolts, pressing bolts, pressing metal rings), loosening of electri-

Turn-to-turn damage is the most difficult damage to a transformer winding, especially if the damage initially affects only one turn

cal connections, reduction in dimensions between the active part and the tank, problems with the tap-changer device (LTC or DETC).

Turn-to-turn damage is the most difficult damage to a transformer winding, especially if the damage initially affects only one turn. An initial breakdown of the insulation leads to internal sparking, which causes a short circuit with low current and high resistance. Then this turn-to-turn fault will propagate randomly, capturing additional turns and layers of the winding for possibly months or even years until it turns into a high-current fault with low resistance, which in turn will lead to fatal short circuits in the windings (Figs. 1, 2) and as a result, the transformer protection will automatically disconnect it from the mains.

One of the other types of transformer faults that can be detected by field testing of no-load condition at low voltage is shown in Fig. 3.

Figure 1. Shorted turn-to-turn (Source: testguy.net)

Figure 2. Damage due to short circuit between the winding discs (Source: http://www.nov-electro.com/2013/foto-transformator-plant)

Regular tests and comparison of measurement results allow timely detection of the faults as mentioned earlier, analysis of trends, and prevention of future failures by stopping transformers for further repair.

The traditional method for detecting damage to windings and cores is the no-load test of a three-phase transformer (usually below rated voltage) with one-, two- or three-phase excitation. To detect defects, voltages, currents, and no-load losses (also called "losses in steel") or only two or one of them are measured:

- Magnetic balance test (MBT) – Indian practice
- Excitation current test – IEEE practice [1]
- No-load test at reduced voltage - the practice of GOST [2]

According to the MBT and IEEE, as a rule, the HV winding is excited, according to GOST, the LV winding, but this is not of fundamental importance because defects in non-excited windings (e.g., a turn-to-turn short-circuit) are also detected by these tests.

In the last quarter of the 20th century, more sophisticated methods of detecting damage to windings and cores (FRA and SFRA [3, 4]) have been developed and are becoming more widespread. But according to the author, these modern methods cannot completely replace simple, cheap traditional methods of offline testing of transformers without load at low voltage. These new methods are not always used in factories (for example, they are not used when testing low-power and distribution transformers). They are more "capricious" in implementation, require fingerprints, and highly qualified personnel to evaluate the test results. In addition, the old methods in most cases make it possible to check the absence of defects in three-phase transformers even in the absence of fingerprints by comparing the measurements in phases.

The tests must be carried out in sunny weather (at lower humidity) on a transformer with clean and dry bushings so

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there is no need for temperature correction of measurement results.

Next, we will consider the old traditional methods in a historical aspect in order of increasing complexity.

NOTE about terms related with the excitation current: In the United States, the terms "exciting current" and "single-phase exciting current" have been used since 1967. In 2002 the term "excitation current" was standardized. In IEEE-2013 [1] it says: "the excitation current test, also known as the single-phase excitation test." ANSI / NETA uses the term "excitation-current test" (through a hyphen). In OMICRON and DV-POWER - first "exciting current measurement", then replaced by "excitation current measurement." In No. 445 CIGRE - "magnetising current". In India - "magnetizing current test" (IEEMA [5]). In GOST - "no-load current at reduced voltage."

Figure 3. The so-called "fire in steel" (Source: Ibragim Murataev, Russia)

2. Indian practice

2.1. The essence of the magnetic balance test

According to the Indian Electrical & Electronics Manufacturers Association (IEEMA), MBT is included in the list of Site Acceptance Tests [5].

MBT (Magnetic Balance Test) is not in IS (Indian Standards), but besides [5], the test is described in the manual Central Board of Irrigation and Power (CBIP, clause B.6 [6]).

According to P. Ramachandran, the MBT was invented about half a century ago by some Indian engineer to test the operation of a distribution transformer in the field, when a 430 V power supply and a simple voltmeter were available anywhere, but there were no thinner tools like a milliammeter, etc. The test is the simplest possible and gives good results when troubleshooting core and windings. Later in India, the test was extended to all types of transformers. In addition to India, the test is popular in the Gulf countries and is used in Algeria, Egypt, Iran, and Saudi Arabia. In South Africa, Nigeria, and other countries in the Eastern Hemisphere, it is mainly used for malfunctions during transformer operation. The test is briefly described in the popular book Kulkarni ([7], section 2.5.2).

MBT is a check (balancing) of the magnetic flux distribution in a three-phase transformer. There are three limbs in the core of the transformer located side by side. One phase winding is wound on one limb. The voltage induced in different phases depends on the corresponding position of the bend in the core. If voltage is applied to only one phase of the winding (for example, to phase A), then only branch A of the transformer will create a magnetic flux. The flux passing through legs B and C will induce a voltage across the winding placed on these legs (Fig. 4), with a higher voltage on phase B. But the sum of the voltages induced across phases B and C must be equal to the voltage applied to phase A (Fig. 4). This is proof that the transformer is magnetically balanced.

Briefly, the MBT procedure is as follows. First, hold the on-load tap-changer of the transformer in the normal position. Now disconnect the neutral of the transformer from the ground. Then apply single-phase 230 AC power to one of the HV winding terminals and neutral. Measure the voltage at the other two HV terminals with respect to the neutral terminal. Repeat the test for each of the three phases.

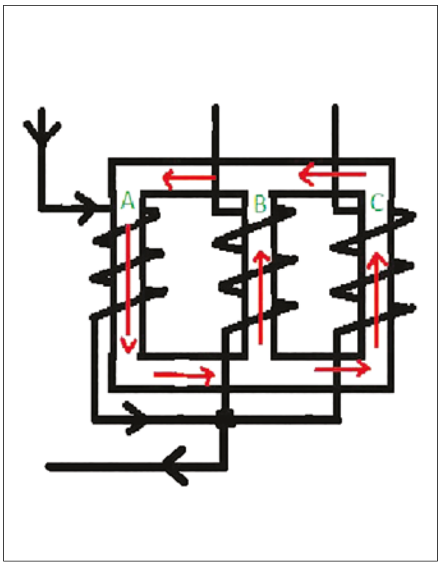

Figure 4. Schematic diagram of the MBT

MBT is a check (balancing) of the magnetic flux distribution in a three-phase transformer, it is very simple, and it gives good results when troubleshooting core and windings

The voltage induced in the centre phase is generally 40-90 % of the applied voltage on outer phases, but it depends on the design features or manufacturing technology

The voltage distribution depends on the geometry of the core, and ideally, the relationships shown in Table 1 should be respected.

In this test, no winding terminal should be grounded; otherwise, results would be inconsistent and confusing. The test shall be performed before winding resistance measurement. The test voltage shall be limited to the maximum power supply voltage available at the site.

Real voltage distributions in transformers differ from those indicated in Table 1 and depend on the design features and manufacturing technology of the transformer, for example, due to some differences in air gaps in the joints of the core, etc.

According to CBIP [6] the voltage induced in the centre phase is generally 40-90 % *(before 26 July 2019, was 50-90 %)* of the applied voltage on outer phases. However, when the centre phase is excited, then the voltage induced in the outer phases will be 30–70 % of the applied voltage. These values will vary depending on the grade of core material used and the rated voltage of the winding. These values are only for reference and should not be considered limiting values. Note that the last two offers were added on 26 July 2019 instead of the excluded offer "zero voltage or very negligible voltage with higher excitation current induced in the other two windings should be investigated."

The voltage that is normally supplied to the HV winding in wye is 230 V, and for the delta winding 440 V. Sometimes 120 V voltage is applied. Typical examples of the actual voltage distribution for MBT are shown in Tables 3 and 4.

Other typical examples of voltage distribution for MBT in transformers without defects are given in Annex 1 [10]. It is also useful to look at [Online], available at https://www.allinterview.com/showanswers/70196-3/core-magnetic-balance-test-transformer-three-phase-star-delta-lv-hv-measure-rega.html

2.2. Residual magnetism

There is almost always residual magnetism in the core, which in most cases does not significantly affect the test results. Substantial / significant residual magne-

Table 1. Theoretical distribution of voltages at MBT

Voltage applied to	A - N	B - N	C - N
Left phase	100 %	67 %	33 %
Central phase	50 %	100 %	50 %
Right phase	33 %	67 %	100 %

Table 2. Distribution of voltages at MBT according to CBIP [6]

Voltage applied to	A - N	B - N	C - N
Left phase	100 %	(40–90) %	(60–10) %
Central phase	(30–70) %	100 %	(30–70) %
Right phase	(60–10) %	(40–90) %	100 %

Table 3. MBT on transformer 25 MVA, 220/11 kV before DC winding resistance measurement test (DC test). The HV winding in wye [8]

Voltage applied to	Measured voltage in Volts			The total voltage induced in the other two phases
	A - N	B - N	C - N	
A - N	226 (100 %)	174 (76.9 %)	55 (24.3 %)	101.3 %
B - N	115 (50.8 %)	226 (100 %)	111 (49.1 %)	100.0 %
C - N	56.7 (25.1 %)	172 (76.3 %)	226 (100 %)	101.4 %

tism (for example, as is often the case from DC winding resistance measurements) can cause an imbalance in the MBT.

As an example, Table 5 shows the results of measurements of the MBT of the same 25 MVA, 220/11 kV transformer as in Table 3, but after measuring the resistance of the windings to direct current [8].

As you can see from Tables 3 and 5, the DC test resulted in a complete unbalance of the MBT.

Residual magnetism also causes higher excitation current and no-load losses at low voltage, changes in TTR and SFRA. In addition, residual magnetism can create large inrush currents. The only reliable method of eliminating the remanence effect is to demagnetize the transformer core.

IEEMA and CBIP do not specify how to demagnetize the transformer. The IEEE and GOST demagnetization methods are presented below as excerpts from these standards.

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2.2.1. Demagnetization according to IEEE [1]

Two techniques can be used to demagnetize the transformer core. The first method is to apply a diminishing alternating current to one of the windings. For most transformers, due to the high voltage ratings involved, this method is impractical and involves safety hazards. A more convenient method is to use direct current. The principle of this method is to neutralize the magnetic alignment of the core iron by applying a direct voltage of alternate polarities to the transformer winding for decreasing intervals. The interval is usually determined when the demagnetizing current reaches a level slightly lower than the previous level, at which time the polarity of the voltage is reversed. The process is continued until the current level is zero. On three-phase transformers, the usual practice is to perform the procedure on the phase with the highest excitation current reading. In most cases, experience has demonstrated that this procedure is sufficient to demagnetize the whole core.

2.2.2. Demagnetization according to GOST [2]

If it is possible, then the test of no-load at low voltage should be performed after removing the residual magnetization by smoothly removing the voltage from the nominal to the minimum.

Residual magnetization can be removed by a series of consecutive passes through the windings of a DC transformer of opposite polarities. The direct current from which the demagnetization process begins must be at least twice the no-load current of the transformer. In this case, each subsequent value of the direct current must be 30-40 % less than the previous one.

The current at which the demagnetization process ends should not be greater than

Residual magnetization can be removed by a series of consecutive passes through the windings of a DC transformer of opposite polarities

Table 4. MBT on transformer for HV winding in delta [9]

Voltage applied to	Measured voltage in Volts			The total voltage induced in the other two phases
	A - B	B - C	C - A	
A - B	400 (100 %)	284.4 (71.1 %)	114.5 (28.6)	99.7 %
B - C	188.4 (47 %)	401 (100 %)	211.4 (52.7 %)	99.7 %
C - A	104.3 (25.9 %)	297.0 (73.9 %)	402 (100 %)	99.9 %

Table 5. Transformer 25 MVA, 220/11 kV. MBT after DC test [8]

Voltage applied to	Measured voltage in Volts			The total voltage induced in the other two phases
	A - N	B - N	C - N	
A - N	233 (100 %)	202 (86.7 %)	**32 (13.7%)**	100.4%
B - N	**151 (64.8 %)**	233 (100 %)	**80.1 (34.41%)**	99.2%
C - N	54.7 (23.5 %)	179 (76.8 %)	226 (100%)	100.3%

Applying voltage to the LV winding is more efficient for MBT because the higher voltage is induced across the HV winding

the RMS current value expected in the open-circuit test at low voltage.

Demagnetization is carried out by passing a current through one of the windings of each of the rods of the magnetic system.

Modern test equipment allows automatically measuring MBT (for example, WA 2293 Haefley, TRT DV Power) and demagnetizing the transformer (WA 2293 Haefely, DEM60C, DEM60R, and TWA500 DV Power, CPC 100 and TESTRANO 600 OMICRON, Power DB form 56000 and TTRU3 MEGGER et al.).

2.3. Evaluation criteria of MBT

When commissioning transformers, it is important to have the results of the office at the factory. The main criterion should be considered the coincidence of the MBT results with the factory data. According to IEEMA ([5, clause 4.3.5. h]), acceptance criteria are (quote):

- "The identical results confirm no damage due to transposition.
- Zero voltage or very negligible voltage induced in any of the other two phases shall be investigated.
- The applied voltage may be expressed as 100 % voltage, and the induced voltage may be expressed as a percentage of the applied voltage. This will help in comparison of the two results when the applied voltages are different.
- The voltage induced in the centre phase shall be 50–90 % of the applied voltage.
- However, when the centre phase is excited, then the voltage induced in the outer phases shall be 30–70 % of the applied voltage.
- Zero voltage or very negligible voltage induced in the other two windings should be investigated."

It is recommended to use literature data in addition to IEEMA criteria. The most popular article about MBT (both in India and abroad) is the work of Vishal Mahire [8], which describes the practice of using MBT at a manufacturing plant.

In contrast to the previously accepted practice of supplying voltage to the HV winding, the author [8] rightly notes the higher sensitivity of the method when the LV winding is excited (with the exception of furnace and rectifier transformers). Applying voltage to the LV winding is more efficient because higher voltage is induced across the HV winding. In addition, the parasitic influence of the magnetic materials of the tank and frame, which is significantly reduced.

It should be noted that in Rajasthan, one of the largest states in India, it has been established that MBT is carried out on transformers 765, 400, 220, and 132 kV only when voltage is applied to the LV or TV windings [11].

In some cases, the voltage distribution across the phases already at the factory may differ significantly from that indicated in tables 1–5. For example, mixing different steels causes a serious imbalance in the MBT. This is sometimes seen with distribution transformer manufacturers. For example, Table 6 shows the total voltage in the unexcited phases is 20–25 % less than the expected value of 100 %. Having received such a result, the plant began to look for the cause, disassembled the transformer, and removed the windings. Having found no defects in the core or windings, the transformer was reassembled, but the MBT practically did not change. After consulting with authors of this article, it was determined that the rocker arm and limb are a mixture of steels from different suppliers.

Vishal Mahire notes that in the case of large autotransformers, the total voltages at the extreme phases exceed the applied voltage by 5–10 % and sometimes by 30–35 % (Table 7). This is caused by the parasitic influence of the magnetic materials of the tank and frame.

Vishal Mahire gives examples of defect detection by the MBT method, for example, closed loop in the B limb (Table 8). With this defect, a very low voltage was measured on phase B (less than 2 %).

Two interesting examples of MBT efficiency are described in [12]. The 90 MVA 132/33 kV transformer and the 240 MVA 275/132/33 kV autotransformer were taken out of service due to malfunctions. All tests carried out on site clearly showed that there were no deviations other than MBT.

In the case of large autotransformers, the total voltages at the extreme phases exceed the applied voltage by 5–10 % and sometimes by 30–35 %

Table 6. Imbalance MBT on the transformer 100 kVA 33/0.4 kV due to the mixing of steels (source: Shashivendra Shukla, India)

Voltage applied to	Measured voltage in Volts			The total voltage induced in the other two phases
	A - N	B - N	C - N	
A - N	255 (100 %)	148 (58 %)	42 (16 %)	190 (**74 %**)
B - N	111 (44 %)	255 (100 %)	96 (38 %)	207 (**81 %**)
C - N	34 (13 %)	158 (62 %)	255 (100 %)	192 (**75%**)

Table 7. Magnetic balance test an autotransformer 315 MVA 400/220/33 kV. Parasitic influence of the magnetic materials of the tank and frame [8]

Voltage applied to	Measured voltage in Volts			The total voltage induced in the other two phases
	3A – 3C	3B – 3A	3C – 3B	
3A - 3C	239.2 (100 %)	238.3 (99.6 %)	75.2 (31.4 %)	**131.1 %**
3B -3A	124.0 (52.1 %)	238.2 (100 %)	114.8 (48.2 %)	100.2 %
3C - 3B	80.2 (33.4 %)	236.2 (99.2 %)	238.1 (100 %)	**132.9 %**

Some defects in the windings, for example, an inter-core circuit, are not detected by the MBT, so the MBT method should be supplemented by measuring the magnetizing current

On a 90 MVA transformer, the MBT, when voltage was applied to phase B, showed an abnormal voltage distribution at the extreme phases (34.78 and 67.70 % - see Table 9). However, measuring the winding resistance, checking the insulation power factor, SFRA, and leakage reactance showed no abnormalities.

The transformer was disassembled, the HV winding was removed. It turned out that 6 cores out of 19 cores of the upper part of the HV winding were short-circuited (Fig. 5).

MBT in autotransformer is shown in Table 10. The total voltage induced in 2 phases was well below 100 %. Other tests such as voltage factor, SFRA, impedance test, winding resistance, insulation power factor, IR test, excitation current at 230 V show that the transformer is in absolutely satisfactory condition. Then it was decided to test the excitation current

Figure 5. Bunched conductor (inter conductor) fault [12]

Table 8. Magnetic balance test a transformer of 50 MVA, 220/33 kV, YNyn0 connected. Closed loop in the B limb [8]

Voltage applied to	Measured voltage in Volts			The total voltage induced in the other two phases
	A - N	B - N	C - N	
A - N	239.0 (100 %)	**4.6 (1.92 %)**	233.8 (87.8 %)	99.4 %
B - N	118.6 (49.8 %)	238 (100 %)	119.0 (50.0 %)	99.8 %
C - N	233.4 (97.8 %)	**3.47 (1.45 %)**	238.3 (100 %)	99.5 %

Table 9. MBT in transformer 90 MVA, 132/33 kV. Winding damage [12]

Voltage applied to	Measured voltage in Volts			The total voltage induced in the other two phases
	A - N	B - N	C - N	
A - N	100 %	94.52 %	6.26 %	100.78 %
B - N	**34.78 %**	100 %	**67.70 %**	102.48 %
C - N	3.70 %	96.87 %	100 %	100.57 %

Table 10. MBT in autotransformer 240 MVA, 275/132/33 kV. Winding damage [12]

Voltage applied to	Measured voltage in Volts			The total voltage induced in the other two phases
	A - N	B - N	C - N	
A - N	232.7 (100 %)	118.1 (50.8 %)	84.6 (36.4 %)	**87.2 %**
B - N	134.1 (57.8 %)	231.8 (100 %)	98.9 (42.7 %)	100.5 %
C - N	73.66 (31.9 %)	125.4 (54.3 %)	230.8 (100 %)	**86.2 %**

at a higher voltage of 5 and 10 kV, which revealed a problem in the winding.

But some defects in the windings, for example, an inter-core circuit, are not detected by the MBT. Therefore, the MBT method is often supplemented by measuring the magnetizing current. Using both methods together is a reliable diagnostic test for detecting faults.

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Author

Vitaly Gurin graduated from Kharkov Polytechnic Institute (1962) and graduated from school at the Leningrad Polytechnic Institute. Candidate of technical sciences in the Soviet scientific system (1970). For 30 years, he tested transformers up to 1.150 kV at ZTZ, including the largest one of that time in Europe, and statistically analysed the test results. For over 25 years, he was the Executive Director of Trafoservis Joint-Stock Company in Sofia (the diagnosis, repair and modernisation in the operating conditions of transformers 20–750 kV). He has authored about 150 publications in Russian and Bulgarian and is the main co-author of GOST 21023.