Transformer handling and transport

Damages that may arise and how to identify them

ABSTRACT

Transformer handling and transport may result in damages to the transformer that sometimes may even lead to transformer failure. This article analyses the damages transformers suffer due to handling and transportation that are considered most harmful to the equipment. The article identifies the types of damage and their causes, outlining special tests which should be performed during Factory Acceptance Tests and Site Acceptance Tests to help detect the non-visible damages that may have occurred.

KEYWORDS

impact, vibrations, IEC standards, distortion, bushings

1. Introduction

Severe damage may be caused to transformers when they are subjected to challenging transport conditions such as troubled sea during sea transportation, or a rough road during road transportation.

Although it is known that transportation under these conditions will cause vibrations and small shocks in packages and equipment, it is also known that if packaging and fixing of the equipment are not suitably performed, the amplitude of those vibrations and shocks can cause non-visible damages which can further lead to a failure of the equipment [1, 2].

It must be emphasized that this paper does not intend to be an in-depth document on these problems because they are generally known; however, as it is unfortunately still a frequent scenario that transformers arrive to site with visible and/or concealed damages caused by improper packing, handling or transportation procedures, the article sets out to reiterate these issues and raise awareness of the procedures aimed at preventing them from happening.

For this reason, it cannot be stressed enough how important it is to draw the attention of manufacturers, logistics and transportation companies, contractors and transformer owners to this issue and the respective consequences.

In order to prevent the cases that lead to damage and destruction, it is necessary to perform some special tests during Factory Acceptance Tests (FAT), such as those defined in IEC Standard 60076-1 [3], IEEE C57.12.90 [4], IEEE C57.152

[5] and IEC 60137 [6]), and then repeat them during Site Acceptance Tests (SAT) whenever the conditions of handling and transportation indicate any potential damage.

Recommended special tests for this purpose include the following:

- Measurement of frequency response analysis (SFRA) (see section 3)
- Measurement of tan δ (dielectric losses) of the bushings (see section 3)
- Determination of capacitances between windings and windings to earth
- Measurement of DC insulation resistance between windings and windings to earth
- Measurement of DC insulation resistance core to earth and core frame to earth
- Single-phase excitation current tests
- Magnetic balancing tests

The test results obtained during FAT and SAT must be compared and conclusions about possible damage to the transformers must be drawn.

Although a reference has been made to both IEC and IEEE standards, IEC stand-

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Figure 1. Scratches in the protective surface coating of a transformer tank

The test results obtained during FAT and SAT must be compared in order to draw conclusions about possible damage to the transformers

ards make the basis for this article considering they are international standards used worldwide; compared to IEEE standards which are U.S. standards used only in a few countries.

2. Problems and damages

Transformers with high rated power and for voltages above 123 kV are usually transported without the oil (their tank being filled with nitrogen or dry air), and without the bushings, the conservator and the cooling equipment. Mechanical shocks above design limits, or about 3 g (g standing for gravitational acceleration of approx. 9.8 m/s^2, and 3 g being the force equivalent to three times the gravitational acceleration) may cause visible and/or concealed damages to transformers such as the following:

Visible damages include, but are not limited to, scratches in the surface protective coating and finishing of the tank, whether they are just hot-dip galvanization or painting, which sooner or later will lead to corrosion (see Figure 1), leaks of nitrogen, and external cracks and chips, even contamination, in the bushings.

Common **concealed damages** inside the transformer, which can negatively impact the reliability of the transformer and whose consequences may become apparent only after an indefinite time upon energizing, include:

- **Geometrical distortion of the winding/core.** Due to the movement of the active part, the insulation between the turns can be abraded, causing a short circuit and damage to the windings that may occur later during operation;
- **Loss of coil clamping pressure.** Mechanical vibrations may cause the windings to lose their clamping pressure, eventually leading to collapse of the windings during electric faults;
- **Contamination of the oil** (resulting from the degradation of windings insulation);
- **Safe clearance** between the tank and the active part may be compromised;
- **Unintentional grounding** of core or core frame that can cause gassing during operation.

Apart from physical damage, incorrect packing and certain transportation procedures can cause other types of damage, namely contamination of oil or of the windings insulation with water, moisture, dust and other contaminants. These contaminations will result in premature aging of insulation materials, meaning that their dielectric strength will be reduced with the corresponding decrease of useful life of the transformer and/or severe failures.

In order to investigate whether transformers have been subjected to excessive mechanical impacts, it is recommended to use **impact (or shock) recorders** during transformer transportation to evaluate the **magnitude** of these *mechanical shocks* (Figure 2).

3. Tests for detecting mechanical damages

IEC standard 60076-1 [3] defines special tests that can be used to identify potential damages resulting from excessive mechanical impacts or some type of contamination. These tests are the following:

- Measurement of frequency response analysis (SFRA)

To assess and monitor the potential damage, it is recommended to use an impact recorder and perform a range of tests during FAT and SAT, comparing the results obtained at both stages

- Measurement of tan δ (dielectric losses) of the bushings
- Determination of capacitances windings to earth and between windings
- Determination of DC insulation resistance between windings and windings to earth

This standard also defines testing procedures and acceptance criteria.

To evaluate the possibility of internal cracks or contamination in transformer bushings, **tan δ test** must be performed to detect the dielectric losses of the insulation material, also known as the *dissipation factor*. However, while the current passing through an ideal insulator is totally capacitive (I_C), real insulators do not have 100 % purity. This means that the current passing through the insulator has also a resistive component (I_R), indicating that the insulator has losses which are represented by tan δ, δ being the angle shown in Figure 3.

Resistive current results from impurities or damages in the insulator and the dielectric strength is inversely proportional to this current.

From the plot in Figure 3 the following is obtained:

$$tan\,\partial = \left| \frac{I_R}{I_C} \right| \quad (1)$$

Hence, with the increase of I_R the losses will increase as well, meaning that the dielectric strength of the insulator will decrease.

Figure 2. An example of an impact recorder *(Photo courtesy of Mobitron)*

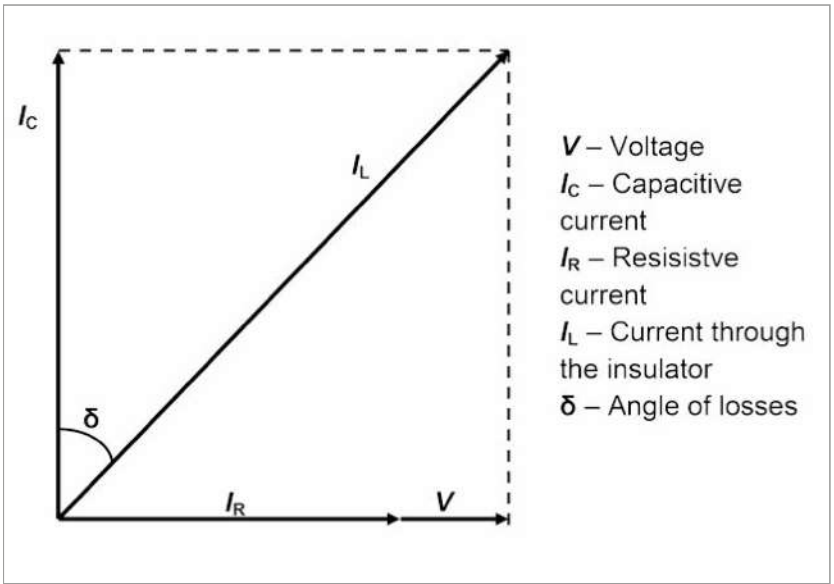

Figure 3. Angle of losses and currents passing through the insulator

Reference standards define special tests that can be used to identify potential damages caused by excessive mechanical impacts or some type of contamination

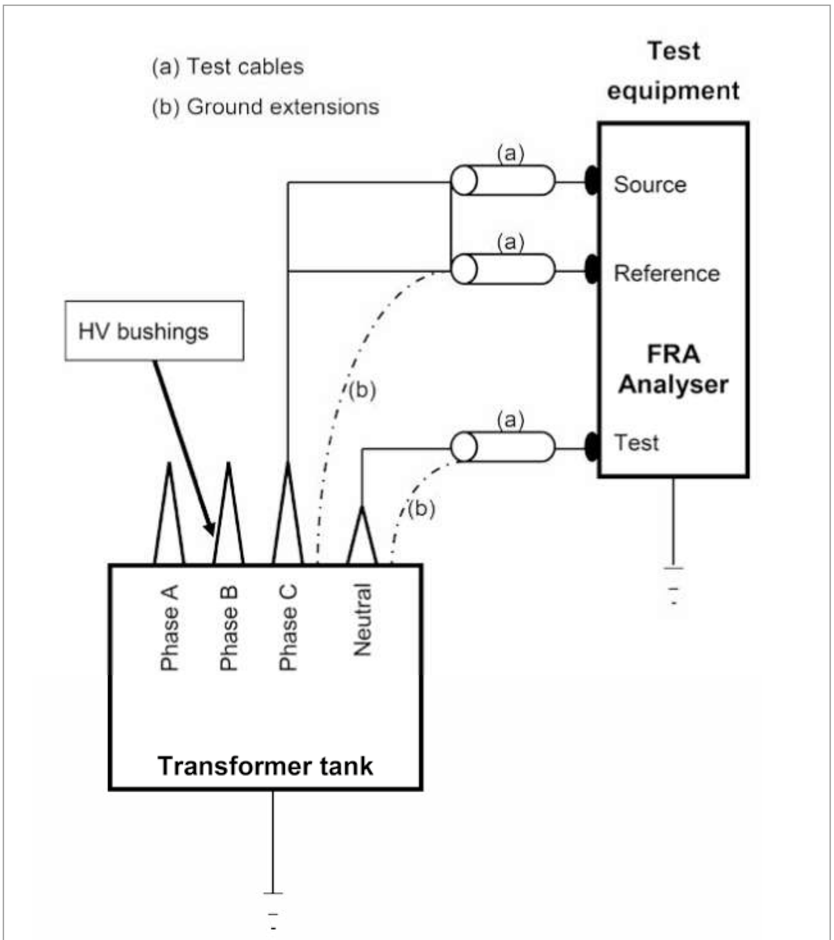

Figure 4. SFRA test

To detect possible damages in the transformer core or windings which have occurred due to an impact greater than what is acceptable, a **Sweep Frequency Response Analysis test (SFRA)** must be performed.

In colloquial language, SFRA is also referred to as *DNA* (deoxyribonucleic acid) or the *finger print* of the transformer. Each winding and the core present a unique frequency response and when sweep frequencies are applied to the transformer, a particular *signature* is produced.

It is important to understand that transformers with the same voltage ratio and rated power, constructed in the same way and using the same materials in the core, windings and insulation, will have a similar and a very close *signature* to sweep frequencies, but not identical – a fact that is considered important.

SFRA test is performed by applying an excitation signal to the transformer in the frequency range of **±5 Hz to ±2 MHz**. The connections for this test are illustrated in Figure 4.

The applied frequencies ranging from **±5 Hz to ±5 kHz** indicate the impact of the core, as well as its magnetization and the residual flux. The frequencies in the range of **± 5 kHz to 500 kHz** show the effect of the relation between the windings and their relative radial and geometrical movements. The frequencies above **500 kHz** indicate the impact of axial movements of the windings and of the internal connection circuits.

However, according to the reference standard used in this paper, the test procedure should be agreed upon between the manufacturer and the purchaser.

The tests measuring the capacitances windings to earth and **capacitances between the windings, and DC insulation resistance between windings and windings to earth** provide important information about possible damage of the windings in case the transformer has been subjected to excessive mechanical impacts.

The capacitances windings to earth and capacitances between the windings are measured to determine the *dissipation*

The test procedures should be agreed upon between the manufacturer and purchaser

factor of the insulation material of the windings. Similar to what was referred to above, an increase of dissipation factor represents a decrease of dielectric strength of the mentioned insulation material.

DC insulation resistance tests are used to measure the insulation resistance between windings and from each individual winding to earth, which is usually calculated from the measured applied voltage and the measured leakage current.

4. Other tests

There are other tests that may also be used to investigate possible damages in a transformer resulting from incorrect handling and transportation procedures, particularly when the special tests prescribed by IEC standard 60076-1 [3] have not been performed during FAT. However, it must be noted that these tests are based on standards that may not be used by all entities involved in the transformer installation (namely the owner, the manufacturer and the contractor), and that they are not necessarily as accurate and reliable as the ones specified by IEC, and which have been discussed above.

DC insulation resistance core to earth and core frame to earth test (not defined in IEC standard 60076-1 [3], either type, routine or special) is similar to the measurement of DC insulation resistance between windings and windings to earth, and may be used to investigate if any damage has occurred, typically whether the core is grounded due to excessive mechanical impacts. According to IEEE C57.12.00 [7], this test is considered to be a routine test for power transformers and a special test for distribution transformers.

Single-phase excitation current test is usually performed during the manufacturing stage and typically used as a basis for diagnosis of secondary windings faults (short circuits and open circuits), eventual core earthing and other fabrication defects. However, in terms of the faults in the windings and core, whenever more accurate tests, namely the SFRA test, were not performed, this test may also be used to detect possible problems on those components.

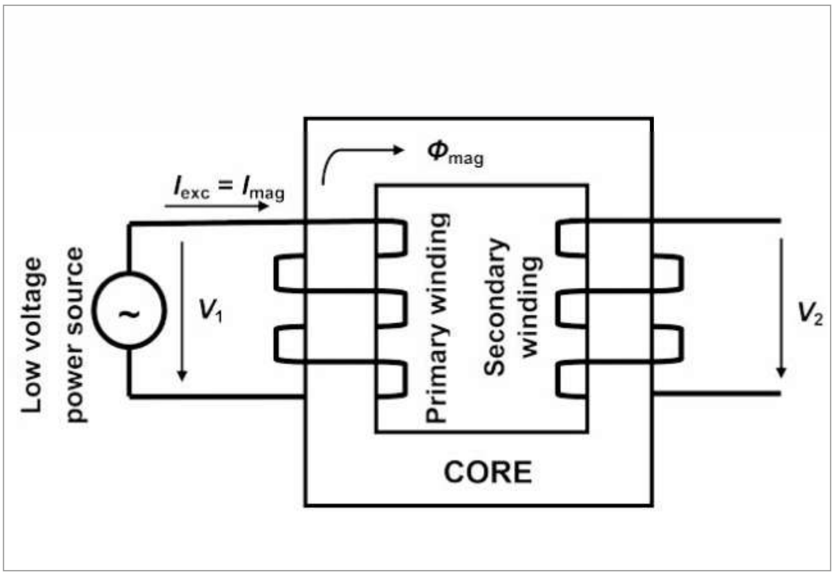

Figure 5. A simplified diagram of the single-phase excitation current test

The basic principle of this test is to apply a low voltage V_1 (usually 400/230 V) on the primary terminal of the transformer: a small current will flow through the excited winding – the **magnetizing current** (I_{mag}), which is the current required to magnetize the core of the transformer and force a magnetic flux – the **magnetizing flux** (Φ_{mag}) – to circulate in the core. If the secondary is open, only a low current is necessary for the magnetic flux to enter the winding and induce a voltage in the secondary which can be referred to as V_2. This low current is the **excitation current** (I_{exc}) of the transformer. Comparing the off-load excitation currents measured at FAT and SAT, if the difference between them is bigger than the tolerance defined in the standards, then there is a strong probability that a defect has occurred in the windings (primary and/or secondary). Figure 5 illustrates this through a simplified diagram.

To identify if the defect is in the secondary winding, the following theoretical principle is used. If a load, requiring a current IL is applied in the secondary, that load has a reluctance that opposes to the move-

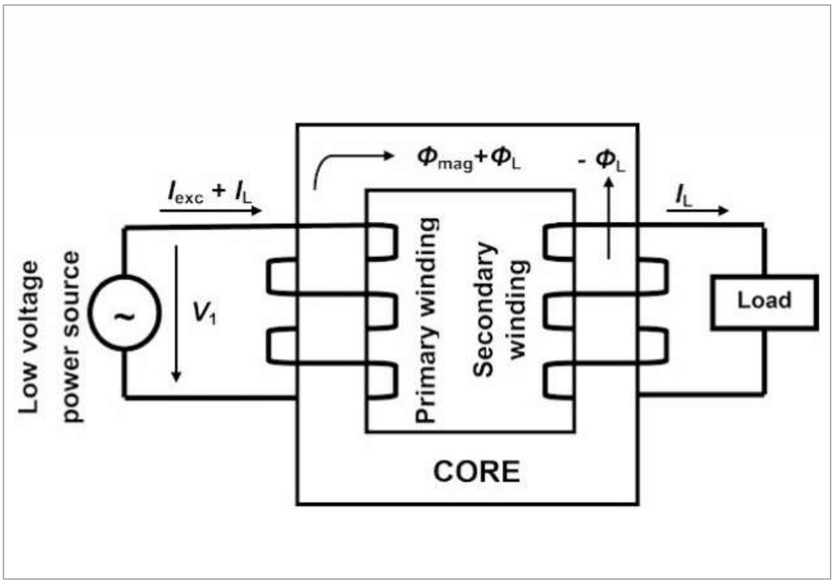

Figure 6. Currents in the transformer with a load in the secondary

The test results should inform the decisions on whether additional tests and/or an internal inspection are needed before the transformer is energized

ment of the magnetic flux in the core. Hence, the current in the primary will increase I_L to overcome that reluctance. This situation is shown in Figure 6.

When the transformer has no load in the secondary and there is a short circuit between the turns of the secondary winding, or this winding has a fault to the ground, by applying a low voltage in the primary, the transformer acts as if the load is connected. Hence, the measured excitation current is higher than it should be.

If the *pattern of the excitation current* is not regular, this may indicate a problem in the core or that there are masked problems which are not possible to identify.

Both the DC insulation resistance core to earth and core frame to earth and single-phase excitation current measurement tests must be performed in accordance with IEEE C57.12.00 [7].

Magnetic balance test is another test used to assess any defects in the turns of the windings (e.g. faults in the insulation of the turns, de-shaping of the windings, etc.) or in the core (e.g. loosen nuts and bolts, failure in the stacking of the laminated sheets, external loops around the core, abnormal magnetizing current caused by faults in the turns of the windings, etc.). This test is usually performed on MV/MV and MV/LV transformers during the manufacturing stage or on site as a pre-commissioning test, but is generally not used for large HV/HV transformers (HV, MV and LV standing for high, medium and low voltage, respectively).

The common procedure for this test is to apply a low voltage (400-231 V, 50 Hz or 60 Hz) between two phases (e.g. phases A and B – V_{AB}) and then measure the voltages between phases B and C (V_{BC}) and phases A and C (V_{AC}) to compare the results.

Under normal circumstances, with no defect in the transformer, this should be equal to the following:

$$V_{AB} = V_{BC} + V_{AC} \quad (2)$$

In case there is a problem in the transformer, then the calculation will probably come to:

$$V_{AB} \neq V_{BC} + V_{AC} \quad (3)$$

The disadvantage of this test is that the results obtained are merely indicative and they themselves do not confirm there is a defect in the transformer, so additional tests must be performed to verify that a real problem exists.

Conclusion

Transformer handling and transportation may cause internal damages to the transformer and transformer components, or possibly lead to contamination of the insulating medium. To assess and monitor the potential damage, it is recommended to use an impact recorder and perform a range of tests during FAT and SAT, comparing the results obtained at both stages. The results of these tests should inform the decisions on whether additional tests and/or an internal inspection are needed on site or at the factory before the transformer is energized.

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