Winding resistance measurement is a standard test performed on transformers

ABSTRACT

The winding resistance measurement requires extended time. According to IEC 60076-1 and IEEE C57.12.90 standards, the test should be performed using DC test current on all phases of the high voltage, low voltage, and tertiary sides, and for all tap positions. Speeding up this measurement is very attractive. This paper presents two approaches to transformer saturation: increasing the test current, and a special connection of the windings to increase the number of turns. The presented case study shows the difference between the regular test procedure and a modified one.

KEYWORDS

transformer testing, winding resistance measurement, transformer saturation, test current, resistance stabilization

Acceleration of LV winding resistance measurement

A case study of an efficient measurement method

1. Introduction

Winding resistance measurement is a standard test performed on transformers. The test accuracy is very important in order to obtain a correct condition assessment of transformers. The measurement is performed using the four-wire (Kelvin) direct current (dc) method. The current through the circuit is established once the dc voltage is applied to the winding under test. This current creates the magnetic flux in the transformer magnetic core. This process is slow due to the inductance

of the transformer (L) which acts as a damper and slows down the process. It is important to understand that the correct value of a winding resistance cannot be measured until the current and the inductance become stable, since these values change at the beginning of the measurement process.
The voltage on the winding terminals is as follows:

$$U = R \cdot I + \frac{d\Phi}{dt} \quad (1)$$

$$U = R \cdot I + \frac{dL \cdot i(t)}{dt} \quad (2)$$

$$U = R \cdot I + L(i,t) \cdot \frac{di(t)}{dt} + i(t) \cdot \frac{dL(i,t)}{dt} \quad (3)$$

where R is the winding resistance, I is the test current, L is transformer inductance, $\frac{di(t)}{dt}$ is change of current (equal to zero if the current is stable), and $\frac{dL(i,t)}{dt}$ is change of inductance (equal to zero if the transformer is saturated).

2. Transformer saturation

Transformer core saturation will reduce the transformer inductance L, thus reducing the measurement time. The time needed for transformer saturation depends on the magneto-motive force (MMF).
The MMF ($\mathcal{F}$) is defined as:

$$\mathcal{F} = N \cdot I \quad (4),$$

where N is the number of winding turns, and I is the test current through the winding.
According to (4), it is easy to notice that the magneto-motive force can be increased by increasing the current value, or number of the winding turns, or both.
Winding resistance measurements of the transformer's LV (low-voltage) side may take a long time, especially if the LV windings are connected in delta (triangle) configuration. The time needed for the winding resistance measurement of large transformers can exceed 30 minutes per phase. Delta winding connection, where the current flows through all three phases, causes the long resistance stabilization time. Another reason for the long measurement time is a small number of winding turns on the LV transformer side, requiring a very high current to reach the core saturation.
As previously described, the resistance measurement of LV windings can be accelerated by saturating the core in one of the two ways:
- using a higher test current value I,
- increasing the number of turns N.

3. Higher test current value

To perform an accurate winding resistance measurement in a reasonable time, the transformer core should be saturated. The nominal current value through the transformer's LV winding is usually very high. Generally, based on our experience, it is necessary to perform the measurement with the minimum test current value of 1-5 % of the transformer nominal current to achieve transformer saturation. For example, generator step-up transformers may have nominal current values of 20,000 A on the LV side. In most cases, a portable test set cannot generate 1-5 % of that current. Additionally, using a high test current requires thicker and heavier test cables.

4. Higher number of winding turns

Using the HV winding turns in the test current loop, as an additional help for transformer saturation, will increase the total number of turns, Fig. 1.

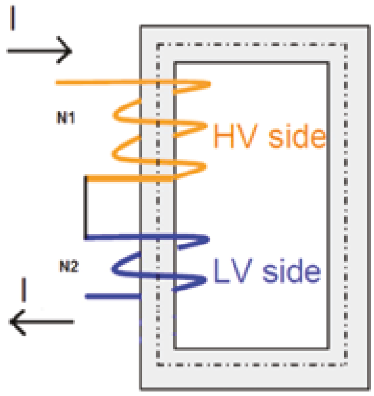

Figure 1. Using HV and LV winding in series to increase the number of turns in the current loop

In this case the magneto-motive force will be:

$$\mathcal{F} = (N_1 + N_2) \cdot I \quad (5)$$

where N_1 is the number of winding turns on the HV transformer side, and N_2 is the number of winding turns on the LV transformer side.
The HV transformer winding contains significantly higher number of turns compared to the LV winding. Injecting the test current through the HV and LV winding will significantly increase the magneto-motive force, thus getting the transformer into saturation faster and significantly reducing the measurement time.

To perform an accurate winding resistance measurement in a reasonable time, the transformer core should be saturated

5. Case study

In this case study, the winding resistance measurement of the LV transformer side of a GSU transformer (whose nameplate is presented in Table 1) is performed in two ways:

- injecting a high current value through the LV winding only
- injecting a lower current value through the HV and LV windings connected in series to increase the number of turns

Table 2 provides information on the testing devices used in these measurements.

The first measurement was performed using the conventional method; connecting the test device between two phases of the transformer LV windings. The intention was to use as high test current value as possible (but not higher than 10 % (according to IEC 60076-1) or 15 % (according to IEEE C57.152) of the nominal current to avoid heating of the winding and thus influence the resistance value). The test current value of 100 A was applied, which is about 1 % of the transformer LV rated current.

Figure 2 illustrates the test current flow and the flux directions in the magnetic core when the winding resistance measurement is performed using a high current injected only through the LV winding.

In the second measurement approach, the HV windings are used as an additional aid to achieve faster saturation. The connection may be established in such a way that the current flows through the HV and the LV winding under test, located on the same transformer core leg. Since the HV winding contains many more winding turns compared to the LV winding, the magneto-motive force is increased significantly. The turns ratio of this particular transformer is 21 (420 kV/20 kV), hence the HV winding has 21 times more turns than the LV winding. Optionally, for the HV wye (Y) connection, the test current can be injected through all three phases of the HV side (A, B, and C). The current source of the measuring device (the ⊕ output of the instrument source) is connected to the phases A and C. The phase B (HV side) is connected to the phase b (LV side) while the returning path is established through the phase a (of the LV side) that is connected back to the source (the ⊖ output of the source). This way the magnetic flux distribution through the core legs is established as presented in Figure 3.

It is very important to establish the current through the HV and LV windings in such

Table 1. Test object information

Transformer type	Generator step-up
Nominal power	400 MVA
Nominal voltage	420 / 20 kV
Nominal current	550 / 11533 A
Vector group	YNd5

Table 2. Test instruments

	Device	Comment	Cables
Model 1	RMO100TT	Single-phase portable device with max test current of 100 A	Thick/heavy
Model 2	TWA40D	Three-phase portable device with max test current of 25 A per phase	Normal/light

The HV transformer winding contains significantly higher number of turns compared to the LV winding

a way that it creates the flux through the corresponding transformer core leg in the same direction – boosting the flux. The flux created from the HV side supports the flux created by the LV side and reduces significantly the stabilization time, Fig. 4.

In this way, in case of YN configuration, the complete magnetic core of the transformer is saturated. The flux created by the current through the HV side will boost the flux created by the LV side d (delta) in all three core legs.

6. Measurement results

6.1 Test 1

The test was performed according to the diagram in Figure 2. The test current of 100 A was used for the LV winding resistance measurement between transformer terminals a and b (measuring Rab). The result stabilization process is plotted in Figure 5. The expected resistance value was 1.135 mΩ. Ten minutes into the measurement process, the resistance value decreased to 1.165 mΩ, which was still not the stable value. The resistance value would have slowly decreased to 1.135 mΩ, which would have lasted another 15 minutes or more.

6.2 Test 2

This test approach was performed according to the diagram in Figure 4. The test current of 25 A was injected (which is a four times lower current than in Test 1), but the HV side was used to saturate the trans-

The transformer saturation using the HV winding connected in series with the corresponding LV winding speeds up the test process

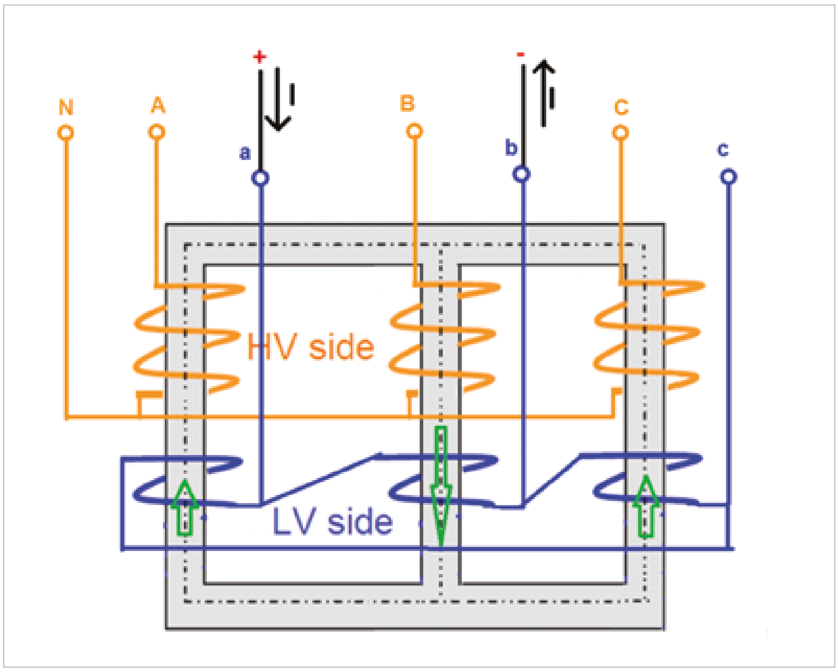

Figure 2. Diagram of LV winding measurement (green arrows represent magnetic flux)

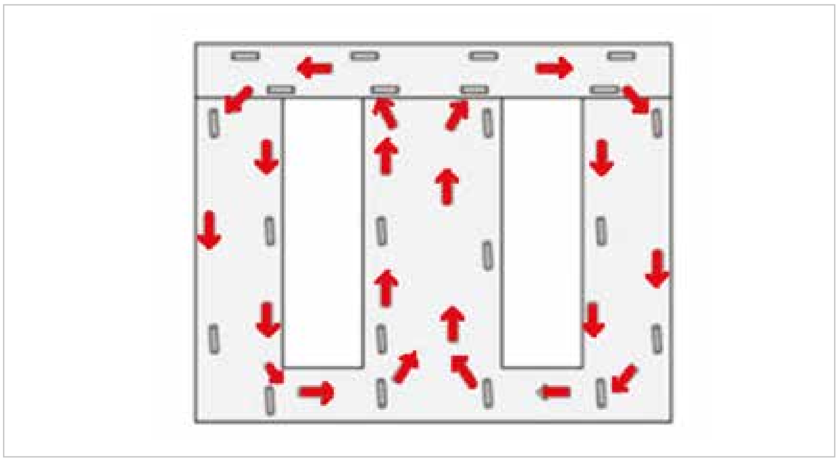

Figure 3. Flux distribution in the transformer core during normal transformer operation

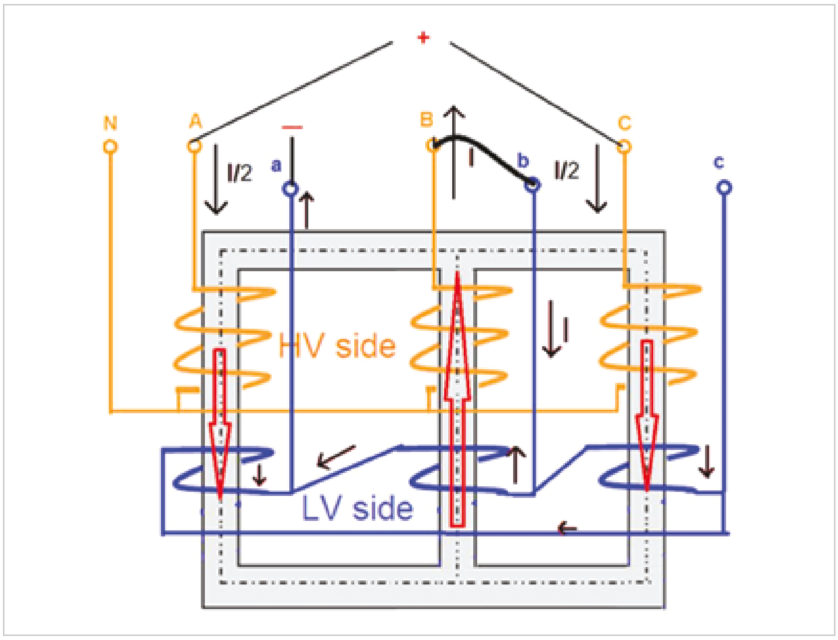

Figure 4. Diagram of HV and LV winding turns connected in series to increase the number of turns in the current loop (red arrows represent total flux flow)

> **Using a high test current requires thicker and heavier test cables**

former. In this way, 21 times more winding turns of the same phase was applied, plus a contribution of the other two phases with half of the current value each – equalling about 42 times more ampere turns. In this approach, the measured resistance value of 1.135 mΩ was established after only four minutes, as seen in Fig. 6. The graphs in Figures 5 and 6 are presented with the same vertical axis scale to provide a better visual indication of the speed, and the difference of the stabilization process time.

Based on the transformer vector group, the three phase TWA test instrument automatically defines the appropriate internal connection to establish a current through the HV and LV windings to get the magnetic flux in correct direction through the corresponding transformer core leg. In addition, only one-time test-cables setup is needed. It saves additional time of the test procedure by internally connecting the HV phase B and LV phase b terminals.

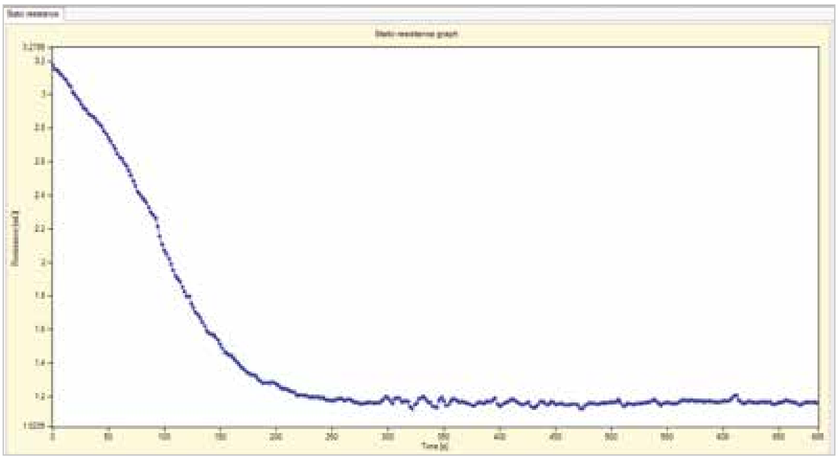

Figure 5. The winding resistance stabilization graph (the current flows through the LV winding only)

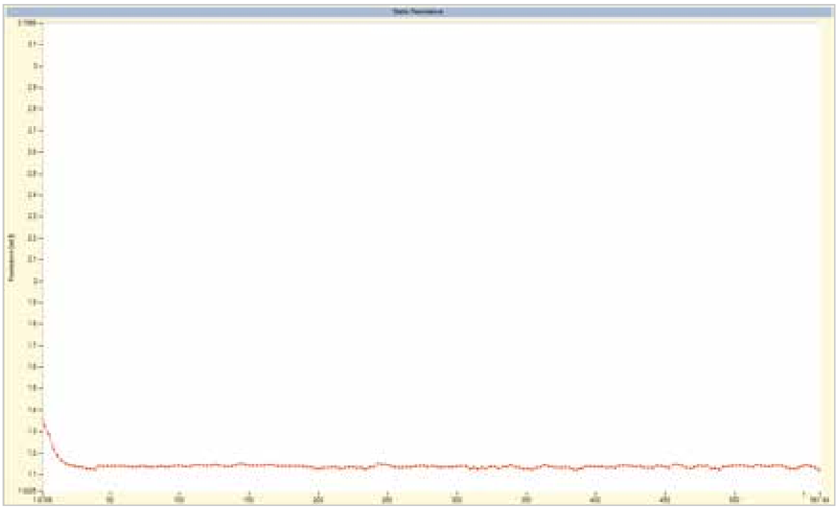

Figure 6. The winding resistance stabilization graph (the current flows through both the HV and LV transformer windings)

Conclusion

The transformer saturation using the HV winding connected in series with the corresponding LV winding speeds up the test process. The testing approach defined in Test 2 can be performed with a lower test current value achieving transformer saturation. The lighter and smaller cross-section test leads can be used, and significantly less time is needed for the measurement due to much faster result stabilization time. All this illustrates the benefit of using the proposed test methodology for the transformer winding resistance measurement, especially for testing the low voltage winding of generator step-up transformers.

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