Diagnostic measurements on instrument transformers – Part I

A classification and overview of diagnostic measurements

ABSTRACT

The article presents the most common diagnostic measurements on instrument transformers (current and voltage transformers) used to assess their condition and reliability. The measurements reveal possible failures which can occur due to aging processes during the lifetime of an instrument transformer. The failures are either related to the transformers' electro-magnetic circuit (for example, short, or open circuits) or to their insulation (for example, partial discharge, moisture ingress). Case studies are presented to underline the importance of conducting regular diagnostic tests.

KEYWORDS

instrument transformer, electro-magnetic circuit, insulation, diagnostic tests

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Diagnostic measurements reveal possible failures which can occur due to aging processes during the lifetime of an instrument transformer

1. Introduction

Instrument Transformers (ITs) are the eyes and ears of the electrical supply system. Although they are less expensive and can be replaced much faster than power transformers or generators, a severe failure can cause serious danger to people and significant damage and costs to the surrounding equipment, putting the overall system at risk. Without these ITs, key components such as transmission lines, power transformers, and generators cannot operate, causing loss of revenue or supply interruptions. Therefore, ITs should be tested on a regular basis to reveal the possible failures which can occur due to aging processes during their operation.

2. A classification and overview

In general, diagnostic measurements on ITs can be subdivided into two main groups:

- measurements on the electro-magnetic circuit
- measurements on the insulation system

2.1 Measurements on the electro-magnetic circuit

As part of the first group, measurements on the electro-magnetic circuit involve the magnetic iron core, the primary and secondary winding and, in case of a Capacitive Voltage Transformer (CVT), the compensation reactor and the capacitor stack. A measurement of the accuracy (ratio error and phase displacement) involves the electrical circuit of an IT. ITs which are used in metering applications require a high accuracy. Inductive current and voltage transformers and capacitive voltage transformers can develop ratio and phase deviations after some time in service. Shorted turns in current transformers and broken capacitive layers in the capacitor stack of a CVT are often undetected. This can lead to: readings errors, loss in revenue, and in some cases, a complete breakdown.

There are different ways to verify the integrity of the electro-magnetic circuit. One possibility is to use a conventional measurement approach, often referred to as the "primary injection method" [1]. Here the ratio error and phase displacement is verified by injecting rated primary current into an IT or by applying rated voltage to it. The transformation ratio and phase displacement is obtained while rated load is applied to the secondary winding(s).

Modern test equipment [2] offers a second possibility by measuring the load-dependent ratio error and phase displacement using a so-called "modeling approach", often referred to as an unconventional measurement method. In this case the instrument transformer is considered as a black box. The test instrument utilizes low voltage and current signals in order to verify the electrical circuit diagram. The parameters of the equivalent circuit diagram are determined by measurements from both the primary and secondary side. Here, the test instrument utilizes low voltage and current signals, compared to the nominal values, and calculates the accuracy of current transformers (CTs) and voltage transformers (VTs), which has a nonlinear dependency to the voltage, current and burden. This modeling method enables on-site calibration of voltage transformers and current transformers with high accuracy in a much shorter

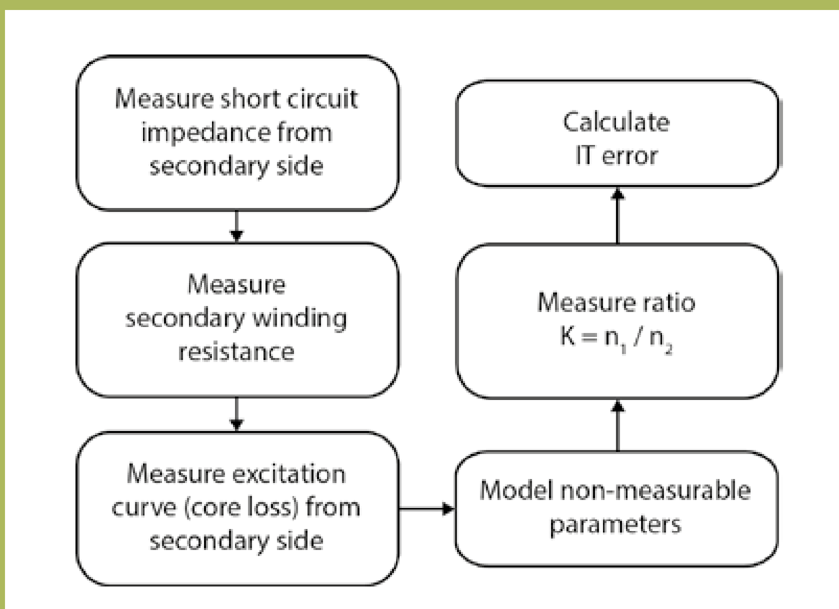

Figure 1: Principle of model-based accuracy determination on ITs [3]

Shorted turns in current transformers and broken capacitive layers in the capacitor stack of a CVT are often undetected

time and with less risk, saving many man hours and substantially reducing the outage time needed. With this method several important parameters can be obtained such as the residual magnetism, the unsaturated and saturated main inductivity, the symmetrical short-current factor, the overcurrent factor, and also the transient dimensioning factor. The different steps of this method are illustrated in Figure 1.

2.2 Measurements on the insulation

The second main measurement group on ITs is the tests on the insulation. The insulation properties of ITs are very similar to those of power transformer bushings, as their insulation manufacturing is mostly done by same companies. New methods have been developed for water content determination in oil-paper insulations. They use the dielectric response measurements, such as Polarization and Depolarization Currents (PDC) or Frequency Domain Spectroscopy (FDS), and are an extension of the approach developed for power transformers.

A Partial Discharge (PD) analysis helps to detect and locate insulation defects. PD testing is the only practicable diagnosis for epoxy (dry) type medium-voltage (1 kV up to 75 kV) ITs. With advanced software filtering methods, sensitive measurements are possible even in noisy testing environments on site.

Table 1 gives an overview of the most common diagnostic measurements on ITs and the type of faults which can be detected.

3. Excitation measurement on voltage and current transformers

The excitation measurement, often referred to as the measurement of the initial magnetization curve, is a very effective measurement method in order to detect any electrical or magnetic issues related to the magnetic core.

During the measurement, the magnetic core is excited by applying a voltage across the secondary winding with all other windings remaining open-circuited. On voltage transformers, the HV insulation of the primary winding has a certain capacity, called primary stray capacitance C_P" (refer to Figure 6). This stray capacitance, which is the capacitance of the high-voltage side to ground, has to be mathematically considered as, otherwise, a capacitive current is measured rather than an inductive excitation current.

Excitation voltage, excitation current, and the phase angle between voltage and current are measured over a wide voltage range, which ranges from low excitation voltages up to saturation voltages. Preferably, the measurement is conducted starting at saturation voltage going down to a low voltage level. This way the iron core is demagnetized after the test.

It is possible to excite the iron core at lower frequencies (50 Hz down to 0 Hz) in order to saturate the core. This makes the entire measurement safer in terms of induced primary voltages on a voltage

The excitation measurement is a very effective method to detect issues related to the magnetic core

Table 1. Diagnostic measurements on instrument transformers

Electrical part of the IT	Detectable fault	Diagnostic measurement
Magnetic core	Mechanical deformation, floating core ground, magnetostriction	Accuracy measurement (conventional and unconventional), Excitation measurement
Winding	Short circuits, open circuits	Accuracy measurement (conventional and unconventional), Winding resistance measurement, Turns-ratio measurement, Excitation measurement
Capacitive voltage divider (only in CVTs)	Partial breakdown of capacitive layers	Accuracy measurement (conventional and unconventional), Capacitance and dissipation/power factor measurement
Reactance coil (only in CVTs)	Short circuits of single turns	Accuracy measurement (conventional and unconventional), Short circuit impedance measurement
Insulation materials	Partial discharge, moisture in solid insulation, aging, contamination of insulation fluids	Partial discharge measurements, Capacitance and dissipation/power measurement, Frequency domain spectroscopy (FDS), Polarization and depolarization currents (PDC)

transformer. Furthermore, the effect of any stray capacitance can be reduced to a minimum.

The principle of using lower frequencies to saturate the iron core is illustrated in Figure 2.

Formula 1 gives a good explanation of the physical behavior of the magnetic flux density (in Tesla) in the core. A decrease in frequency at a constant excitation voltage causes an increase of the magnetic flux density in the core. This has the same effect as using a constant frequency and increasing the applied excitation voltage instead.

$$\hat{B} = \frac{\hat{V}_c}{n * 2 * \pi * f * A} \qquad (1)$$

For the exact representation of the initial magnetization curve at line frequency, the non-linear core losses have to be considered accordingly.

In terms of analyzing the test results, one can compare the initial magnetization curve (main inductivity and complete curve) with reference data from the Factory Acceptance Tests (FAT). If the FAT report is not available at the time, a cross comparison between the phases can be done. It is important to only compare ITs of the same type and class together.

The PX class is defined in the IEC 61869-2 standard for protective current transformers of low-leakage reactance without remanent flux limit [4a]. The PX class assesses the knee-point, exciting current, secondary winding resistance and the turns-ratio error. On PX-class protection current transformers, the rated knee-point voltage and the excitation current at the rated knee-point voltage are specified on the nameplate. This is a reference point which can be used to assess the initial magnetization curve. The assessment is done as follows:

As an example, a class 0.02PX100R25 is used here. The class designation actually means that the rated knee-point voltage is 100 V. The measured knee-point voltage must be greater than 100 V. The rated excitation current at 100 V is 0.02 A. The measured excitation current at 100 V must be lower than 0.02 A. Furthermore, the measured DC winding resistance corrected to 75 °C has to be less than 25 Ω.

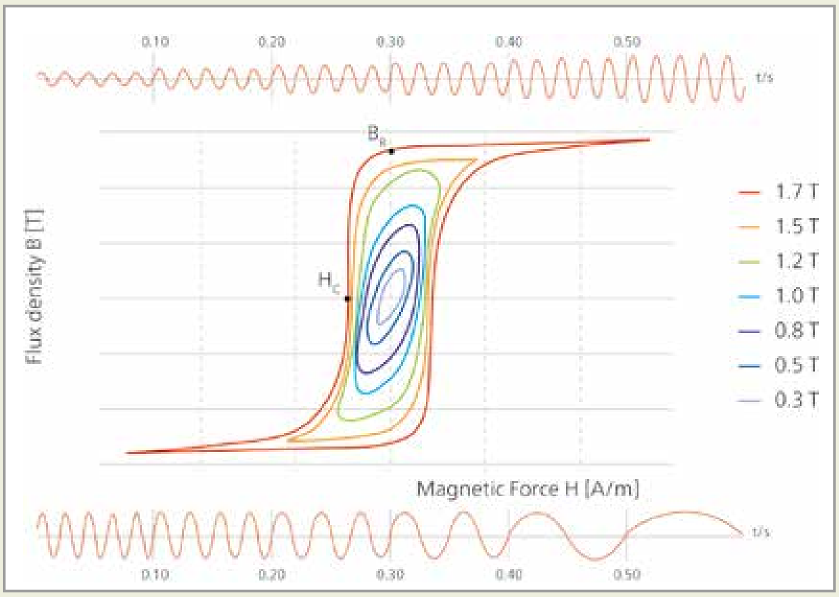

Figure 2. Hysteresis loop family

For analysis, the results of the initial magnetization curve can be compared with reference data from the FAT

3.1 Case study I - CT excitation measurement

Two current transformers of the same type and class were investigated. One transformer produced a much higher ratio error and phase displacement than the other. As both ratio and phase error were affected, it was assumed that the issue was related to the core. An increase of the ratio error and the phase error is the result of an excessive excitation current.

The excitation current (RMS current in Figure 3) is the sum of the currents through the main inductivity L_m and the current which is caused by the core losses (eddy and hysteresis losses), refer to Figure 5. Any increase in the core losses will always also result in an increased ratio error and phase displacement. A measurement of the initial magnetization curve on both transformers confirmed the issue to be related to the magnetic core, see Figure 3.

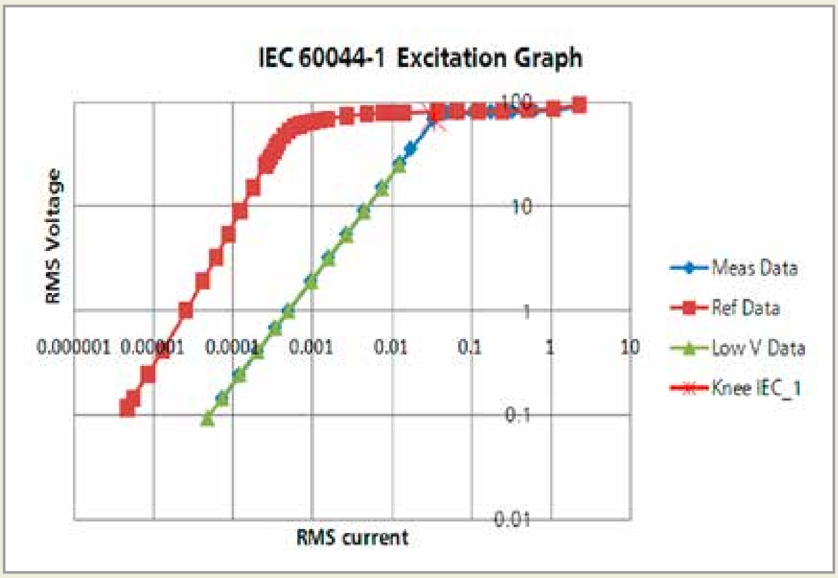

Figure 3. Comparison of the initial magnetization curves

The DC-winding resistance measurement helps detect shorted turns or open circuits

The red curve is the reference excitation graph. The faulty transformer (green-blue curve) showed much higher excitation currents at the same excitation voltage (RMS voltage in Figure 2) compared to the healthy transformer.

The root cause of the issue was found to be a shorted screen (no connection of screen to ground potential).

4. Winding resistance measurement

The DC-winding resistance measurement is a well-established measurement method for detecting any shorted turns or open circuits. The approach is very simple: A DC current (I_{DC}) is injected into the winding while the resulting DC voltage drop (U_{DC}) is measured across the winding. Due to the inductive nature of the core both the current and voltage have to stabilize and settle first. The resistance profile over time will have a profile as indicated in Figure 4.

One way to verify a stable resistance reading is to look at the resistance deviation over time. If the deviation drops below a certain threshold (typically < 0.1%) the resistance reading is considered to be stable. The DC-winding resistance can then be derived using Formula 2.

$$R_{DC} = \frac{V_{DC}}{I_{DC}} \qquad (2)$$

In terms of assessing the test results, one can compare the on-site resistance reading with either reference results from the factory or with ITs from the other two phases (same class ratings). It is important to make a temperature correction of the measured resistance (R_{meas}) which was measured at ambient temperature (T_{meas}). Typically, a reference temperature of 75 °C (T_{ref}) is used when comparing results [1].

The temperature correction for a copper winding is indicated in Formula 3.

$$R_{ref} = \frac{R_{meas} * 235 + T_{ref}}{235 + T_{meas}} \qquad (3)$$

5. Turns-ratio measurement

The turns-ratio measurement is a very effective method for detecting any shorted turns on ITs (including CVTs).

On current transformers, an AC voltage is applied across the secondary winding (V_{sec}), and the resulting induced voltage is measured at the primary side (V_{prim}). Due to the no-load losses (I_{exc}) it is important to compensate the voltage drop across the winding resistance. The turns-ratio (N) can then be derived as indicated in the Formula 4 below.

$$N = \left| \frac{V_{sec} - I_{exc} * R_{DC}}{V_{prim}} \right| \qquad (4)$$

With modern test equipment it is possible to perform very precise voltage and current measurements. It is even possible to detect single turn-to-turn short circuits.

Sometimes a turn-to-turn short circuit only occurs at a certain voltage level. In these cases the secondary voltage applied can be increased to check for any high-impedance turn-to-turn short circuits. By doing so, the test frequency should also be increased in order to prevent any core saturation effects which influence the turns-ratio measurement accuracy. For this test there is no reactive compensation required.

When testing inductive and capacitive voltage transformers, a direct measurement of the turns-ratio is not possible as there are no-load losses inside the transformers which have to be considered mathematically. A no-load voltage ratio of Inductive Voltage Transformers (IVTs) can be measured by applying a voltage across the primary winding and measuring the induced voltage across the secondary winding with a high-impedance voltage meter.

6. Accuracy measurement on current and voltage transformers

The accuracy measurement involves the measurement of the ratio error and the phase displacement (see Figure 1). When it is done using the above mentioned modeling approach, it is based on the measurement of an IT's equivalent circuit diagram.

The losses of a current transformer are represented by the core losses. Those losses need to be measured and can be subdivided into copper losses and iron losses. The copper losses are described as the winding resistance R_{CT} of the current transformer. The iron losses are described as the eddy losses (represented by the eddy resistance R_{eddy}), and the hysteresis losses as hysteresis resistance R_H of the core.

Using the values of the total losses of the core, a mathematical model can be used to calculate the current ratio error and the phase displacement for any primary current and for any secondary burden. There-

When the accuracy measurement is done using the modeling approach, it is based on the measurement of an IT's equivalent circuit diagram

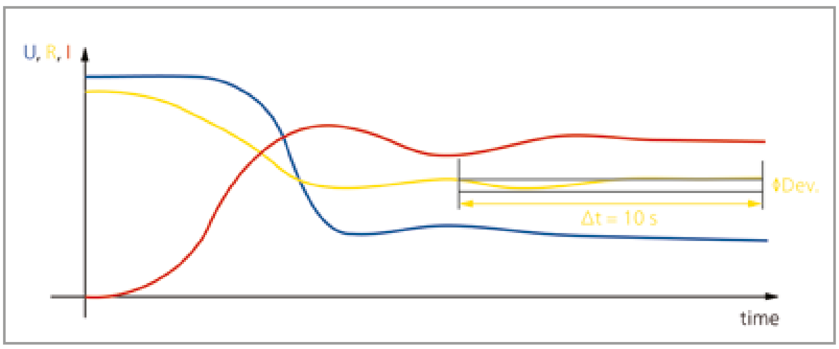

Figure 4. (DC) Winding resistance profile over time

fore, all operating points described in the relevant standards for current transformers can be ascertained.

Additionally, other important parameters can be obtained such as the residual magnetism, the unsaturated and saturated main inductivity, the symmetrical short-current factor, the overcurrent factor, and also the transient dimensioning factor (according to the IEC 60044-6 standard for transient fault current performance calculations [5]).

The following measurements have to be performed consecutively in order to measure the parameters according to the equivalent circuit diagram:

- measurement of the secondary winding resistance (R_{CT})
- measurement of the initial magnetization curve (core represented by L_m)
- measurement of eddy losses and hysteresis losses (R_{eddy} and R_H)
- measurement of the turns-ratio N (core ratio)
- calculation of the current ratio error and phase displacement at desired burden and primary current values based on the vector diagram for a current transformer

The modeling approach (Figure 5) is a very powerful tool, not just for regular calibration of current transformers, but also for diagnostic measurements as it involves all the diagnostic tests on the electrical circuit diagram presented so far.

The losses of a voltage transformer consist of the core losses and the primary and secondary stray losses. In the case of an IVT, the following measurements have to be performed consecutively to measure the parameters according to the equivalent circuit diagram (Figure 6):

- measurement of the short circuit impedance
- measurement of the secondary winding resistance (R_2)
- measurement of the primary stray capacitance (C_p")
- measurement of the initial magnetization curve (core represented by L_m)
- measurement of eddy losses and hysteresis losses (R_{eddy} and R_H)
- measurement of the turns-ratio, respectively the no-load ratio
- calculation of the voltage ratio error and phase displacement at desired burden and primary voltage values based on the vector diagram for a voltage transformer.

The modeling approach is a very powerful tool, not just for regular calibration of current transformers, but also for a lot of diagnostic measurements

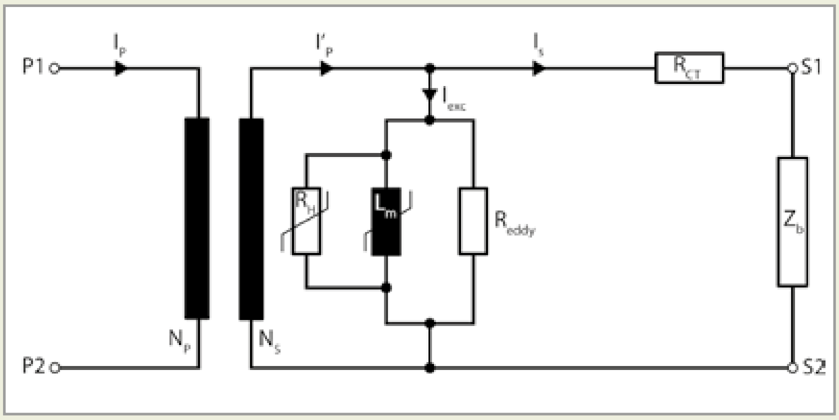

Figure 5. Equivalent circuit diagram of a current transformer connected to a burden Z_b

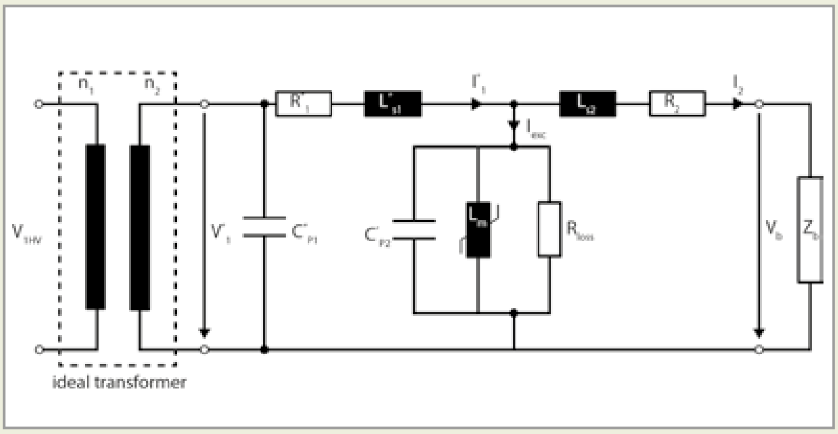

Figure 6. Equivalent circuit diagram of an IVT

On a capacitive voltage transformer (CVT) the voltage ratio of the capacitive stack is measured additionally.

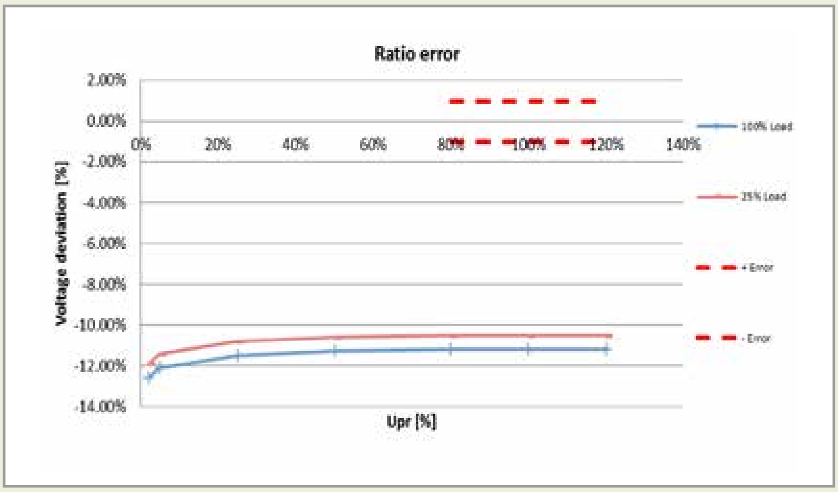

Figure 7. Ratio error of the CVT under test

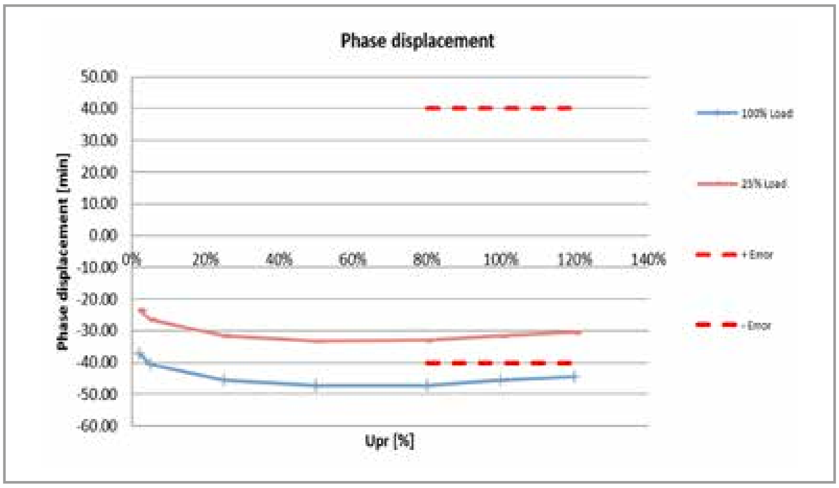

Figure 8. Phase displacement of the CVT under test

6.1 Case study II – CVT ratio measurement

A CVT producing a secondary voltage that is too low was investigated. The primary voltage, the load-dependent ratio error, and phase displacement of the suspect CVT were measured and analyzed.

The CVT had the following nameplate specifications:

- Voltage ratio: 110 kV / 100 V
- Nominal capacitive ratio 7.5 (ratio of capacitance at frequencies between 10 mHz and 50 Hz [6])
- Class: 1 metering
- Rated load: 120 VA @ power factor of 0.8

The results for the ratio error and phase displacement are shown in Figures 7 and 8. The dashed lines in red represent the error limits which are defined in the standard.

The measurements confirmed that the voltage ratio error of the CVT was too negative, leading to a secondary voltage which was lower than the rated voltage. A closer look at the measured capacitive voltage ratio confirmed a ratio of 8.37. The rated ratio of the capacitor stack was 7.5 which indicated a partial breakdown of capacitive layers of C2 (part 2 of the capacitive divider). The CVT was dismantled and the partial breakdown could be confirmed. As a consequence the device was replaced.

Part II of this article, which is in the process of publication, will in more detail discuss capacitance and dissipation / power factor measurement, short circuit impedance measurement, dielectric response analysis and partial discharge measurements.

Bibliography

[1] IEC 60044-1 Edition 1.2 / 2003-02, *Instrument Transformers, Part 1: Current Transformers*, Reference number CEI/IEC 60044-1:1996+A1:2000+A2:2002

[2] M. Freiburg, F. Predl, *A new approach for on-site calibration of voltage transformers*, Part I and Part II, ITMF 2013

[3] M. Freiburg, Messung und Modellierung des Magnetisierungsverhaltens induktiver Spannungswandler, ETG-Fachtagung 2014 in Berlin

[4] IEC 61869-2 Edition 1.0 / 2012-09, *Instrument Transformers, Part 2: Additional requirements for current transformers*

[5] IEC 60044-6 First Edition / 1992-03, *Instrument transformers, Part 6: Requirements for protective current transformers for transient performance*, Reference number CEI/IEC 44-6:1992

[6] S. Raetzke, M. Koch, M. Krueger, A. Talib, Condition assessment of instrument transformers using dielectric response analysis, CIGRÈ 2012, Paris

Authors

Florian Predl started with OMICRON Austria in 2007 as an application engineer within the Engineering Services team with special focus on advanced instrument transformer diagnostics. He also provided technical support to world-wide users of OMICRON products. In 2013 Florian joined the OMICRON team in Australia where he is currently employed as a Field Application Engineer. Before starting at OMICRON he attended the Federal Higher Technical Institute in Rankweil, Austria, where he graduated in 2007 with a focus on high-frequency technology. His final thesis focused on range extension of RFID systems for business applications by using high-frequency amplifiers.

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