



## Diagnostic measurements on instrument transformers

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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# 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 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.

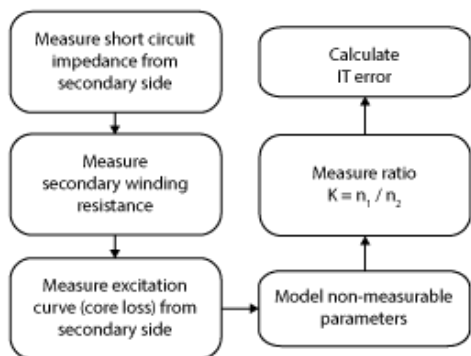


Figure 1: Principle of model-based accuracy determination on ITs [3]

## 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.

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)

### 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 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.

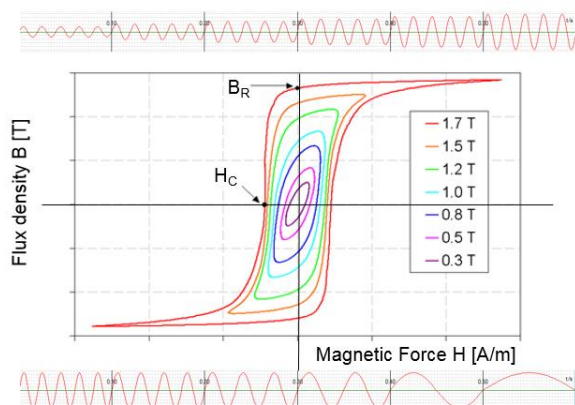


Figure 2: Hysteresis loop family

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.

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

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 kneepoint 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.

### 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.

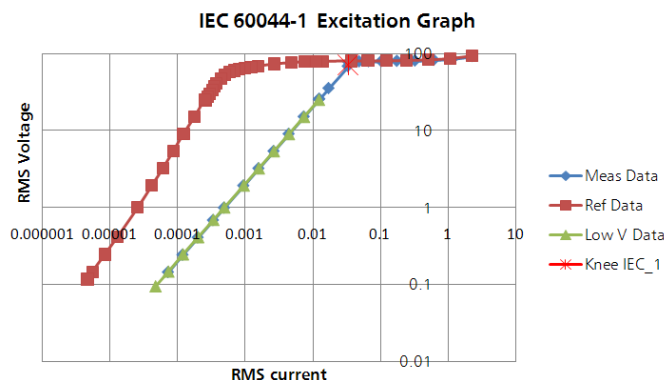


Figure 3: Comparison of the initial magnetization curves

The 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.

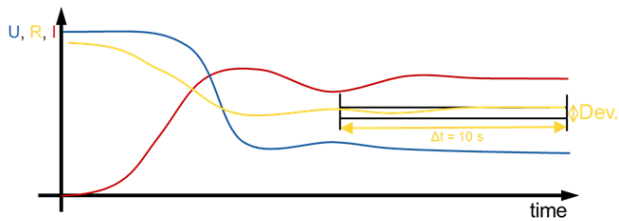


Figure 4: Winding resistance profile over time

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.

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

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.

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

## 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.

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

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. Therefore, 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.

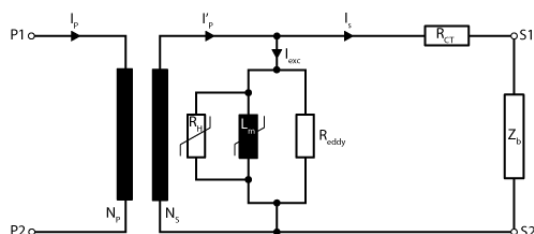


Figure 5: Equivalent circuit diagram of a current transformer connected to a burden  $Z_b$

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):

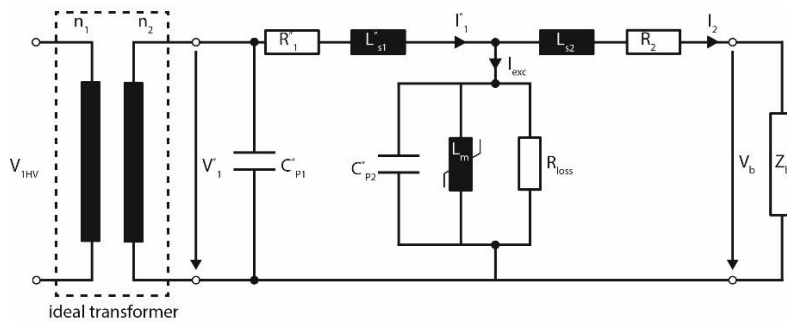


Figure 6: Equivalent circuit diagram of an IVT

- 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.

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

## 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.

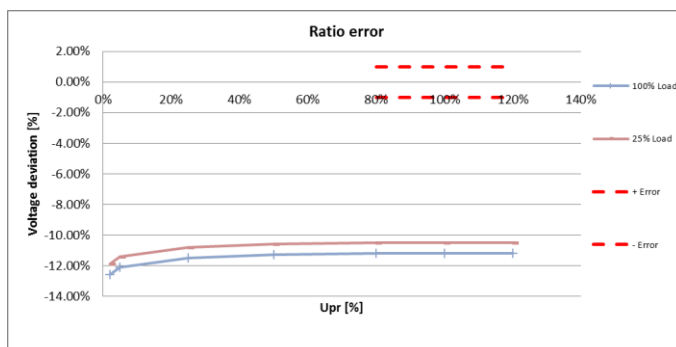


Figure 7: Ratio error of the CVT under test



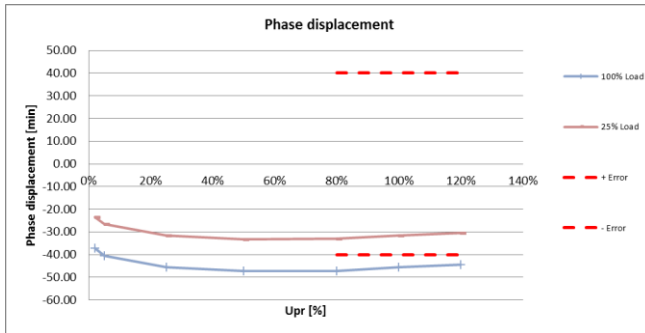


Figure 8: Phase displacement of the CVT under test

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.

## 7 Capacitance and dissipation/power factor measurement

The dissipation factor is measured by comparing the current of a test object to a known reference (“ideal” capacitive current). The phase difference between the reference current and the test object current is determined. Calculating the tangent of  $\delta$  gives the dissipation/loss factor.

The capacitance and dissipation/power factor measurement is a well-established method to evaluate the insulation condition. An ideal (loss-free) insulation consists of a vacuum capacity also referred to as the geometrical capacity  $C_0$ . If insulation material other than vacuum is being used, one or more polarization processes can be observed. They represent the electrical behavior of the used insulation material(s). Polarization processes cause losses, for example due to a rotation of dipoles. This will furthermore increase the capacitance measured due to a dielectric constant greater than 1. In addition, the insulation material has a certain conductivity which creates conductive losses [7]. A dissipation factor measurement measures a combination of these losses, see Figure 9.

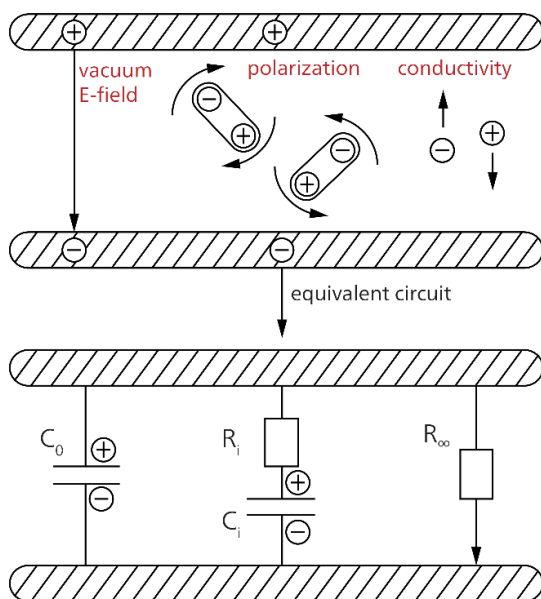


Figure 9: Insulation and its losses

A voltage tip-up test (ramping up of the test voltage) can be used to check whether or not there is any PD activity present. An increase in the dissipation factor at a certain inception voltage indicates possible PD activity. This is a common diagnostic tool on generators and motors. However, a dissipation factor measurement does not give an exact localization of PD. It can only give an overall representation of the insulation condition.

A capacitance and dissipation/power factor measurement on the capacitive stack of a CVT can reveal any possible insulation degradation or even shorted capacitive layers. The physical construction of the capacitive stack is similar to that of condenser bushings. If a capacitive layer should break down, the overall capacitance of the stack will increase.

Likewise, if the dissipation factor increases, it is an indication of an aging process taking place (moisture ingress, partial discharge, etc.).

Leakage currents through the insulation of a CVT winding often lead to difficulties in obtaining a balance of dissipation factor. This means that the apparent dissipation factor readings are below the true value, or even a negative value, although the capacitance value obtained will be correct [8]. A change on the result of the measured capacitance results ( $C_1$  in series with  $C_2$ ) from one routine test to another is a reason for additional investigations.

In the case of IVTs, an insulation capacitance and dissipation/power factor measurement cannot be performed on all parts of the insulation. The main insulation, which is located between the individual turns of the primary winding, cannot be accessed for measurements. However, the dissipation/power factor can be measured between the primary and secondary winding, as well as between the primary winding and ground. If the transformer is equipped with a screen electrode, the measurement between the primary winding and the screen is the preferred measurement method. It depends on the type of the IVT if a screen is equipped and if it is accessible in the secondary terminal.

## 8 Short circuit impedance measurement

A CVT must have a compensation reactance, often called reactance coil ( $L_{comp}$ ). This coil compensates the phase shift caused by the capacitor stack. Hence, the reactance of the coil is tuned to the reactance of the capacitor stack at line frequency. The coil is typically operated at around 10 kV – 30 kV, depending on the manufacturer. In Figure 10 a simplified electrical diagram of a CVT is shown. Shorted coil turns cause the inductance to drop. The capacitor stack is therefore no longer properly compensated, leading to a drift in the phase displacement.

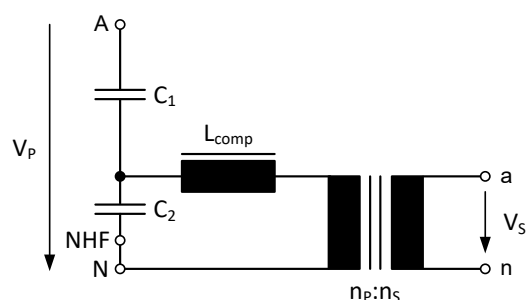


Figure 10: Capacitive voltage transformer – simplified electrical diagram

A short circuit impedance test at line frequency can be used to check the integrity of the coil. An AC current is injected into the secondary winding while the voltage drop and the phase angle between voltage and current is measured across the secondary winding. The primary side (capacitor stack) must be short circuited to ground (Figure 11). The reactive part of the complex short circuit impedance should be close to 0  $\Omega$  indicating that the capacitor stack ( $C_1$  and  $C_2$ ) is properly compensated.

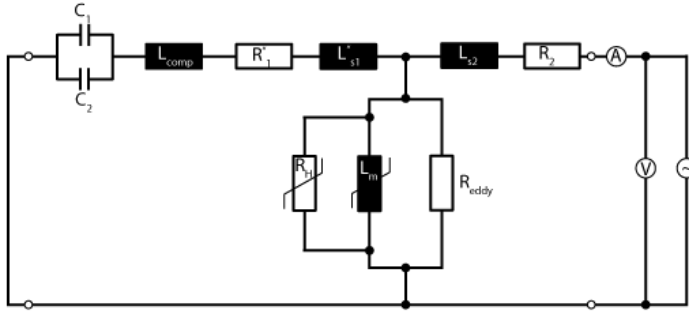


Figure 11: Short circuit impedance measurement on a CVT

### 8.1 Case study III – CVT accuracy measurements

Two CVTs were investigated after one of the two units revealed high gas levels after oil sampling. The Dissolved Gas Analysis (DGA) result indicated PD and arcing.

Both devices were measured to check the integrity of the electrical circuit. The nameplate information is shown in Table 2.

Table 2: Nameplate information of the CVTs under test

Rated primary voltage	220/ $\sqrt{3}$ kV	Line to ground		
Low-voltage terminals	Secondary voltage (V)	Ratio(to 1)	Accuracy class	Rated output (VA)
1 <sub>a2</sub> – 1 <sub>a1</sub>	110/ $\sqrt{3}$	2000	0.2/3P	0 - 100
2 <sub>a2</sub> – 2 <sub>a1</sub>	110/ $\sqrt{3}$	2000	0.2/3P	0 - 100
Total nominal capacitance	6200 pF	C <sub>1</sub> 7106 pF	C <sub>2</sub> 76393 pF	

The CVT with the elevated dissolved gas results during oil sampling also showed a much higher ratio error and phase displacement. A closer look at the short circuit impedance test result confirmed that the reactive part of the “faulty” CVT showed capacitive behavior.

This confirmed that the reactance coil had shorted turns. The capacitor stack was no longer compensated at line frequency.

The ratio error and phase displacement of the faulty CVT are indicated in Figures 12 and 13.

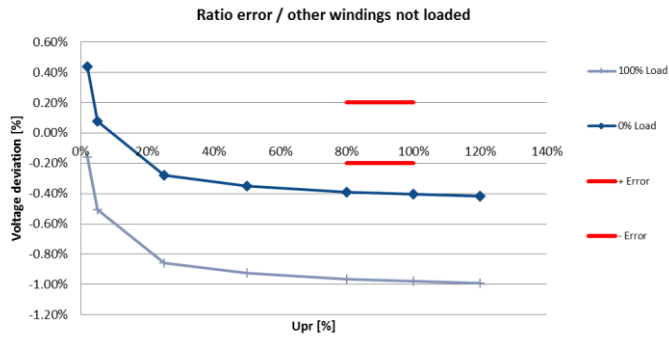


Figure 12: Ratio error of the faulty CVT

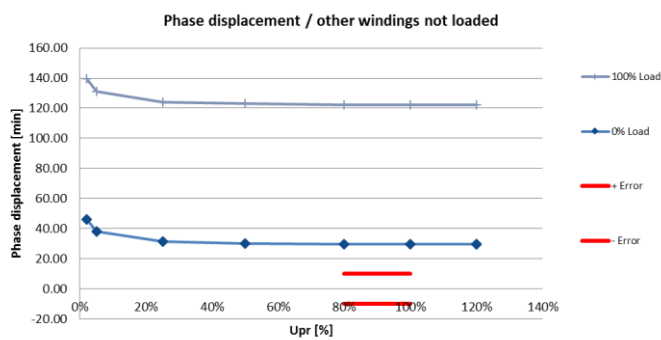


Figure 13: Phase displacement of the faulty CVT

## 9 Dielectric response analysis

A high water content in the oil-paper insulation of ITs can lead to a failure of the insulation and, as a consequence, can even result in the complete destruction of the asset. Therefore, it is important to be able to assess the ITs' water content. This proves to be quite challenging as, in contrast to power transformers, its measurement techniques such as oil sampling are quite difficult to perform due to the rather small oil volume and often a lack of simple and easy access to it.

Over the last few years the dielectric response analysis has become well established to assess the moisture in the solid paper insulation. It is done by measuring the power factor/dissipation factor over frequency.

The measurement of the dielectric response over a wide frequency range (for example, 100  $\mu$ Hz up to 5 kHz) provides information about the insulation condition and, especially for oil-paper insulations, about the water content in the solid insulation.

For calculating the water content, the measured dielectric response curve is compared to a modeled curve (Figure 14).

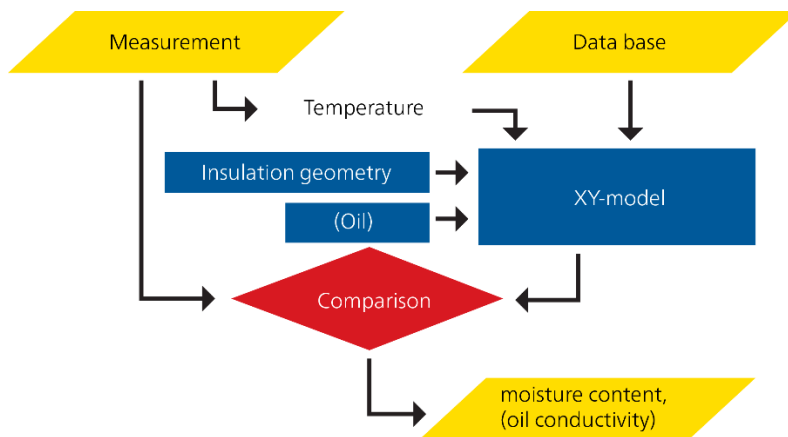


Figure 14: Calculation of the water content based on the XY Model

The curve modeling is done with help of a database including material properties of cellulosic material with different water contents and temperatures. Using the so-called XY model [9] a dielectric response is calculated under consideration of the insulation geometry, temperature, oil and moisture content. A matching algorithm aligns the modelled response of the database to the measured curve of the real insulation and automatically delivers the water content of the cellulosic material as well as the water saturation or the oil conductivity.

The appropriate test setup on current transformers depends on whether or not the CT has a screen electrode and whether or not the screen electrode is accessible. Sometimes this is documented in the datasheet of the CT. In case there is no information about the screen, contact the manufacturer. Figures 15 to 17 show proposed setups for these cases [10].

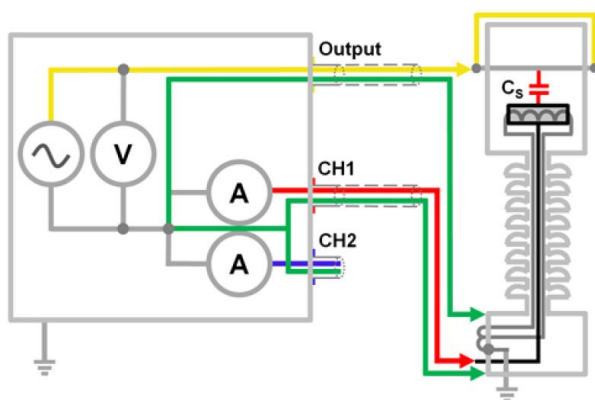


Figure 15: Test setup for a CT with an accessible screen electrode; Measured insulation HV to screen; Guard applied to ground

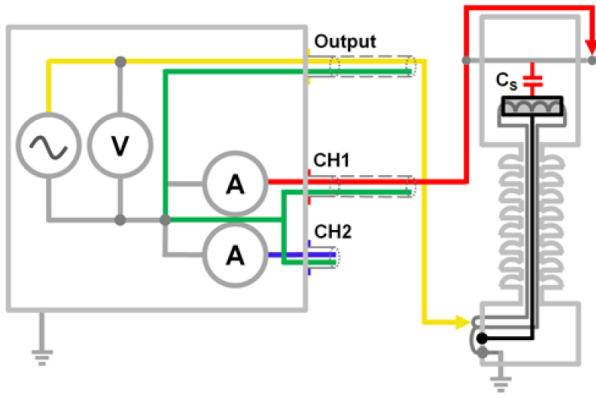


Figure 16: Test setup for a CT without accessible screen electrode; Measured insulation HV to ground; No guard applied

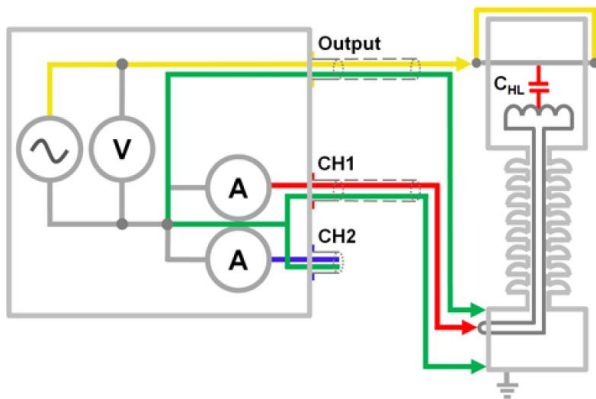


Figure 17: Test setup for a CT without screen electrode; Measured insulation HV to secondary winding; Guard applied to ground

## 9.1 Case study IV – IT insulation test

Two combined ITs were investigated as one unit showed a high concentration of hydrogen in an oil sample. The concentration was 699 ppm. There was no methane involved. Therefore, it was not very likely that the high H<sub>2</sub> concentration was caused by PD activity.

The test results in Table 3 show a summary of the dielectric response values measured. CT2 is the IT with a high concentration of H<sub>2</sub>.

Table 3: Dielectric response results

	CT1	CT2
Tan( $\delta$ ) @ 50 Hz	0.28 %	0.29 %
Oil conductivity	23 fs/m	22 fs/m
Moisture content	1.6 %	1.8 %
C_10 mHz/C_50 Hz	1.02	1.03

The ratio of the complex capacitance measured at 10 mHz and 50 Hz provides further information on the insulation conditions of ITs. Field studies have shown that the capacitive ratio should be below 1.05 for a healthy and dry insulation [11]. The advantage of the capacitive ratio is that this parameter is not dependent on the geometry of the insulation.

The dielectric parameters obtained on both ITs did not indicate any aged insulation. The very high concentration of H<sub>2</sub> was most likely caused by stray gas. The transformer manufacturer was asked for information related to the stray gas and they revealed that a chemical reaction between a certain detergent and the inside materials of the transformer could have produced the high H<sub>2</sub> values. Therefore, the tested transformer is still in operation.

## 10 Partial discharge measurements

PD is a localized dielectric breakdown of a small portion of a solid or liquid electrical insulation system under high-voltage stress. PD only partially bridges the insulation between conductors [12]. PD activity deteriorates the insulation material over time, which can eventually lead to a total breakdown of the insulation.

PD releases parts of the energy as an electromagnetic wave. For PD measurements a test circuit is installed so the shorted capacitance is reloaded from the coupling capacitor. The current during reloading can be measured and correlated to the discharge level. PD is measured in pC either according to IEEE Std C57.13TM-2016 [13]) or according to the IEC 60270 standard.

Figure 18 shows a PD measurement setup according to IEC 60270 [12]. It involves a blocking impedance, a coupling capacitor, and a coupling device which is attached to the PD measurement instrument.

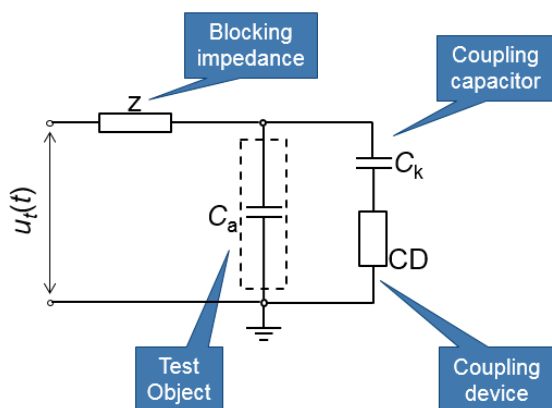


Figure 18: PD Measurement setup according to IEC 60270

ITs for medium-voltage (1 kV up to 75 kV) applications typically have a cast resin insulation. Voids or cavities in this insulation can be a result of shock and vibration or manufacturing faults. If the electrical field strength in the insulation becomes higher than the dielectric strength of the gas inside the void, a total breakdown will appear inside the void. At this very moment the electrical field in the void extinguishes. The dissipated energy will be recharged by the coupling capacitor. The coupling device connected to the coupling capacitor is able to measure the recharge current. The recharge process depends on the voltage gradient of the applied voltage. The process is fastest at the steepest part of the voltage gradient. Therefore, PD often occurs close to the zero crossing of the applied voltage (Figures 19 and 20).

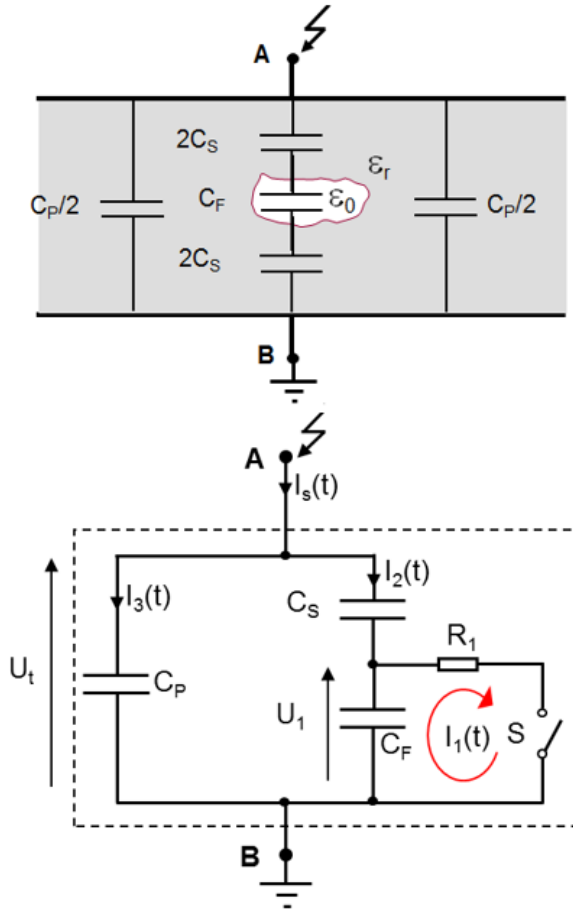


Figure 19: Recharge process explained on the principle of a void discharge

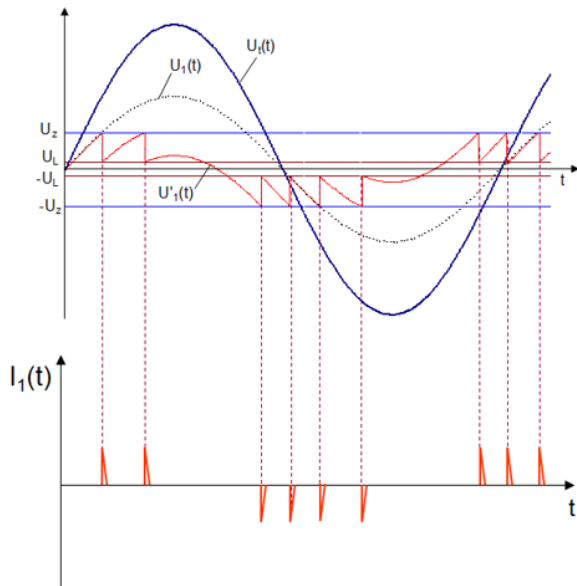


Figure 20: Recharge process explained on the principle of a void discharge



Figure 21 shows a typical phase-resolved PD pattern (PRPD pattern) for a void discharge happening inside a solid insulation of a medium-voltage transformer. The cluster represents a histogram of all discharges recorded over 1 min 36 sec. In accordance with the IEC 61869-1 standard [14] and depending on the test voltage, the discharge level should not exceed 50 pC, where in this case discharges up to several nC have been measured.

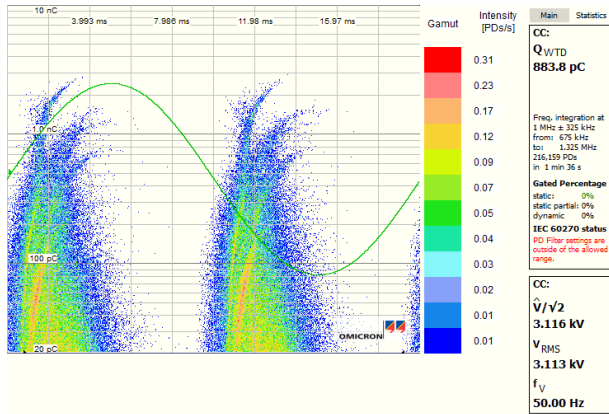


Figure 21: PRPD pattern of void discharges

## 11 Conclusion

Different diagnostic measurements on instrument transformers help to assess their condition. Their results give valuable information about possible faults related to specific parts of an IT (Table 1). By combining the test results of the various diagnostic tests, an overall picture of the health condition of the IT can be derived. As a consequence, failures can be detected before they turn into severe failures which endanger people or result in costly damage to connected equipment.

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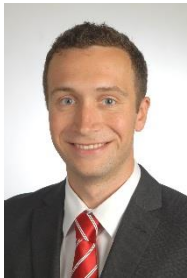
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