Diagnostic measurements on instrument transformers

– Part II

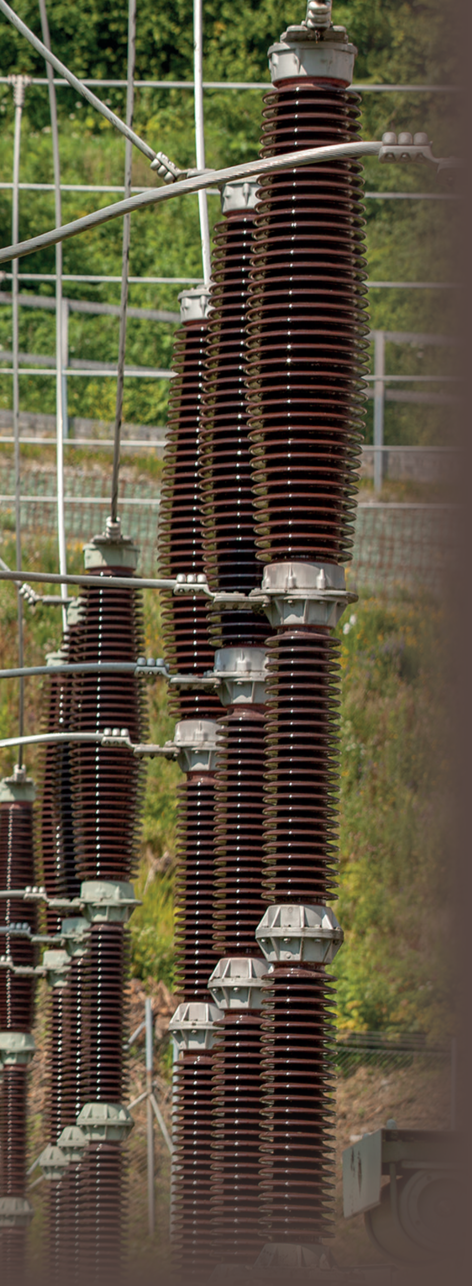
A classification and overview of diagnostic measurements

ABSTRACT

Part 1 of this article, published in Volume 3 Issue 4, pages 100ff, describes the measurements of excitation, winding resistance, turns ratio and accuracy as the most common diagnostic measurements on instrument transformers (current and voltage transformers) for condition and reliability assessment. Case studies show the failures which can be derived from the results and underline the importance of conducting regular diagnostic tests. Part 2 gives more details about the measurements of capacitance and dissipation/power factor, short circuit impedance, dielectric response analysis and partial discharge.

KEYWORDS

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



> **The capacitance and dissipation/power factor measurement is a well-established method to evaluate the insulation condition**

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 δ 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.

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.

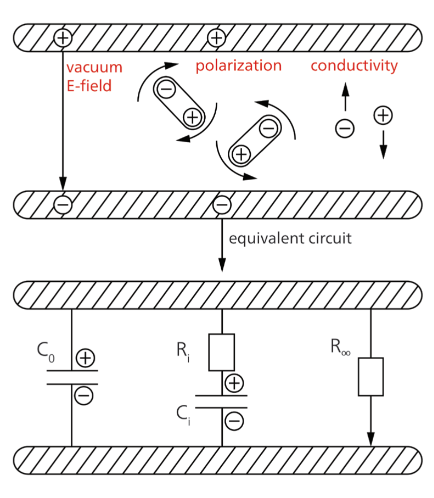


Figure 9. Insulation and its losses

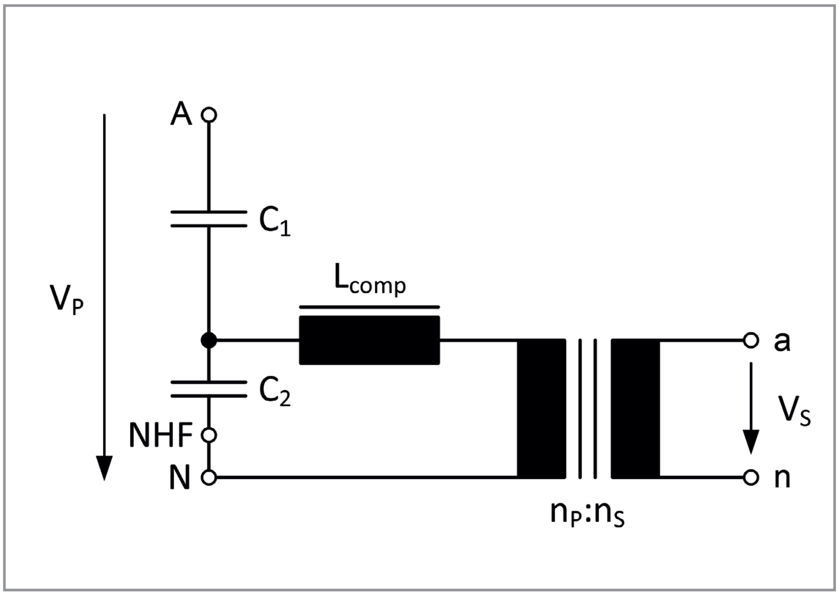


Figure 10. Capacitive voltage transformer – simplified electrical diagram

> **A short circuit impedance test at line frequency can be used to check the integrity of a CVT's reactance coil**

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 Ω indicating that the capacitor stack (C_1 and C_2) is properly compensated.

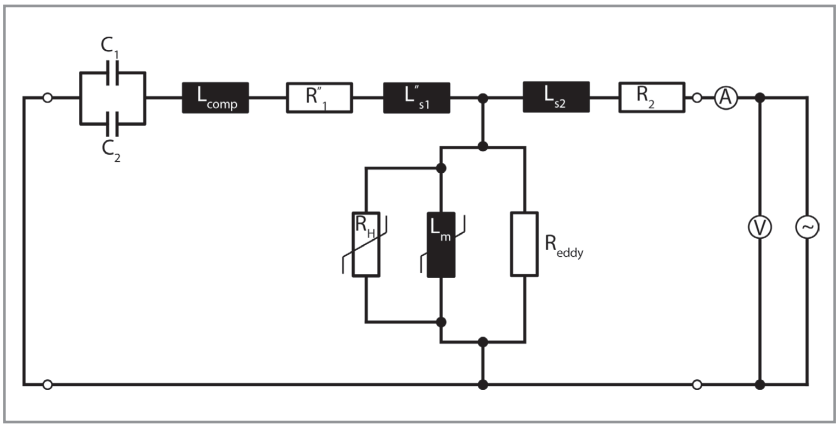


Figure 11. Short circuit impedance measurement on a CVT

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.

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.

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.

Table 2. Nameplate information of the CVTs under test

Rated primary voltage	220/√3 kV	Line to ground		
Low-voltage terminals	Secondary voltage (V)	Ratio (to 1)	Accuracy class	Rated output (VA)
$1_{a2} - 1_{a1}$	110/√3	2000	0.2/3P	0 - 100
$2_{a2} - 2_{a1}$	110/√3	2000	0.2/3P	0 - 100
Total nominal capacitance	6200 pF	C_1 7106 pF	C_2 76393 pF	

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 µHz 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). 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].

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_2 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_2.

The ratio of the complex capacitance measured at 10 mHz and 50 Hz provides further information on the insulation

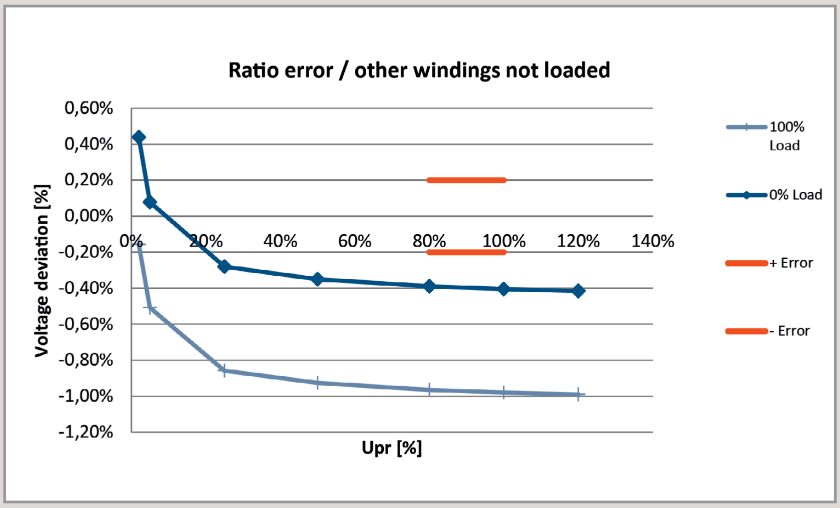


Figure 12. Ratio error of the faulty CVT

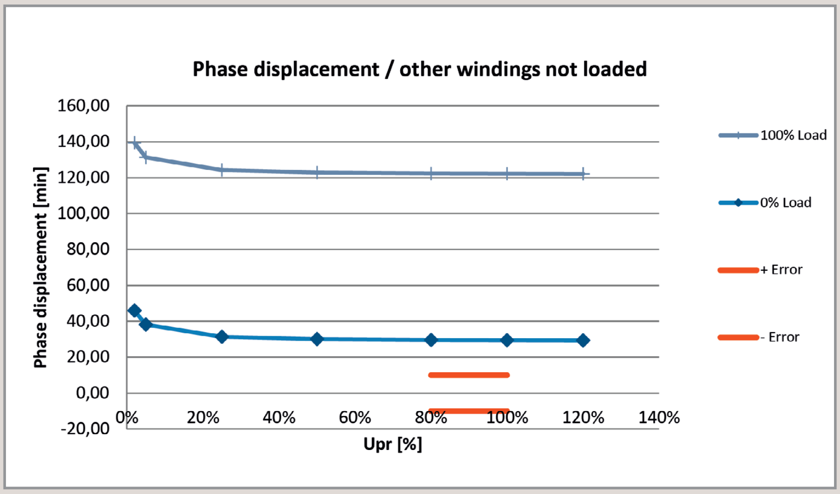


Figure 13. Phase displacement of the faulty CVT

A dielectric response analysis assesses the moisture in the solid paper insulation

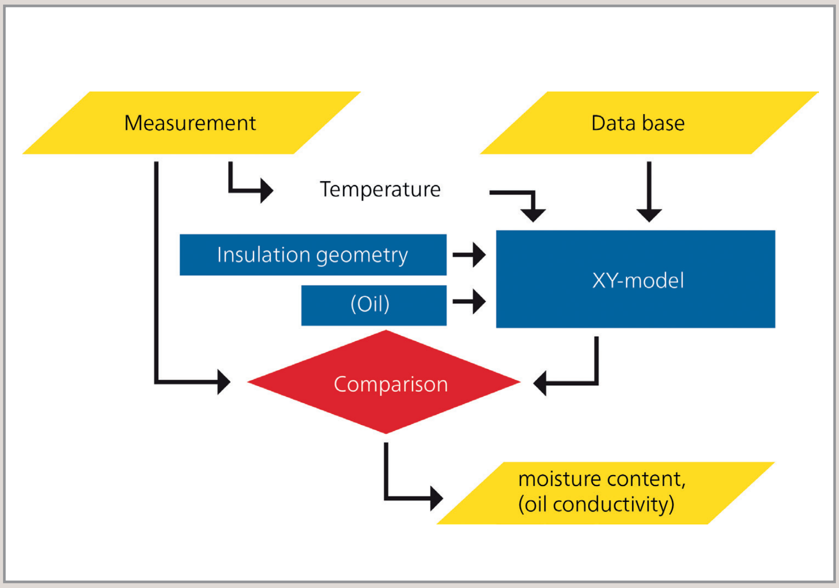


Figure 14. Calculation of the water content based on the XY Model

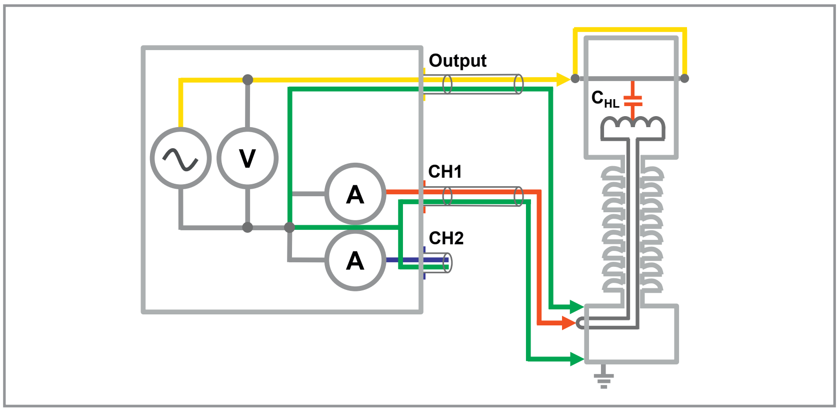


Figure 15. Test setup for a CT with an accessible screen electrode; measured insulation HV to screen; guard applied to ground

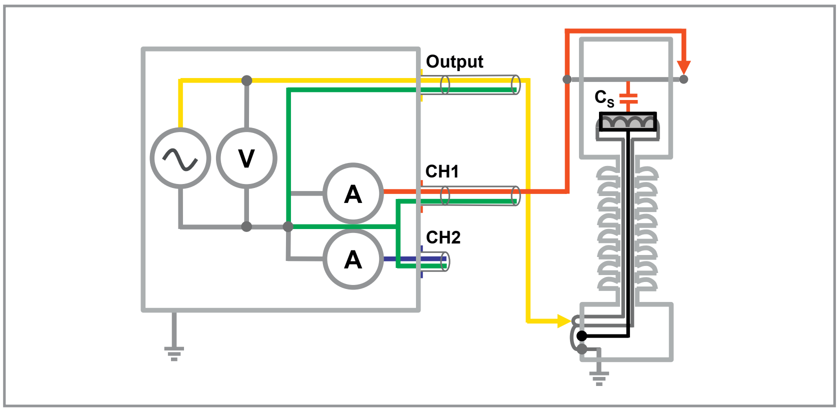


Figure 16. Test setup for a CT without accessible screen electrode; measured insulation HV to ground; no guard applied

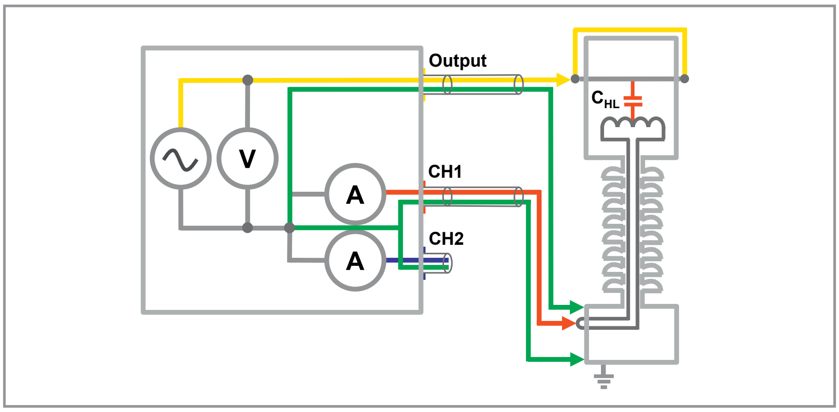


Figure 17. Test setup for a CT without screen electrode; measured insulation HV to secondary winding; guard applied to ground

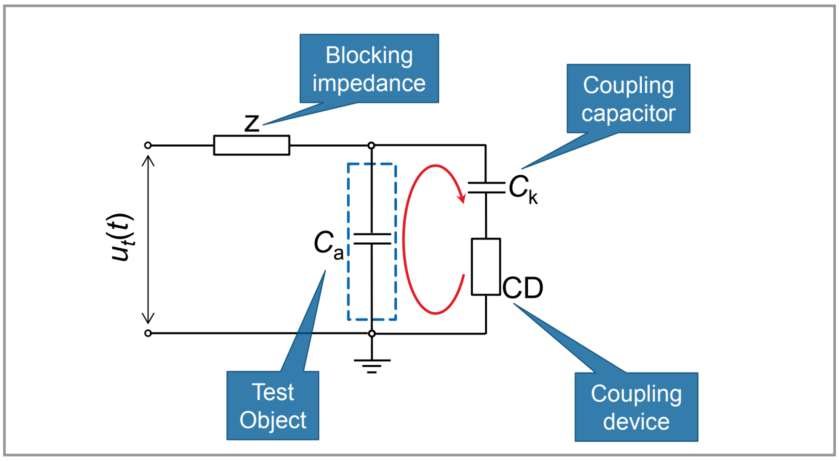


Figure 18. PD Measurement setup according to IEC 60270

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_2 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_2 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 C57.13™-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,

Table 3. Dielectric response results

	CT_1	CT_2
Tan(δ) @ 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

> **Partial discharge measurements reveal weak points in the insulation before a total breakdown of the insulation can occur**

and a coupling device which is attached to the PD measurement instrument.

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 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.

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.

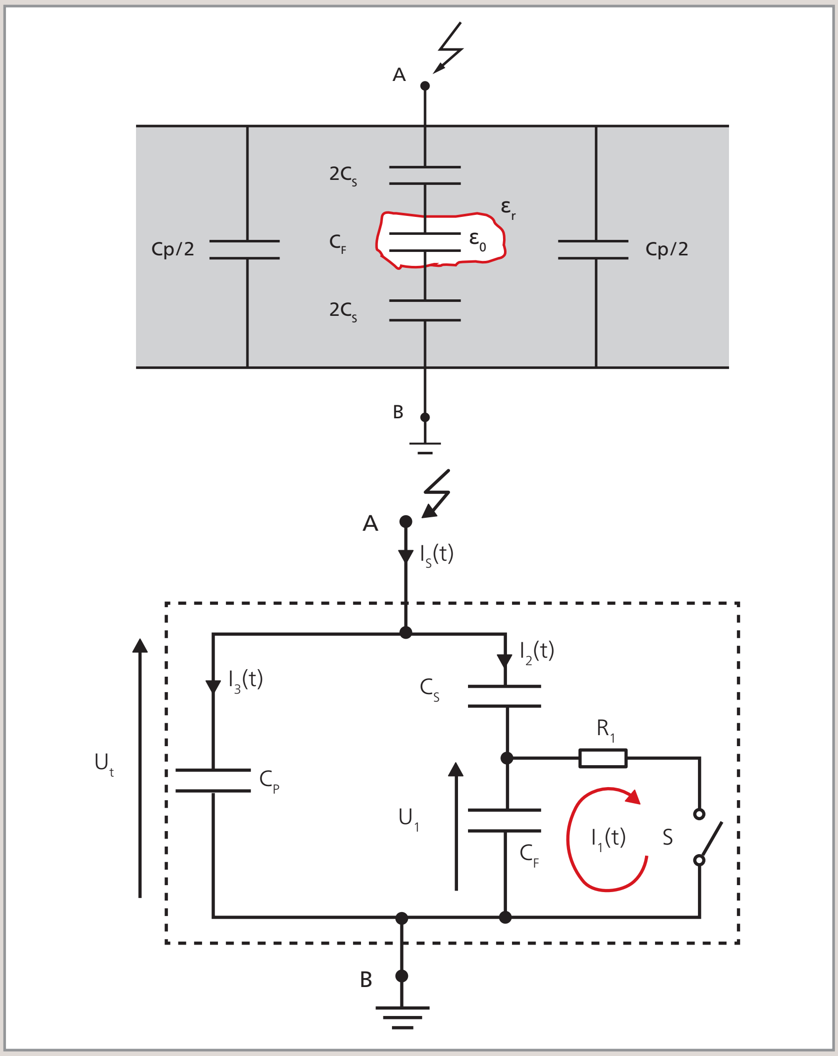


Figure 19. Recharge process explained on the principle of a void discharge

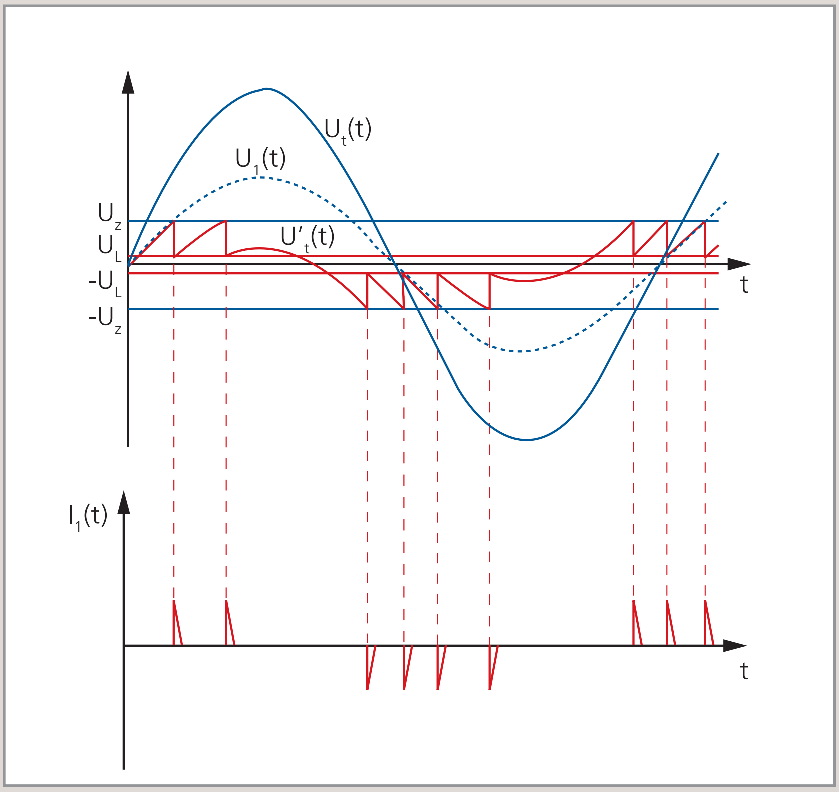
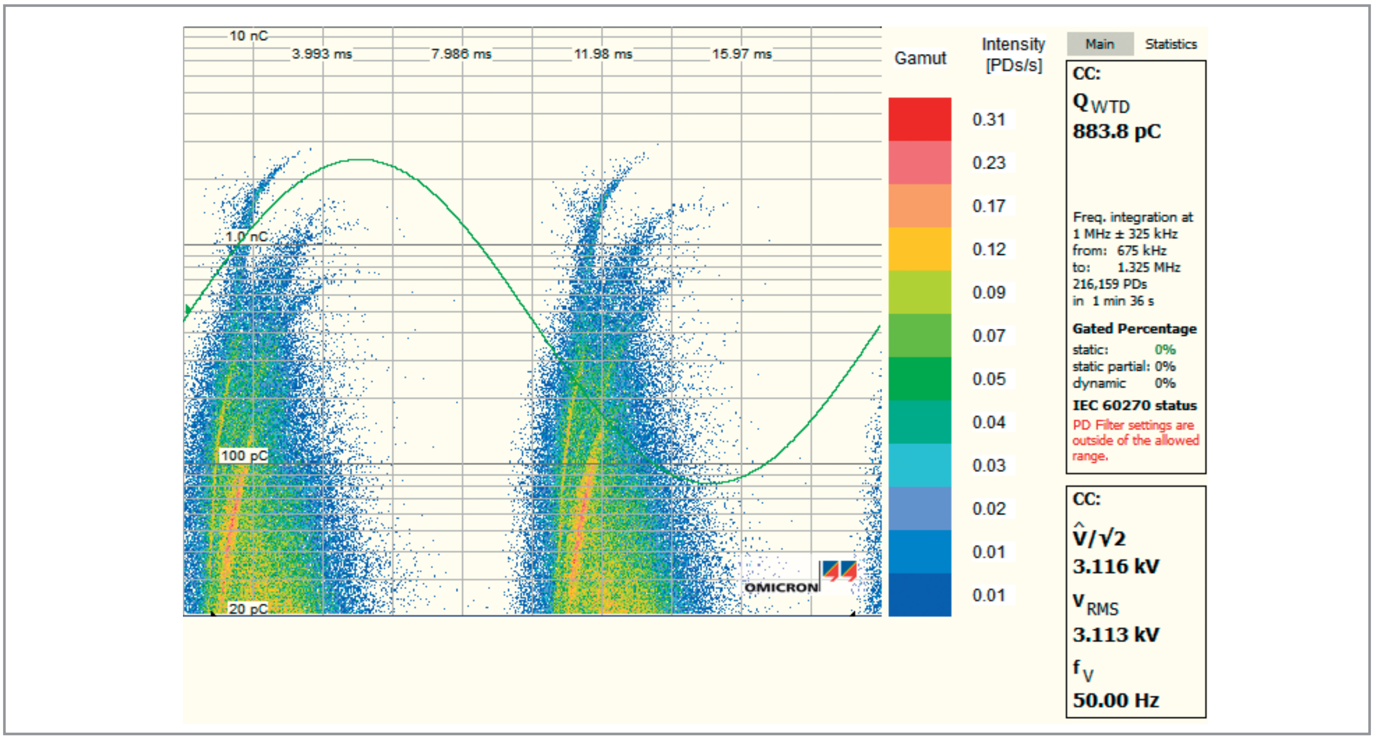


Figure 20. Recharge process explained on the principle of a void discharge



CC:
Q_{WTD}
883.8 pC

Freq. integration at
1 MHz ± 325 kHz
from: 675 kHz
to: 1.325 MHz
216,159 PDs
in 1 min 36 s

Gated Percentage
static: 0%
static partial: 0%
dynamic 0%

IEC 60270 status
PD Filter settings are outside of the allowed range.

CC:
$\hat{V}/\sqrt{2}$
3.116 kV
V_{RMS}
3.113 kV
f_V
50.00 Hz

Figure 21. PRPD pattern of void discharges

Bibliography

[7] *A. Küchler, Hochspannungstechnik*, Heidelberg 2009

[8] *Trench Instruction Manual Coupling Capacitor Voltage Transformers*, Bulleting 20 95 05, Revision 03, 02/2012

[9] M. Koch, *Reliable Moisture Determination in Power Transformers*, PhD thesis, Institute of Energy Transmission and High Voltage Engineering, University of Stuttgart, Sierke Verlag Göttingen, Germany, 2008

[10] DIRANA application note: Measuring and analyzing the dielectric response of current transformers

[11] M. Anglhuber, *Isolationsdiagnose an Messwandlern mit dielektrischer Antwortmessung*, Diagnosewoche 2015 in Austria

[12] IEC 60270 Third Edition / 2000-12, *High-voltage test technique – Partial discharge measurement*, Reference number CEI/IEC 60270:2000

[13] IEEE Std C57.13$^{\text{TM}}$-2016, IEEE Standard Requirements for Instrument Transformers, New York

[14] IEC 61869-1 Edition 1.0 / 2007-10, Instrument transformers – Part 1: General requirements

[15] IEEE, *Standard Requirements for Instrument Transformers*, IEEE Std C57.13TM-2008

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.

Dr. Michael Freiburg is responsible for instrument transformer tests and diagnostic equipment and is currently working as a product manager at OMICRON electronics in Austria. Prior to that, he worked as a research and teaching assistant at the Technical University in Dortmund, Germany. His research interests include the diagnostics of high voltage equipment and material science. In his undergraduate studies he focused on automation and control engineering before studying power engineering in his post-graduate courses. He received an engineering degree in 2010 and his PhD degree in high voltage engineering in 2014.

Dr. Martin Anglhuber received his degree in electrical engineering from the TU München in 2007. From 2007 to 2011 he worked as a scientific assistant at the Institute for High Voltage Technology and Power Transmission of the TU München, Germany and performed research on polymer nanocomposites as insulating material in high-voltage apparatus. He received his Dr.-Ing. (Ph.D.E.E.) degree in 2012. He joined OMICRON in 2012 as an Application Engineer and currently holds the position of a Product Manager in the area of dielectric transformer diagnostics. He is member of VDE and IEEE.