Condition assessment of transformer insulation during routine partial discharge (PD) tests and in-service monitoring

Routine testing of a distribution transformer using conventional and alternative PD methods as well as the advantages of continuous PD monitoring

ABSTRACT

To compare the results of in-service PD measurements with the results of conventional measurements previously performed during transformer routine testing in the factory, the use of alternative PD methods in the factory is proposed. The effective comparison of PD data results is possible with a measuring system with advanced hardware and software features. The minimum requirements of such a versatile PD measurement system are presented, and an example of the comparative measurements with conventional and alternative methods performed on a 1.6 MVA, 20 kV distribution transformer during routine testing is shown.

Also, the advantages of having continuous online PD monitoring systems installed on 500 MVA power transformers and 220 kV power cable lines are presented. The PD defect identification and its accurate localization made it possible to avoid a serious service failure.

KEYWORDS:

power transformer, electrical insulation, partial discharge, measurement, monitoring, synchronous multi-channel technique

Bogdan GORGAN, Wojciech KOLTUNOWICZ, Patrick ZANDER

Partial Discharge (PD) measurement is the most common, non-destructive method to detect even minor insulation defects in the electrical insulation system

There is an increasing demand from the users to have the possibility to compare the results of in-service measurements with the results of conventional PD measurements previously performed during routine testing

1. Introduction

Partial Discharge (PD) measurement is the most common, non-destructive method to detect even minor insulation defects in the electrical insulation system. The use of PD measurements is generally required during type and routine testing [1], and it is recommended for on-site commissioning and in-service dielectric testing of power transformers. The PD measurement results allow users to evaluate the insulation condition and trigger the detection and localization of critical defects [2–4].

Different methods were developed to increase the sensitivity of PD measurements based on different physical characteristics of the PD processes and can be split into conventional [5] and alternative methods. Among them, electromagnetic methods are based on the measurements of PD signals from high frequencies (HF) to ultra-high frequencies (UHF) [6].

For conventional PD measurements, the apparent charge is measured in pC. It is an integrated current impulse caused by a partial discharge, which flows through the test circuit. It allows a precise calibration. However, it needs a high signal-to-noise ratio (SNR) in the measurement circuit, which is often impossible to attain on site [2–3]. Regarding field-testing, where a very high background noise level is present, alternative methods showed to have an advantage. Measurements performed with UHF and acoustic sensors were proposed for PD detection. Until now, there are no dedicated international standards referring to these methods, as has been the case over the years for the conventional method [5].

There is an increasing demand from the users to have the possibility to compare the results of in-service measurements with the results of conventional PD measurements previously performed during routine testing in the factory. To meet such requirements, users are asking for the modification of the PD measurement procedure in the factory and include PD measurements with alternative methods. The type and frequency range of PD sensors are well-defined and follow the user PD Policy. The complete PD routine tests are recorded and stored in a user database. It must be underlined that when making PD measurements with alternative methods, it is not possible to quantitatively correlate or calibrate the received signal level in terms of apparent charge values in pC [6]. However, the PD defect patterns acquired with all methods show many similarities and enable the recognition of the PD defect type. The complete measurements can be helpful in evaluating the PD results during the on-site commissioning of the transformer and immediately afterwards during the first period of its service covered by the manufacturer´s guarantee. The efficient comparison of PD data results is possible when the PD measurement system has advanced hardware and software features. The minimum requirements of such fully digital and versatile systems will be presented in this paper. An example of the comparative measurements with conventional and alternative methods performed on a 1.6 MVA, 20 kV distribution transformer during routine testing will be shown.

The second part of this paper presents the advantages of continuous PD monitoring systems installed on 500 MVA power transformers and 220 kV power cable lines connected to a GIS when in-service together. The user decided to install the monitoring systems after a failure that occurred on a related transformer. The monitoring systems detected a PD signal coming from the repaired but not directly monitored transformer. The PD defect identification and its accurate localization allowed the user to avoid a serious service failure.

2. Minimum measurement system requirements for effectively combined PD measurements

Multiple sensors can be used to detect PD signals, like capacitive (coupling capacitors), inductive (high-frequency current transformers, also known as HFCTs), transient earth voltage (TEV), and acoustic or ultra-high frequency (UHF) sensors. Generally, all types of PD tests are performed with different equipment, so the direct comparison of the results is difficult. To make this possible, the PD acquisition unit should be fully digital and fulfil the following defined hardware and software requirements:

- Multi-channel and synchronous signal acquisition
- Wide and freely selected frequency range of measurements
- Post-processing of acquired signals
- Efficient techniques for separating PD defects from noise

Digital data acquisition and pre-processing units using high-performance FPGA technology are preferable. A highly sensitive analogue-to-digital converter at each channel can guarantee the acquisition of the signals from different types of sensors.

Multiple sensors can be used to detect PD signals, like capacitive, inductive, transient earth voltage, and acoustic or ultra-high frequency sensors

The PD measurement shall be performed synchronously with the conventional measurement method in three phases, and additional channels should be dedicated to acquiring the signals from HFCT and TEV sensors. The HFCT is designed to pick up induced partial discharge signals in the HF range, from easily accessible positions, at a safe distance from high voltages. It is primarily intended for use on grounding connections. The TEV sensor is an electromagnetic sensor that can detect high-frequency radiation coupled into earthed metal surfaces from PD.

It is advantageous to observe the PD pulses coming from all the sensors simultaneously in time and in the frequency domain and remark very fast changes in the related phase-resolved partial discharge patterns

It is advantageous to observe the PD pulses coming from all the sensors simultaneously in time and in the frequency domain and remark very fast changes in the related phase-resolved partial discharge (PRPD) patterns. The PD filter can be tuned to the measurement frequency range with an optimal signal-to-noise ratio (SNR).

For post-processing evaluation, a data stream is recorded and can be replayed at any time. The user can select the time range for the trending of PD (green trend) and voltage signal (red trend), which is shown in Fig. 1.

To separate noise from PD, different methods can be applied. The most common methods for noise separation are synchronous multi-channel or multi-spectral techniques and time-frequency classification maps [7–9].

With the multi-channel method, the system uses the synchronous processing of PD signals from sensors in three phases (3PARD diagram). The 3PARD displays the relation among amplitudes of a single PD pulse in one phase and its crosstalk in the other two phases. The three amplitude values are moved into a vector related to their voltage phase of origin. In the end, the addition of these three vectors results in a single dot position in the 3PARD diagram. Repeating this for larger number of PD signals, PD sources within the test object, as well as external noise, appear as multiple clusters (Fig. 7). Evaluating the individual clusters, a separation between noise / disturbance and PD signals is possible [7, 8, 10].

3. Conventional and alternative PD measurements during routine testing of a distribution transformer

The manufacturer agreed to perform the routine tests with simultaneous use of conventional and alternative methods. For the latter, HFCT and TEV sensors were connected to the versatile acquisition unit. The location of the sensors and measurement settings are well defined and recorded, as future in-service measurements have to follow the same guidelines. The fingerprint of the internal PD signal giving the amplitude within the acceptance level, obtained in the factory, can be monitored in-service with alternative methods.

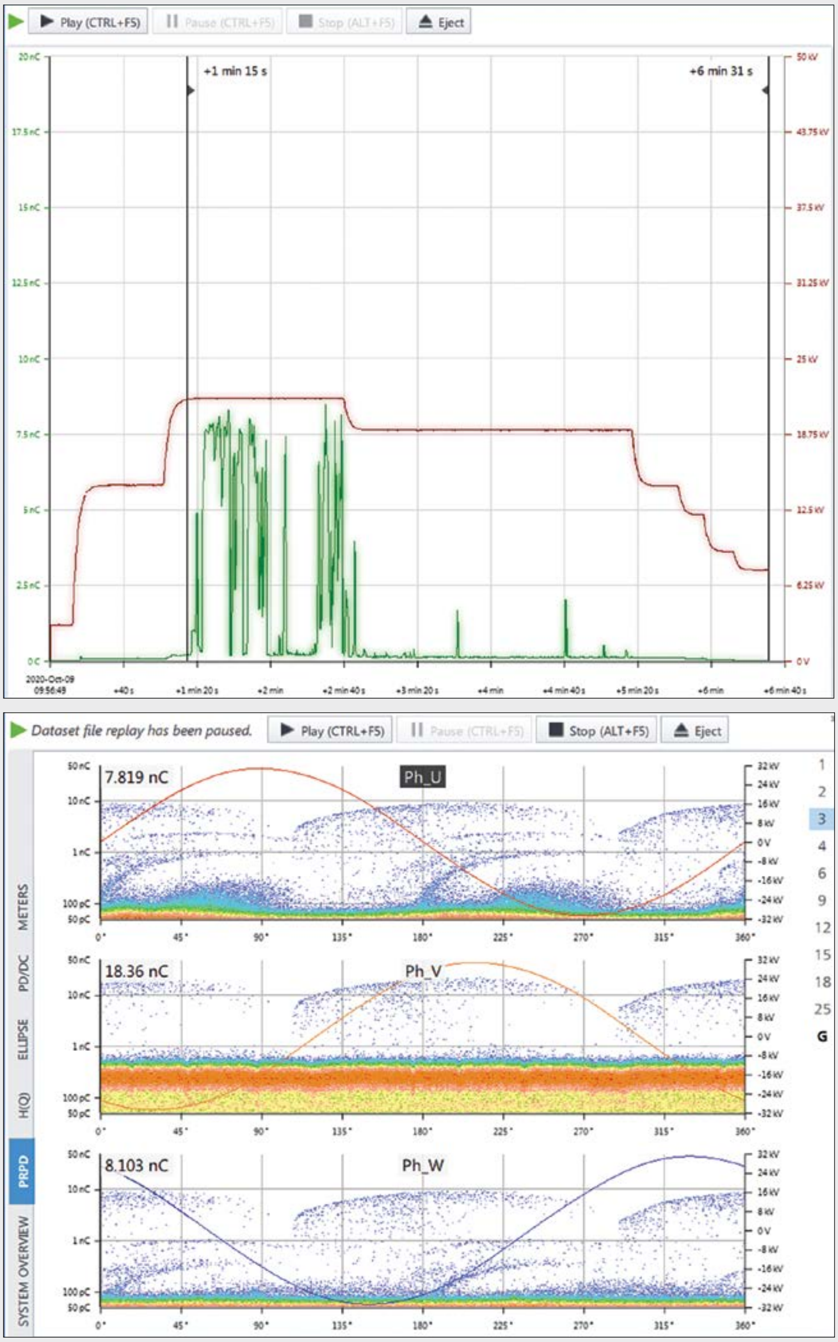

Figure 1. Replay diagram with recorded PD activity (green trend) and voltage applied during the test (red trend)

Combining the conventional and alternative measurements offers the advantage of confirming the internal insulation defects within the tank

PD measurements were performed in a factory on a 1.6 MVA, 20 kV distribution transformer (Fig. 2). For the conventional PD measurements, 2 nF external coupling capacitors were used. A noise level of 6 pC was achieved at a central measuring frequency of 250 kHz with a bandwidth of 300 kHz. The calibration was successfully performed for the conventional method.

PRPD patterns were synchronously recorded from the coupling capacitors, HFCT and TEV sensors. The PRPD patterns indicating internal defects were recorded by conventional measurements and with an HFCT placed at the low voltage neutral connection (Fig. 3).

Fig. 4 shows a comparison of PRPD patterns measured with the conventional method for U and V phases and with the two TEV sensors located at the top and bottom of the transformer. Similar PRPD patterns obtained with all types of sensors were noted.

Combining the conventional and alternative measurements offers the advantage of confirming the internal insulation defects within the tank. The conventional measurements performed synchronously in three phases give additional information about the phase location of the PD source. This was even obtained on the tested distribution transformer smaller in size compared to much bigger transmission units.

4. Benefits of monitoring systems installed on connected power transformers and power cables

After a failure on one of the 500 MVA power transformers (Transformer 2), the user decided to install a PD monitoring system on two other 500 MVA, 400/220 kV power transformers (Transformer 1 and Transformer 3) as well as on four connected 220 kV power cables (Fig. 5). PD monitoring allows users to observe PD activity related to various operational conditions or loads to support asset management decisions.

After the installation and calibration of the monitoring system on both transformers, the monitoring systems detected and recorded an increasing PD signal at both transformers. Alarms were triggered based on the pre-set levels and automated reports were sent to the user. The PD signals with lower amplitude were also detected at the cable terminations. The PD charge trends for Trans-

Figure 2. Tested distribution transformer and the setup for the conventional PD measurements

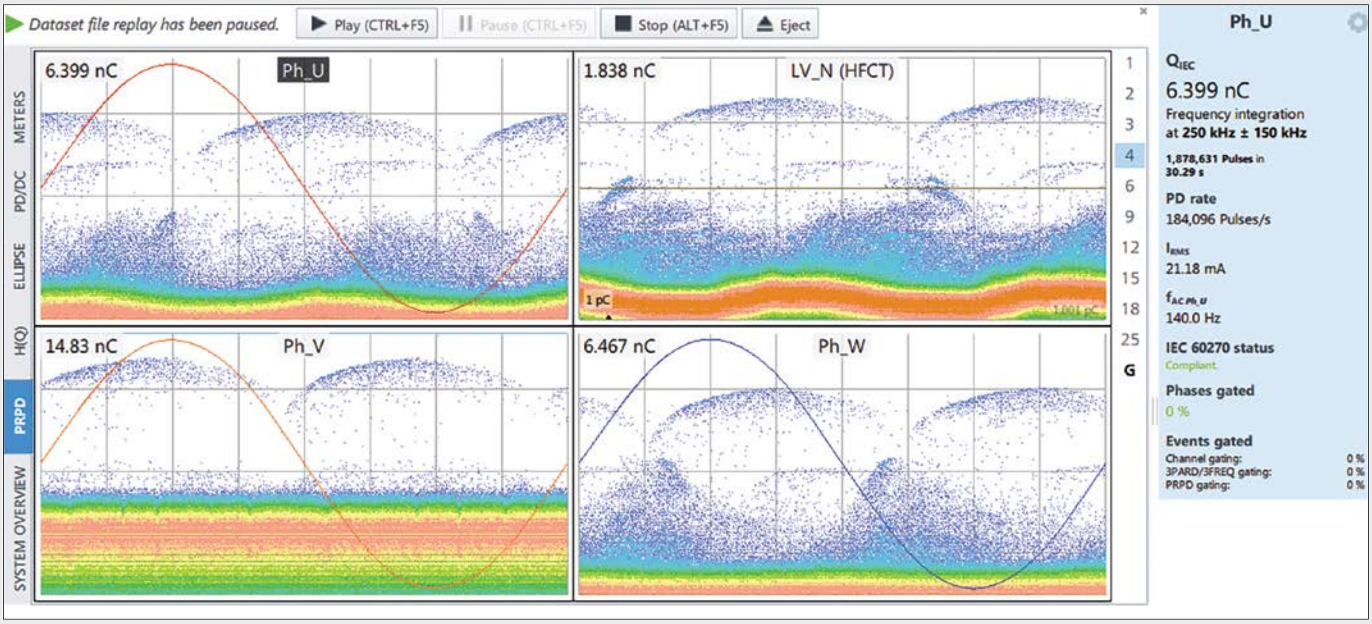

Figure 3. PD measurements with coupling capacitors and HFCT sensors placed at the grounding connection

former 3 are presented in Fig. 6. The PRPDs and 3PARDs for Transformer 3 are presented in Fig. 7.

After the installation and calibration of the monitoring system on both transformers, the monitoring systems detected and recorded an increasing PD signal at both transformers

The PD signal appearing as horizontal lines and equal in amplitudes for both voltage polarities is typical for a bad contact pattern. It had a very good coupling between the different electrical equipment close by, and its amplitude increased steadily. Dissolved gas analysis (DGA) was performed on samples from the two transformers, and the results showed no abnormalities. To confirm that the source of the PD activity is outside of the monitored transformers and cables, additional online PD measurements were performed using HFCTs installed on the 220 kV (LV side) cable

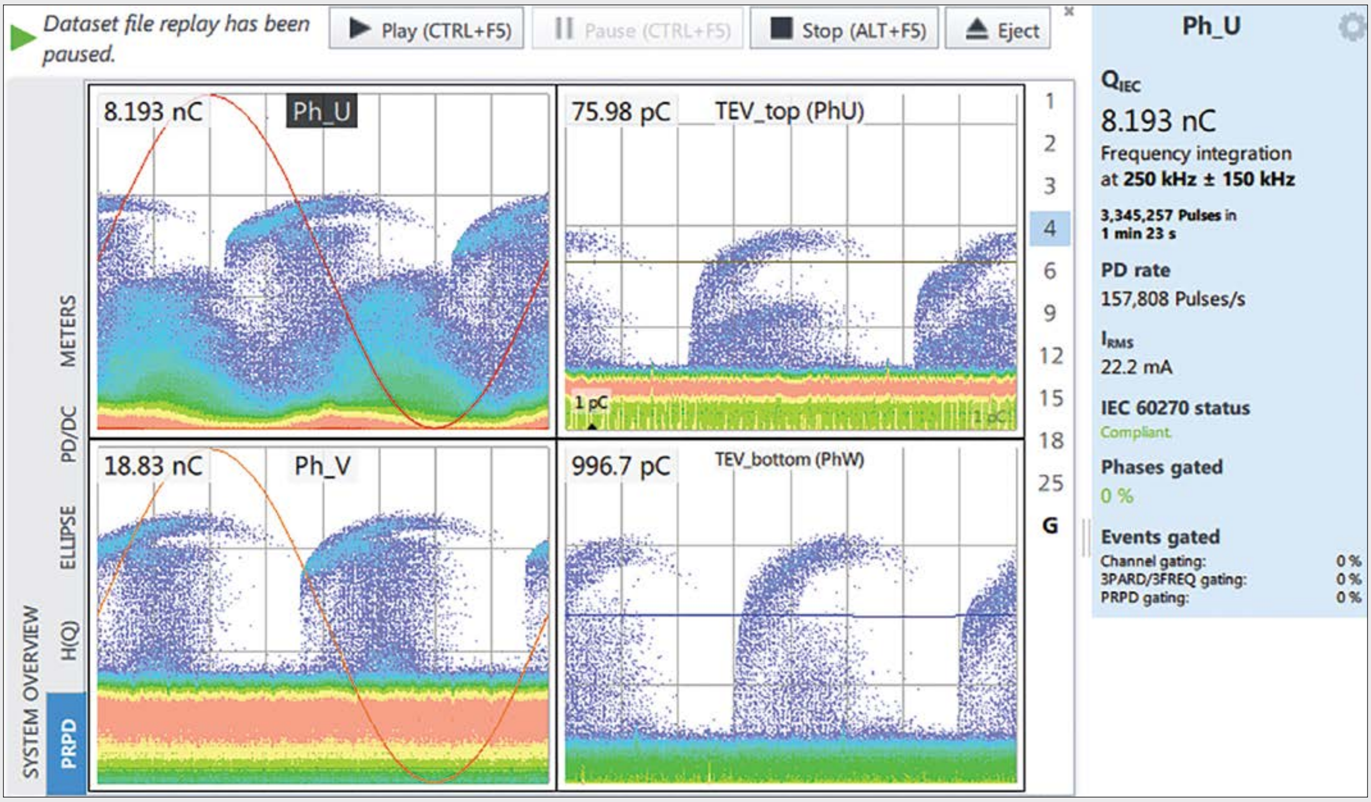

Figure 4. PRPD patterns with the conventional method for U and V phases (left) and the alternative method using two TEV sensors (right)

Based on the evaluation of the PD signal amplitude with the 3PARD technique, the location of the PD defect was identified in phase W at Transformer 2

screens connected to the initially repaired Transformer 2. Three-channel synchronous PD measurements were performed in two configurations:

1. Between the same phase of Transformers 1, 2 and 3, and
2. By connecting all phases of Transformer 2.

Based on the evaluation of the PD signal amplitude with the 3PARD technique, the location of the PD defect was identified in phase W at Transformer 2. The amplitude of the signal measured at 4 MHz (best signal-to-noise ratio) was approximately 119 nC (Fig. 8).

To confirm the findings, Transformer 2 was switched-off, and further off-line diagnostic measurements were performed. After the transformer was switched-off, the PD signal disappeared from all PD acquisition units. The PD charge trend on Transformer 3 is presented in Fig. 9.

The surge arrester on the 220 kV side of the Transformer 2 was discovered to be defective, and its replacement was necessary to avoid serious failure in the system. Using the results from the installed monitoring systems, it was possible to detect an ongoing defect originating from a nearby electrical component.

5. Conclusions

The simultaneous use of conventional (IEC 60270) and alternative PD methods based on measurements with TEV and HFCT sensors during factory tests of a 1.6 MVA, 20 kV distribution transformer is proposed. The comparison of PD data results was possible with the PD

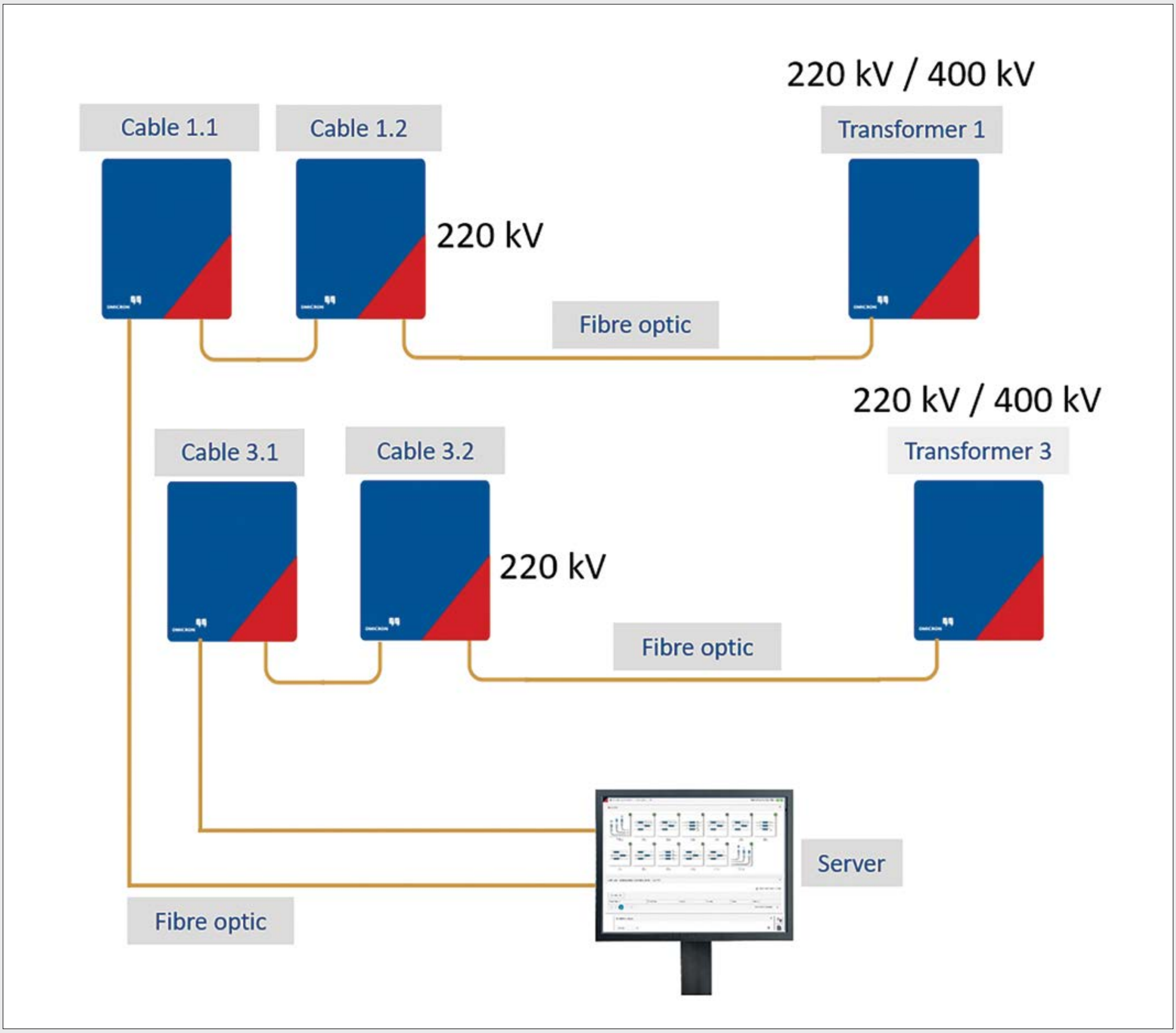

Figure 5. PD monitoring system architecture

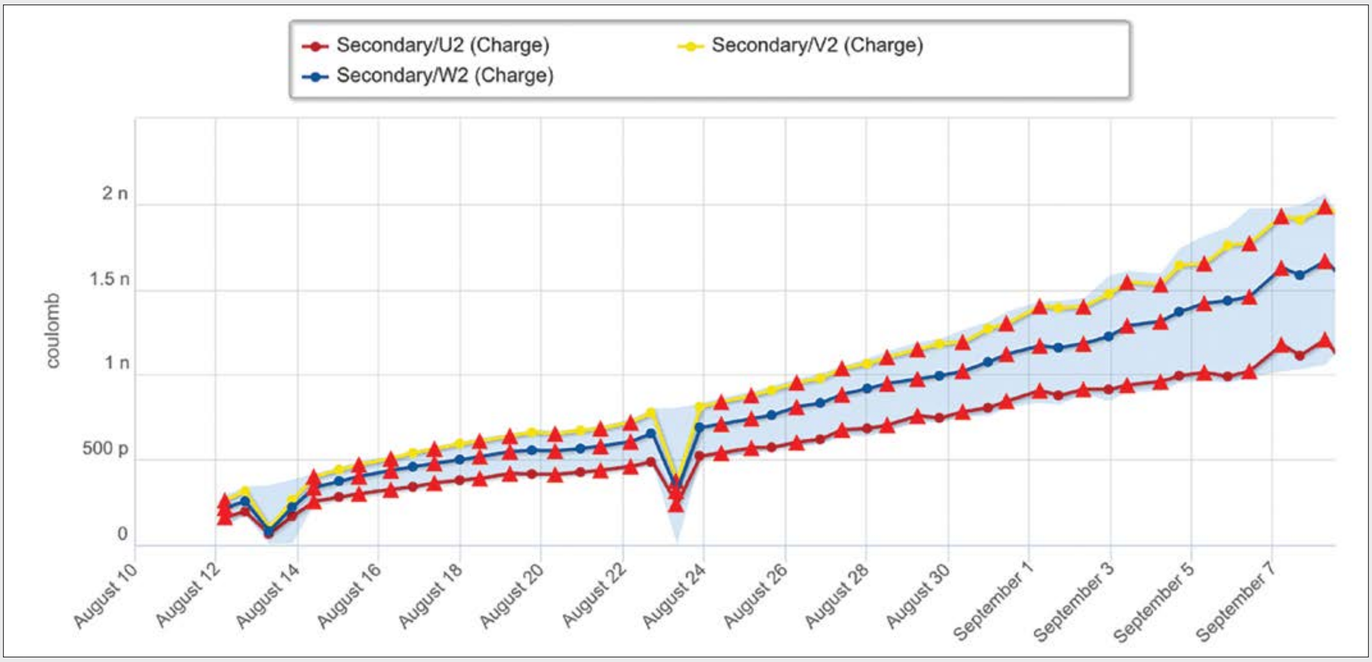

Figure 6. PD signal trends for Transformer 3 (red – phase U, yellow – phase V and blue – phase W)

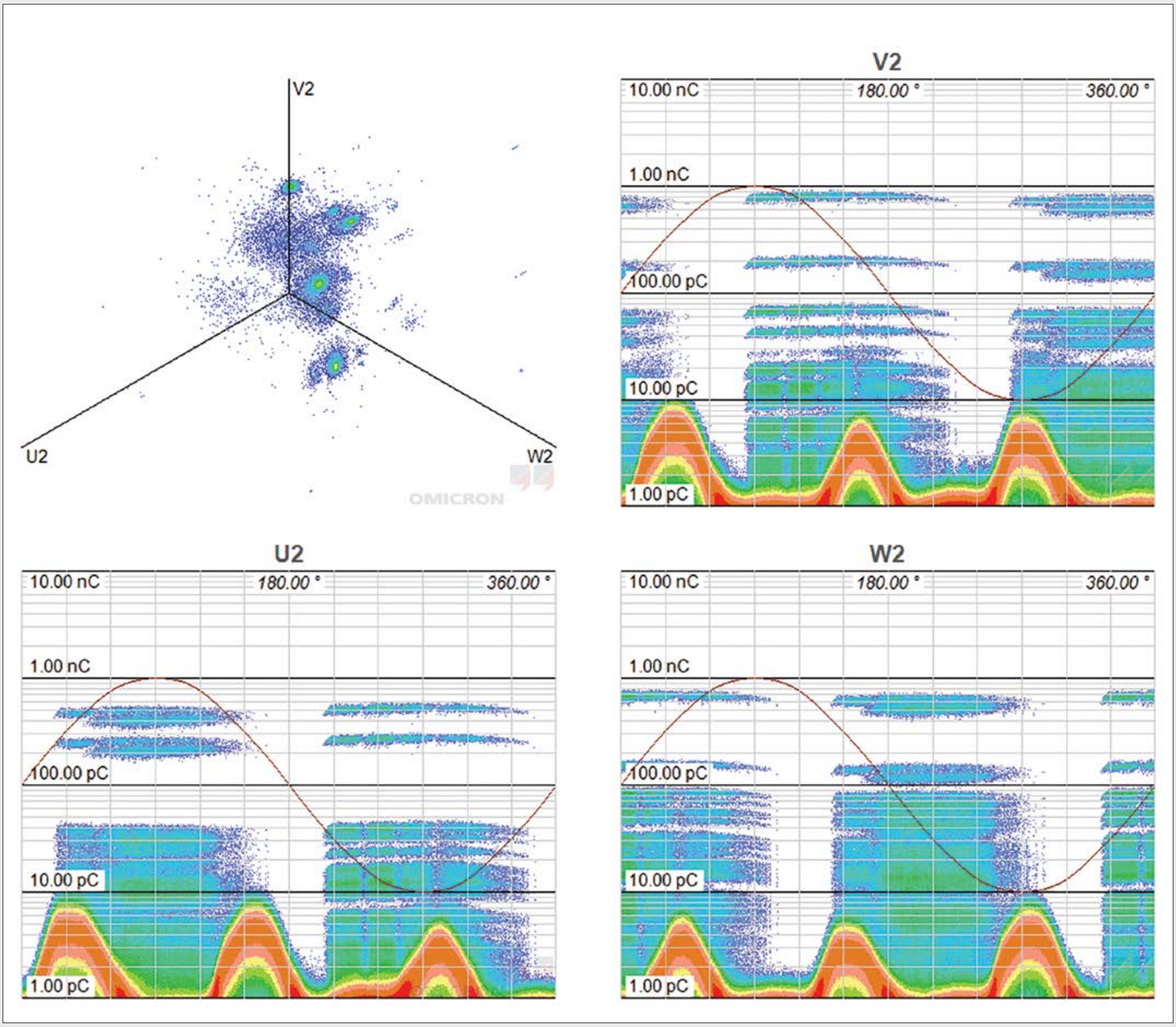

Figure 7. PRPD and 3PARD for Transformer 3

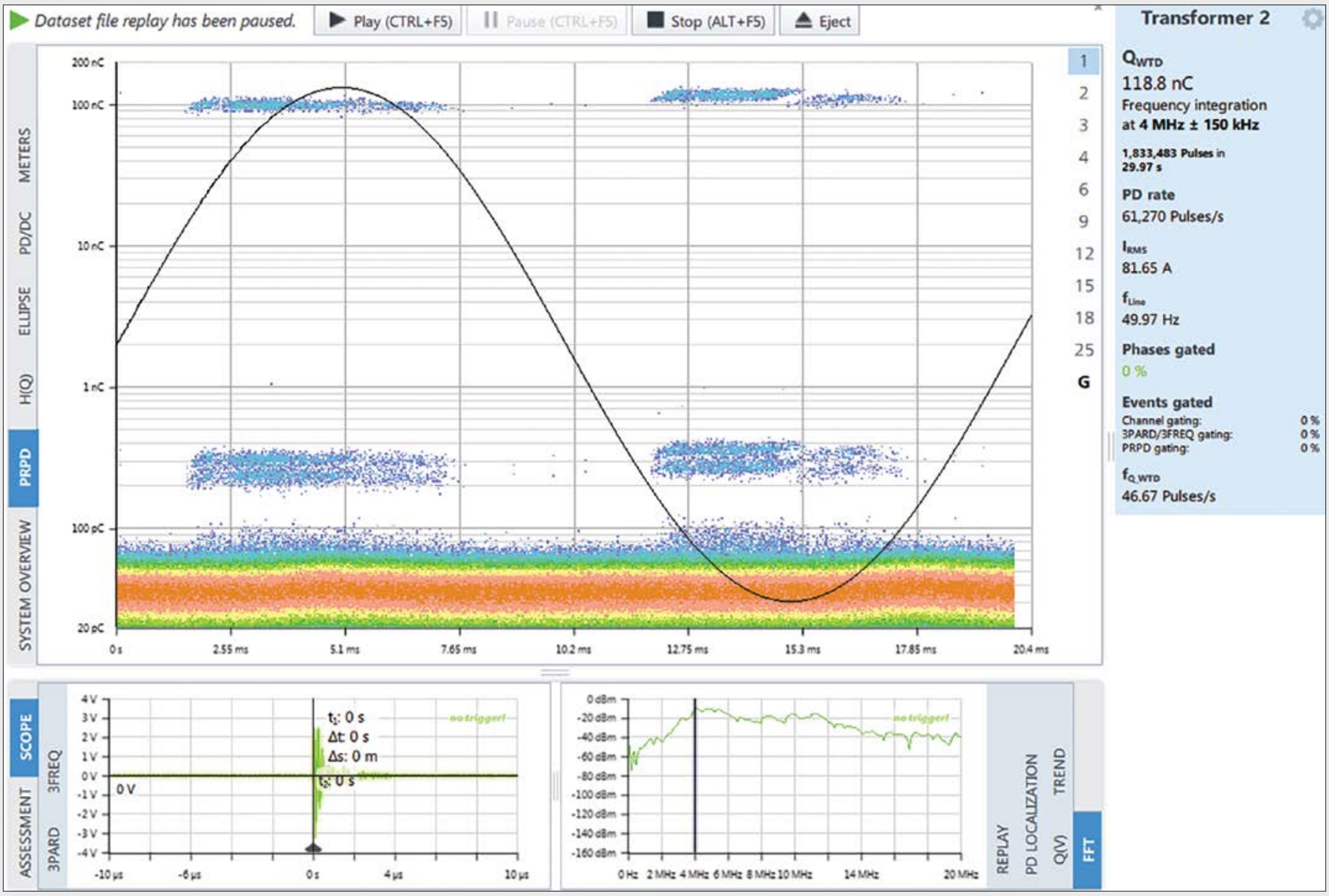

Figure 8. PRPD of Transformer 2, phase W

The surge arrester on the 220 kV side of the Transformer 2 was discovered to be defective, and its replacement was necessary to avoid serious failure in the system

measurement system having advanced hardware and software features, such as multi-channel and synchronous signal acquisition, a wide and freely selected frequency range of measurements to cover the frequency operating range

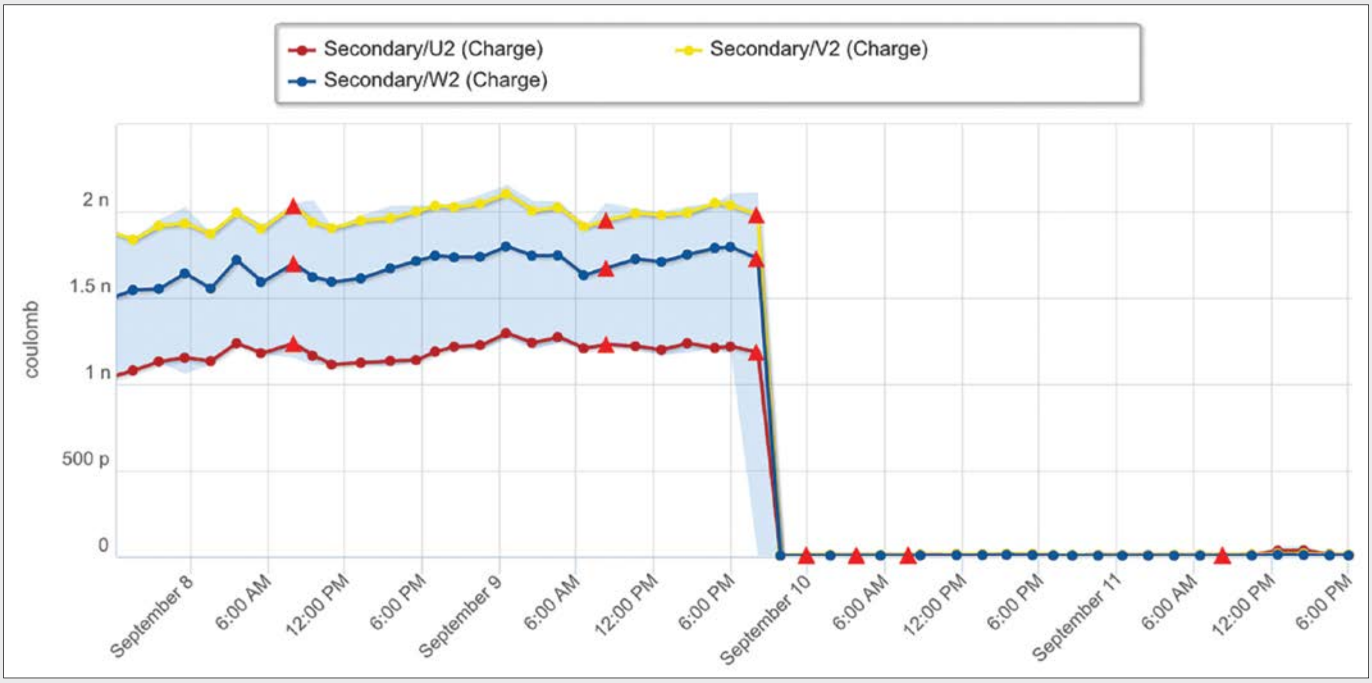

Figure 9. Charge trend for Transformer 3

of the different PD sensors, detailed post-processing of acquired signals, and an efficient 3PARD system to separate PD defects from noise.

The advantages realized by the continuous PD monitoring systems installed on the in-service 500 MVA, 400 kV power transformers and 220 kV power cable lines are demonstrated as follows:

- The warning threshold levels were properly configured, so the incipient defects were identified. The automated reports were generated and sent to the user.
- A trending function enabled the user to observe the behaviour of the PD signals and helped to take the appropriate actions.
- The 3PARD technique was successfully used to separate PD signals from noise and identify the defect´s type and its phase of origin. The presence of the defect was confirmed with additional diagnostic measurements.
- The user was able to avoid a serious service failure.

Bibliography

[1] IEC 60076-3, Edition 3.0, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*, 2013

[2] CIGRE TB 676, *Partial Discharges in Transformers*, February 2017

[3] CIGRE TB 662, Guide*lines for partial discharge detection using conventional (IEC 60270) and unconventional methods*, August 2016

[4] CIGRE TB 857, *On-site assembly, on-site rebuild, and on-site high voltage testing of power transformers*, December 2021

[5] IEC 60270, *High-voltage test techniques – Partial discharge measurements*, 2015

[6] IEC TS 62478, *High voltage test techniques – Measurement of partial discharges by electromagnetic and acoustic methods*, 2016

[7] W. Koltunowicz, R. Plath, *Synchronous multi-channel PD measurements*, IEEE Transactions on Dielectrics and Electrical Insulation, 15, No. 6, pp 1715–1723, 2008

[8] W. Koltunowicz, B. Gorgan, U. Broniecki, J. Nadaczny, B. Pawlik, J. F. Cordova, D. A. Barbadillo, *Evaluation of stator winding insulation using a synchronous multi-channel PD technique*, IEEE Transactions on Dielectrics and Electrical Insulation, 27, No. 6, 2020

[9] A. Cavallini, A. Contin, G. C. Montanari, F. Puletti, *Advanced PD inference in on-field measurements, Part I, Noise rejection*, IEEE Transactions on Dielectrics and Electrical Insulation, 10, No. 2, pp. 216–224, 2003

[10] B. Gorgan, W. Koltunowicz, T. Bednarczyk, *Evaluation of transformer insulation with different PD methods using a synchronous multi-channel technique*, Proceedings of the 22nd International Symposium on High Voltage Engineering (ISH), 2021

Authors

Bogdan Gorgan was born in Buzau, Romania in 1985. He received Dipl.-Ing. and PhD degrees in electrical engineering from University Politehnica in Bucharest, Romania, in 2009 and 2013, respectively. From 2012 to 2016, he was with Simtech International in Bucharest, Romania, where he was mainly involved in HV testing and diagnosis of power transformers. From 2016 to 2021, he worked as an HV application engineer with OMICRON Energy Solutions GmbH in Berlin, Germany. His focus was on the monitoring and diagnostic services of HV equipment as well as customer training. Since 2022, he has been a product manager for PD monitoring solutions at OMICRON Energy Solutions GmbH.

Wojciech Koltunowicz was born in Gliwice, Poland in 1956. He received his M.S., PhD and Dr. habil. degrees in electrical engineering from the Warsaw University of Technology in 1980, 1985 and 2004, respectively. From 1987 to 2007, he worked at CESI in Italy, where he was mainly involved in the HV testing and diagnostics of electrical equipment. In 2007, he joined OMICRON Energy Solutions GmbH in Berlin, Germany, where he was involved in monitoring of HV equipment. He is convenor of CIGRE WG D1.66 and a member of CIGRE AG D1.02 and AG D1.04. He is also a senior member of IEEE.

Patrick Zander works as a sales and application engineer for partial discharge diagnostic and monitoring solutions at OMICRON Energy Solutions GmbH, based in Berlin, Germany. He received his bachelor's degree in service engineering in 2015 at the University of Cooperative Education Leipzig (Germany). Before joining OMICRON, Patrick worked as an application engineer in Baumüller Services, being an automation system and drive specialist focusing on testing and assessing high-voltage electrical equipment, such as rotating electrical machines and power transformers. In 2018, he joined OMICRON as part of the partial discharge technical specialist team, delivering training and consultation services to customers and extended support to the research and development department for new products. He is currently responsible for coordinating PD monitoring application-related queries in Asia, Central Europe, and Pacifica as a cross-regional product promoter within OMICRON.

PEER REVIEWED