EXPERIENCE FROM PARTIAL DISCHARGE MONITORING OF ROTATING MACHINES

L.V. Badicu, W. Koltunowicz, and A. Piccolo
OMICRON Energy Solutions GmbH, Lorenzweg 5, Berlin 12099, Germany

Abstract: The insulation of rotating machines has to withstand Thermal, Electrical, Ambient and Mechanical (TEAM) stresses during its service lifetime. Partial discharge (PD) measurements applied to coils and complete stator windings detect manufacturing defects and also insulation degradation caused by aging processes. To detect insulation degradation at an early stage and to prevent severe failures in service, continuous monitoring of PD has been proposed for proper maintenance management to guarantee a high level of asset reliability.
In this paper, the experience from continuous partial discharge monitoring to assess the condition of generator stator winding insulation is presented. The case studies are related to monitoring of hydro and turbo generators of different rated power from 140 MVA to 1160 MVA. The advanced features for elimination of disturbances and for separation of different types of insulation defects based on synchronous, multi-channel and multi-frequency techniques are shown. The examples of data evaluation are described in detail and the use of the automated PD pattern recognition system is also discussed.

1 INTRODUCTION

A partial discharge (PD) is a complex physical phenomena resulting from local electrical stress concentration in the insulation. On the one hand, the PD variety and its unstable stochastic behavior, make PD measurement one of the most difficult tasks in high voltage testing. On the other hand, PD measurement is a worldwide accepted method for insulation diagnosis and a required part of acceptance testing of most high voltage (HV) assets.
PD measurements applied to coils and complete stator windings detect manufacturing defects like poor impregnation of mica paper layers, but an increase of PD activity also indicates insulation degradation caused by aging processes such as overheating, load cycling and coil vibration. The worldwide return of failure experience in hydro generators is presented in Fig. 1.

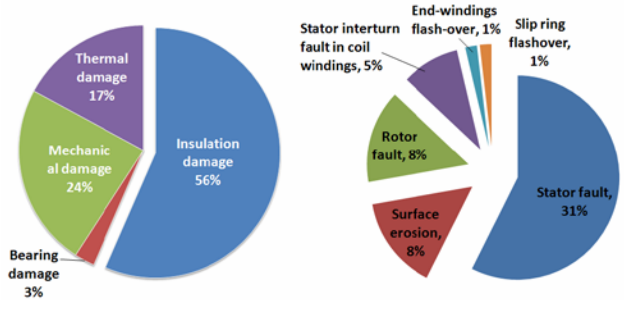

Figure 1 Return of failure experience on hydro generators [1]

To detect insulation degradation at an early stage and prevent severe failures in service, detailed information on the actual insulation condition is necessary. To fulfill these requirements monitoring of PD has become a well-recognized tool for proper maintenance management to guarantee a high level of asset reliability.
On-line, continuous partial discharge (PD) monitoring has been used for decades to assess the condition of a generator stator winding insulation system [2]. Modern digital monitoring equipment, with advanced hardware and software capabilities, has allowed improving insulation diagnostics by means of PD analysis. The determination of the type of defect and its severity is easier to observe in normal machine operating conditions and the results of the data evaluation are more accurate. This helps maintenance engineers set up an effective condition based maintenance program [1].
The first part of the paper describes in details the concept and elements of a modern PD diagnostic system [3]. The second one deals with the aspects of interpretation of PD monitoring data, coming from practical cases studies. Four cases related to machines with different insulation technology as well as different rated voltages and powers are considered:

- Turbo generator of 1160 MVA and 27 kV
- Turbo generator of 436 MVA and 20 kV
- Turbo generator of 180 MVA and 16.5 kV
- Hydro generators of 140 MVA and 16.5 kV.

2 PD MONITORING CONCEPT

OMICRON has developed an advanced concept of a modern on-line continuous PD monitoring system (Fig. 2). The signals from PD sensors are synchronously acquired in a three-channel data acquisition unit, which performs pre-processing of the raw data to remove disturbances and to determine PD characteristics.

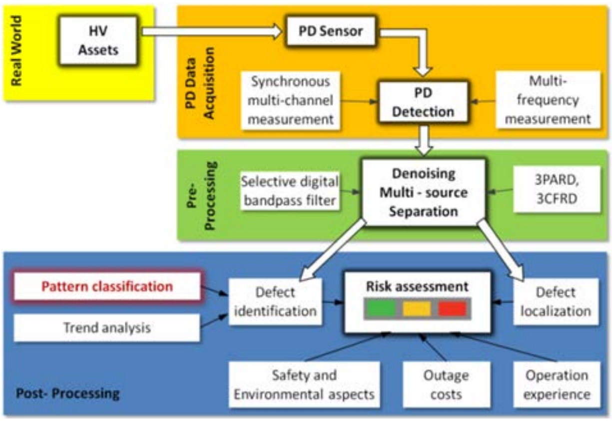

Figure 2 Concept for continuous PD monitoring

The output of the PD data pre-processing is transferred to a server that enables long-term data storage. Advanced intelligent pre-processing reduces the amount of data to adequate levels for transmission over a communication network. An expert system performs intelligent data post-processing to get useful information about the insulation condition. The type of the PD defect is identified by means of an automated pattern classification system [3].

The main key to perform automatic diagnosis of the state of insulation is the exact separation of different PD sources and effective suppression of external noise. To achieve this, synchronous multi-channel and multi-spectral evaluation techniques are applied.

Synchronous Multi-channel PD Evaluation Technique (3PARD) was originally developed for evaluation of three-phase PD measurements because its application requires three independent PD observers such as coupling capacitors connected to the three terminals of a generator. The 3PARD (star diagram) visualizes the relation among amplitudes of a single PD pulse in one phase and its crosstalk generated signals in the other two phases. By repetition of this procedure for a large number of PD pulses, PD sources within the test object as well as outer noise appear as clearly distinguishable concentration of dots in a 3PARD diagram [3].

Synchronous Multi-spectral PD Evaluation Technique (3CFRD) enables synchronous multi-spectral PD measurements to separate PD sources. In contrast to 3PARD, 3CFRD evaluation is performed on a single channel PD measurement. Multi-spectral measurements are based on pulse spectra correlation by applying three different band-pass filters simultaneously. The three band-pass filters can be tuned to areas with low disturbance level. Through proper choice of the band pass center frequencies, it becomes feasible to perform PD measurements according to the IEC 60270 standard, and at the same time to remove practically all superimposed disturbances. The 3CFRD correlates the output of the three band pass filters exactly like 3PARD does with the pulse magnitudes of a PD triple simultaneously detected on three phases.

Both, 3PARD and 3CFRD diagrams show different pulse-type sources in separable clusters. Each cluster can be selected individually and the pattern displayed in a PRPD. No other sources are included in the pattern (Fig. 3).

OPTICS (Ordering Points To Identify the Clustering Structure [5]) is a highly efficient hierarchical density-based clustering algorithm. It is applied for the automatic clustering of heterogeneous 3PARD and 3CFRD data.

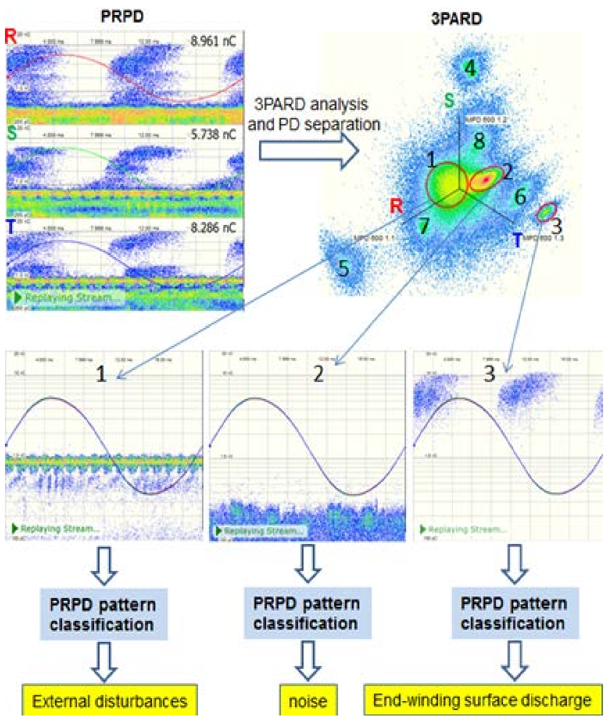

Figure 3 An example of automatic diagnosis of the state of insulation

3 OMS MONITORING SYSTEM ELEMENTS

3.1 Hardware of the system

Solid state coupling capacitors – called MCC – with nominal capacitance of 1.1 nF, integrated impedance and transient voltage suppressor diode, are designed for HV rotating machines (12 and 24 kV rated voltage). They can detect PDs in the frequency range according to the international standard IEC 60270 and consequently check all part of the winding exposed to HV stress. The high-frequency PD signal and the low 50 Hz signal for synchronization are available at sensor TNC output. Both signals are subsequently separated in the PD acquisition unit. Their strong mechanical robustness permits the installation of the MCC sensors in vertical as well as in horizontal positions (Fig. 4).

Figure 4 Capacitive sensors installed horizontally

The PD acquisition part of the OMS system consists typically of one three-channel acquisition unit for each motor/generator connected to a data controller. One data controller collects monitoring data from acquisition unit(s) via optical fibers (point-to-point or daisy-chain topology) and routes them via Ethernet to a laptop computer (Fig. 5). On a laptop computer pre-processing functions such as band-pass integration, gating, de-noising and multi-source separation are performed.

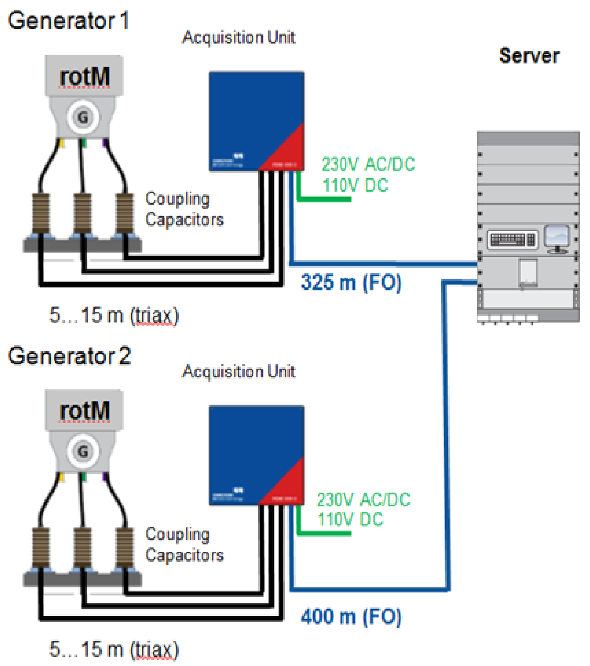

Figure 5 Architecture of the PD monitoring system

The PD signals are filtered, amplified and digitized in real-time (pipeline architecture). With an amplitude quantization of 14 bit and a sampling rate of 64 MS/s, a sub-sample time accuracy of ± 2 ns is achieved for synchronous multi-channel measurements. The quasi integration is achieved by a digital band-pass filter. The center frequency and the bandwidth can freely be chosen in the range from dc up to 30 MHz (selectable filter bandwidth from 9 kHz up to 3 MHz) to avoid disturbances and to reach an optimal SNR, even under noisy on-site conditions. All data acquisition and pre-processing routines are performed in the acquisition unit, which guarantees an optimum performance in speed and signal quality. Also included are an oscilloscope mode and an FFT-based spectrum viewer to analyze input signals with full bandwidth as well as a viewer to locate PD by time-domain reflectometry.

3.2 Software architecture

The OMS PD monitoring system includes a highly modular, scalable distributed software system. The system architecture consists of the Windows-based core part and the web-based control part (Fig. 6). The core part of the monitoring software is realized as Windows services and runs continuously without any direct user interactions.

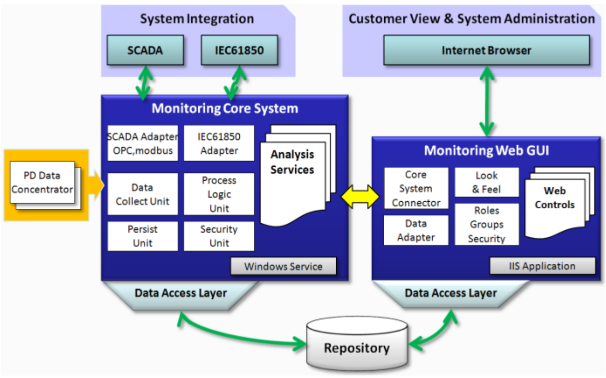

Figure 6 PD monitoring system architecture

The core system implements:

- Collection and persistence of measurement data served by a variety of connected PD acquisition devices in a repository (database) for long term storage through the flexible interfaces on the data access layer;
- Data post-processing and analysis through the process logic unit and the variety of analysis services (trending observation, pattern classification, risk assessment, estimation of the condition of monitored asset);
- Security tasks for data access and system operations, as well as a check of system integrity (housekeeping, self-monitoring);
- External interfaces (system integration layer) for data exchange over Ethernet or field bus

(e.g. Profibus DP, Modbus) with remote applications like SCADA or other monitoring systems.

The control part of the monitoring software system provides a graphical user interface for access and administration (Fig. 7). For continuous monitoring applications, the only software needed is an actual web browser running on the remote computer. This way, deployment and maintenance of special remote access software is avoided and remote access becomes completely platform-independent. The control part implements the functions for user interactions such as user identification, system administration, customizing of the monitoring system design and set-up parameters, post-processing data access, and reporting.

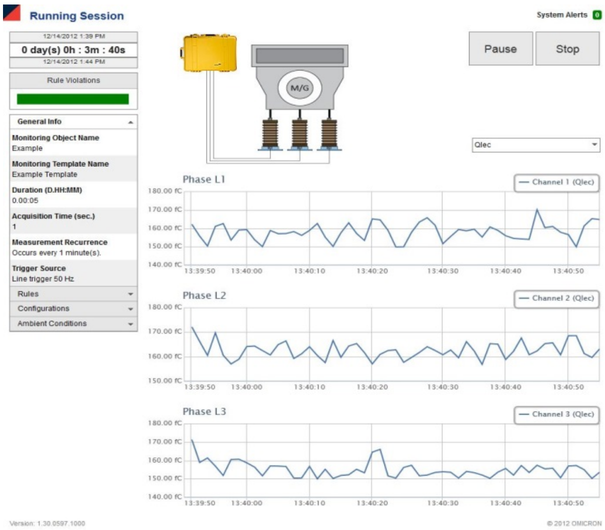

Figure 7 Example of graphical user interface

3.3 Data processing

The PD monitoring system provides PD data from each of the channels of the acquisition unit in time intervals defined by the user. PD activity is displayed as PRPD for each phase/sensor and for each separated PD source, respectively. Trend diagrams of statistical parameters such as PD magnitude, frequency of occurrence of PD pulses etc. are available. Suited filter options enable the user to constrain the data display according to his specific interest. The user can set limits, which cause warning or alarm messages when exceeded.

The monitoring data can be acquired in two modes, permanent and periodic, which are flexible and can be defined by the user. During normal operation only data from the periodic mode is stored to avoid overloading of the database. An example of data from periodic mode is shown in the PD trend diagram in Fig. 7. For each measurement, scalar values (apparent charge, repetition rate of the pulses, AC voltage phase and the absolute time) and phase resolved partial discharge (PRPD) patterns are saved.

In case of an alarm (threshold violation), data acquired in the permanent mode will be automatically stored and displayed in the trend diagram. Thus, only the most relevant monitoring data is kept for analysis while redundant information is discarded.

Automatic PD Defect Identification:

An automated PD defect identification is developed to classify several classes of stator winding PD defects and disturbances such as.:

- PD within the voids in the main insulation due to poor impregnation during manufacturing and because of thermal aging;
- PD on the surface of stator bars due to loose coils in the stator core or poorly manufactured electric stress relief coatings;
- Interferences.

The automated PD defect identification combines probabilistic (pattern recognition) and deterministic (knowledge-based analysis) approaches (Fig. 8). PRPD pattern recognition is a powerful and effective means to classify PD defects but involves algorithms, which have limited clarity for the user. Knowledge-based analysis imitates an expert's visual interpretation of PRPD data and provides an explanation of the reasons for the classification results.

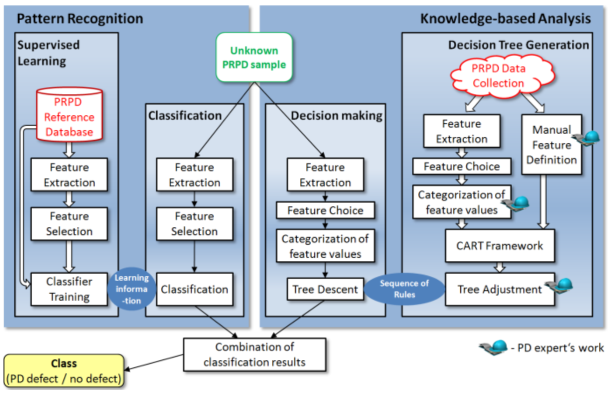

Figure 8 PD defect identification architecture

PRPD pattern recognition includes two modes: ‘supervised learning’ as a preprocessing mode and ‘classification’ as an operation mode. The ‘supervised learning’ is performed in advance to prepare for the classification of unknown samples. It is based on the reference database, which contains PRPD patterns labeled with classes. The result is learning information containing the setup data for the classifier. The content of the setup data depends on the classifier itself. The learning mode can be repeated to train the system for new features, a new classifier or for an updated reference database. ‘Classification’ is applied for each unknown sample. It contains the same feature extraction and feature selection steps, which were used during the learning mode, and it uses a classifier initialized with the derived learning

information. After 'classification', the sample is assigned to a particular class with some probability or it is rejected by the classification. The effectiveness of the classification is highly dependent on the algorithms and methods implemented in each step. An exhaustive comparative analysis was performed on numerous algorithms to optimize the classification performance. The most appropriate algorithms and effective performance evaluation procedures are applied in each step of PD defect recognition.
Knowledge-based analysis of PRPD data contains two modes as well: 'decision tree generation' as a preparation mode and 'decision making' as an operation mode. 'Decision tree generation' aims to express the PD diagnostic knowledge from a heterogeneous PRPD data collection in a form of classification tree for PD defects by using semi-automated and manual work of experts. Generated numeric and categorical features of PRPD data were used in a CART (Classification and Regression Trees) framework to construct the tree, which is adjusted further by experts to provide a proper hierarchical PD diagnostic model. The derived tree produces a sequence of heuristic rules using combinations of explanatory features (series of questions). During the 'decision making', which is applied for each unknown sample, tree descant is performed based on these rules. After 'decision making', the sample is provided with a diagnostic explanation (answers to the questions), which allows the sample to be assigned to a particular class [5].
A combination of classification results from these two approaches provides a reasonable certainty for the reasons to identify a particular PD effect. The results are shown in the automatically generated report (Fig. 9) including PRPD pattern, description of the identified PD defect as in the international standard, and its location in the rotating machine insulation schematic view. In addition, the details of two PD classification approaches and algorithmic characteristics describing PD behavior are presented.

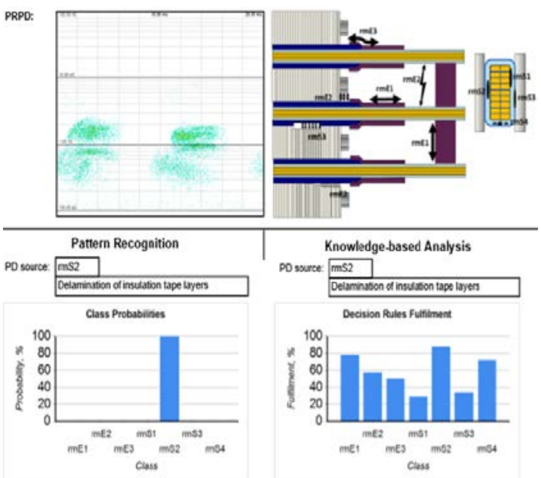

Figure 9 Automated pattern classification report

For more reliable assessment of the insulation risk failure probability, additional information has to be taken into account, for example: particular machine design knowledge, operation conditions and service experience, visual inspections and maintenance history, as well as the results of various non-PD offline diagnostic tests.

4 CASE STUDY: TURBO GENERATOR 1160MVA, 27KV

The 1160 MVA, 27 kV turbo generator was put in operation in 1998 and in 2012 was taken out of service for regular maintenance.
The on-line PD monitoring system was installed during the outage and it started immediately collecting data when the generator was put back into operation. It can be seen in the three-phase PD trend diagram (Fig. 10) that the PD level decreases after start up. After the conditioning time of two months, a data processing was performed with the support of an automated pattern classification system. The accuracy of automatic data evaluation depends on the efficiency of preliminary separation of different PD sources and on effective suppression of disturbances and background noise. To achieve this, synchronous multi-channel evaluation techniques were applied [4]. In Fig. 3, the external disturbances (cluster 1) and background noise (cluster 2) are separated from internal PD-like phenomena. The pattern of cluster 3 shows surface discharges in the end winding area of the phase T. Patterns of similar defect are identified by analyzing clusters 4 and 5.
Back transformation of clusters 6-8 has also been performed. Automated pattern classification was applied for the PRPD pattern corresponding to cluster 6 and the report is presented in Fig. 9.
According to the automatically generated report this pattern shows delamination of the insulation layers (class rmS2 – table 1). Similar data evaluation procedure was applied to PRPD patterns of clusters 7 and 8. The findings – reason for the PD activity evidenced by all clusters – are presented in Table 1. The defects classes are nominated as in [7].

Table 1 Classification of PD defects

Defect´s class	Defect´s type
rmS1	Discharges in micron cavities
rmS2	Delamination of the insulation layers
rmS3	Delamination of the insulation on the copper side
rmS4	Delamination of the insulation on the core side
rmE1	End-winding surface discharge (tracking)
rmE2	End-winding surface discharge (because of insufficient space)
rmE3	Discharge between corona protection and stress grading layers

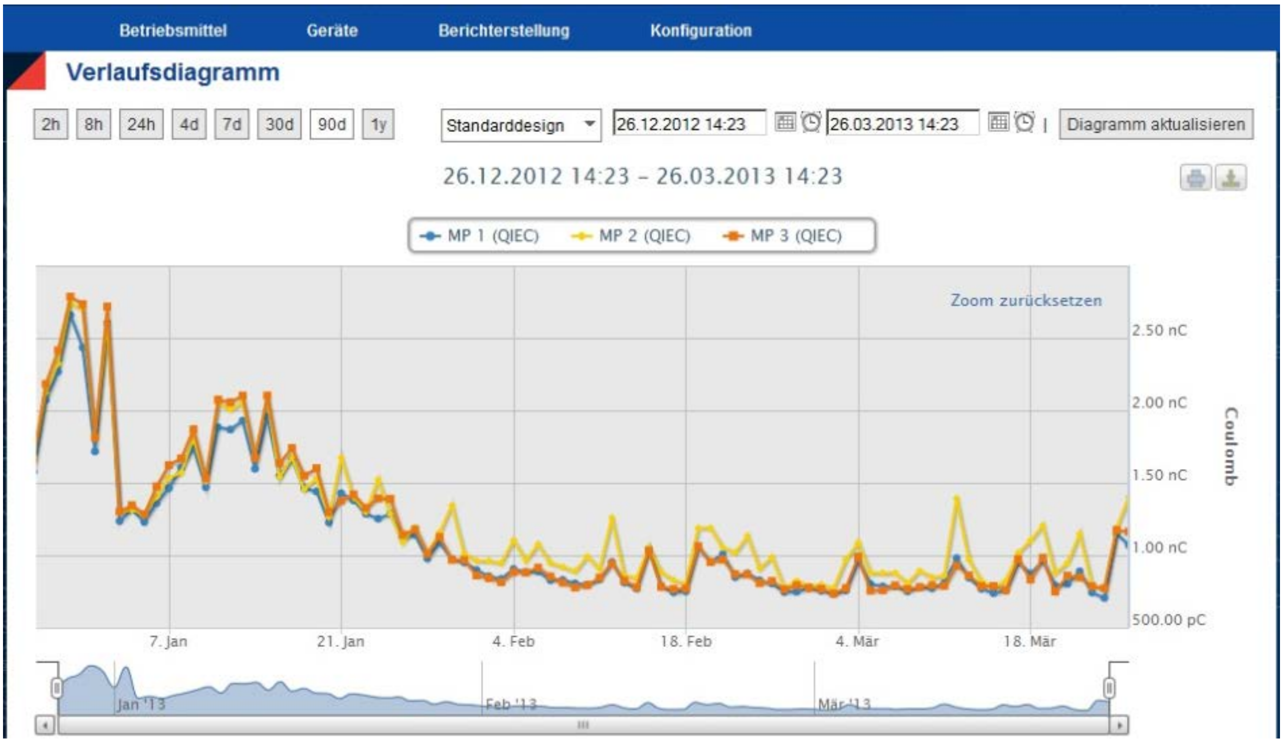

Figure 10 Three phase PD trend diagram

5 CASE STUDY: TURBO GENERATOR 436 MVA, 20 KV

On-line PD monitoring is installed on twin 436 MVA, 20 kV turbo generators, manufactured in 2007. The architecture of the monitoring system is shown in Fig. 5. Installed PD sensors are 1.1nF coupling capacitors.

Another key element in the separation of PD sources from each other and from the background noise is the digital band-pass filter of the acquisition unit. Center frequency and bandwidth can be freely chosen in the range from dc up to 30 MHz (with a selectable filter bandwidth from 9 kHz up to 3 MHz) to avoid disturbances and to reach an optimal signal-to-noise ratio (SNR), even under noisy on-site conditions. In this case the PD measurements in the Acquisition Unit are set to a center frequency of 1 MHz and bandwidth of 300 kHz in order to get an optimal SNR.
The start-up process of Generator 2 was monitored and in Fig. 11 the charge variation (green curve) during the increase of the voltage (red curve) is shown. The increase of PD activity can be correlated to the changes in load conditions (zones 2 and 3). The PD value increased from a few pC (background noise level) to 3.7 nC (Zone 2) and then to 5.7 nC (Zone 3) when the machine was at full load. The displayed voltage value is measured at the input to the acquisition unit. To get the real voltage value on the bus bar these values have to be multiplied by a divider factor of about 1000.

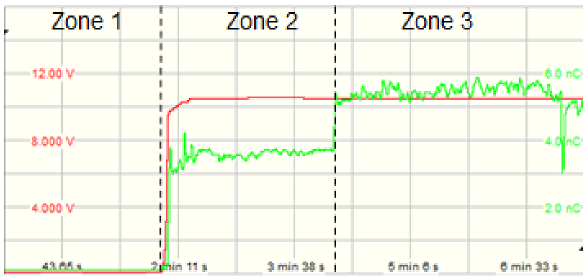

Figure 11 PD trend during the start-up process

The three-phase PRPD pattern of zone 3 is presented in Figure 12a. The 3PARD feature was applied to identify PD defects in the PRPD diagram. The back transformation of cluster 1 from the 3PARD diagram was performed (Fig. 12b) and the equivalent PRPD pattern is presented in Fig. 12c. This pattern has similarities with those generated by surface discharge in the end winding area, with the highest amplitude in phase S. The moisture contamination of the insulation surface during the outage might be one of the reasons for this type of PD. It should diminish with the operation time of the machine. The PD activity should remain under control. Clusters 2-4 from 3PARD diagram were discarded as they do not originate from the insulation system of the generator.

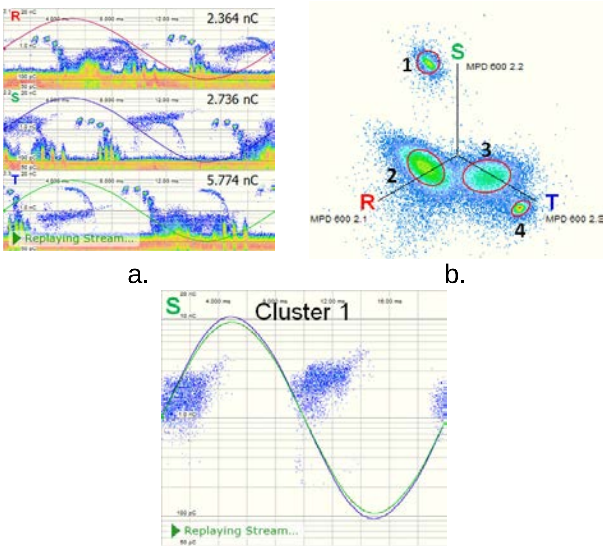

Figure 12 PD data evaluation using 3PARD feature

6 CASE STUDY: TURBO GENERATOR 180MVA, 16.5KV

This case study shows an example where preventive maintenance activity was triggered by the results from on-line PD monitoring. The device under monitoring is a 180 MVA turbo generator. Fig. 13 shows the three phase PD trend diagram and the PRPD patterns and 3PARD diagrams saved under each measured value.

According to the trend diagram, the increase of the PD signal in phase W (blue trend) from 20 nC to 75 nC within two months (June – August) was noticed. By analyzing the PRPD patterns within this time interval, the increase of PD activity generated by surface discharge in the end winding area was suspected. The separated PRPD pattern of this PD source is presented in Fig. 14.

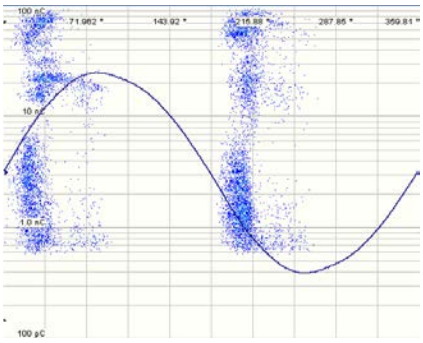

Figure 13 PRPD pattern showing end winding surface discharge separated using 3PARD

Consequently, the generator was taken out of service for further investigations. The high concentration of surface contaminants was confirmed as one of the causes of the steep increase of discharge activity. During the maintenance activity the end section of the stator windings was cleaned and no more surface discharges were detected, see Fig. 13 (after maintenance section). Based on the PD results obtained before and after the maintenance of the machine, the effectiveness of the maintenance program can be evaluated and the time when the generator has to be taken out of service for maintenance can be decided

7 CASE STUDY: HYDRO GENERATOR 140 MVA, 16.5 KV

On-line PD monitoring was installed on eight identical hydro generators into operation since 1987. Preventive maintenance was triggered by the high PD values recorded at one of these machines (G1). By analysing the three-phase PD trend diagram of G1 (Fig. 15) over three months, the increase of the PD level in phase S was observed (yellow trend).

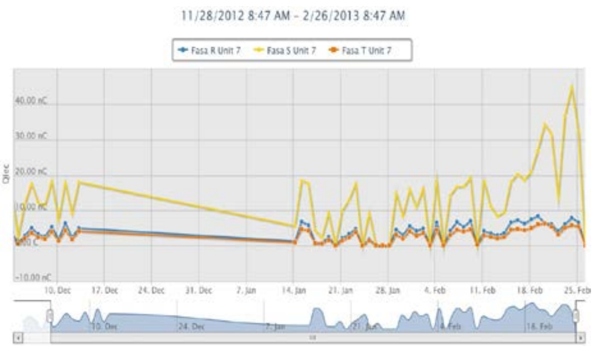

Figure 14 Three phase PD trend diagram

This indicated the existence of a PD source in this phase. Furthermore, data post-processing and automated pattern classification were applied in order to find the source of the high PD amplitude signal. The PD level is measured using 1.1 nF coupling capacitors and the digital filter was set to center frequency of 3 MHz and frequency bandwidth of 300 kHz. The three-phase PRPD pattern was analyzed and the 3PARD tool was applied to separate all PD sources from each other and from the background noise (BN). Fig. 16 shows the separation of the main PD source in phase S from the BN.

After the separation, the back transformation to individual PRPD pattern was performed and automated pattern classification was applied. The results indicated advanced delamination of the insulation layers of the stator bars, typical in machines in service for more than 20 years. PRPD patterns indicating the same type of PD source were discovered in the other phases of the machine. They show a lower PD level either because the delamination stage is less advanced or the PD sources are located deeper inside the windings, therefore subjected to more attenuation. Similar symptoms of insulation delamination were also observed on the other identical generator in the plant.

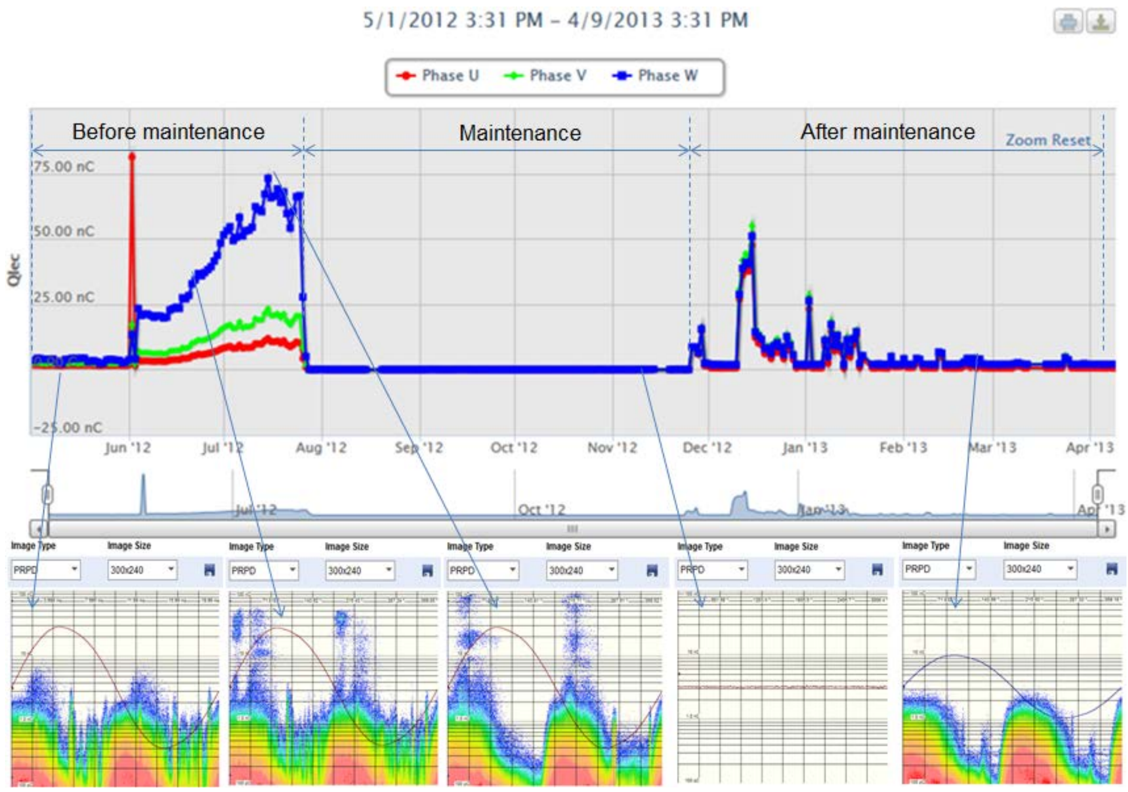

Figure 15 Three phase PD trend and PRPD patterns before and after maintenance

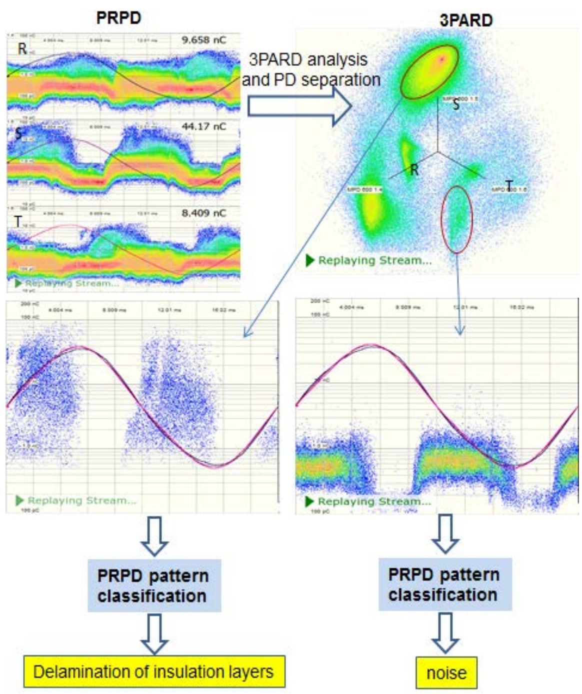

Figure 16 Advanced post-processing of PD

After the separation, the back transformation to individual PRPD pattern was performed and automated pattern classification was applied. The results indicated advanced delamination of the insulation layers of the stator bars, typical in machines in service for more than 20 years.

PRPD patterns indicating the same type of PD source were discovered in the other phases of the machine. They show a lower PD level either because the delamination stage is less advanced or the PD sources are located deeper inside the windings, therefore subjected to more attenuation. Similar symptoms of insulation delamination were also observed on the other identical generators in the plant.

8 CONCLUSIONS

Continuous PD monitoring systems identify the degradation mechanisms in the insulation of the stator winding. This way, weak points can be detected at an early stage and power failures can be avoided through the early implementation of maintenance and repair measures.

OMICRON's OMS monitoring system offers clever solutions to manage the difficult tasks of PD monitoring in noise environments. Synchronous multi-channel and multi-spectral evaluation techniques efficiently separate different types of PD sources and distinguish them from disturbances.

The modular and scalable distributed software system is applied for complicated PD data processing and analysis, flexible usage and long-term storage of the data.

The automated PRPD pattern classification efficiently identifies PD defects by combining probabilistic pattern recognition and deterministic knowledge-based analysis approaches.

9 REFERENCES

[1] CIGRE Brochure 392, "Survey of Hydrogenerators Failures", Oct. 2009.

[2] G.Stone, "A Perspective on Online Partial Discharge Monitoring for Assessment of the Condition of Rotating Machine Stator Winding Insulation", IEEE Electrical Insulation Magazine, September/October, vol.28, no.5.

[3] W. Koltunowicz, A. Obralic, A. Belkov and R. Plath, "Continuous PD Monitoring of Stator Insulation", in the proceedings of CMD 2010, Tokyo, 2010.

[4] W. Koltunowicz and R. Plath, "Synchronous multi-channel PD measurements", IEEE Transactions on Dielectrics and Electrical Insulation, vol.15, no.6, December 2008, pp. 1715-1723.

[5] M. Ankerst, M. Breunig, H.-P Kriegel, J. Sander: “OPTICS: Ordering Points To Identify the Clustering Structure”, Proc. ACM SIGMOD, Philadelphia, PA, 1999, pp 49-60.

[6] A. Belkov, W. Koltunowicz, A. Obralic, R. Plath "Advanced Approach for Automatic PRPD Pattern Recognition in Monitoring of HV Assets", published in the proceedings of IEEE ISEI, San Diego, 2010.

[7] IEC 60034-27 TS Ed.1.0, Rotating electrical machines.

The authors

Dr. Laurentiu Viorel Badicu received the Dipl.-Eng. and the Ph.D degree in electrical engineering from University “Politehnica” of Bucharest, Romania in 2008 and 2012, respectively. His research interests include ageing mechanisms of electrical insulation, insulation systems testing, especially cellulose-based insulation and mineral oil. In 2012, he joined OMICRON and deals with partial discharge data evaluation from on line monitoring of HV assets

Dr.hab. Wojciech Koltunowicz received the M.S., PhD and Dr. hab. degrees in electrical engineering from the Warsaw University of Technology in 1980, 1985 and 2004, respectively. From 1984 to 1987, he was with Institute of Power in Poland, as a research scientist in the High Voltage Department. From 1987 to 2007 he was with CESI, Italy, where he was mainly involved in HV testing and diagnostics of HV equipment. In 2007, he joined OMICRON, where he is involved in monitoring of HV equipment. He is Secretary of CIGRE Advisory Group D1.03 “Insulating Gases” , WG D1.25 and Member of AG D1.02 “High Voltage and High Current Test and Measuring Technique and Diagnostic” and WGs D1.28, D1.37 and D1.51. He is also member of IEC TC42 WG14. He is author of dozens of international reports.

Andrea Piccolo received the M.Sc. in Electrical Engineering from University of Trieste, Italy, in 2010. From 2009 to 2011 he was with TechImp SpA as R&D engineer. From 2011 to 2013 he was responsible for electrical diagnostics at Nidec ASI (former Ansaldo Sistemi Industriali), leading the development of the electrical diagnostics services (off-line and on-line) for motors and generators. In 2013 he joined Omicron Energy Solutions as Application Engineer with focus on rotating machines. His main research interests are related to testing and monitoring of MV rotating machines. He is a member of CIGRÉ WG A1.42-Survey on Hydro Generator Instrumentation & Monitoring.

OMICRON

OMICRON is an international company serving the electrical power industry with innovative testing and diagnostic solutions. The application of OMICRON products allows users to assess the condition of the primary and secondary equipment on their systems with complete confidence. Services offered in the area of consulting, commissioning, testing, diagnosis, and training make the product range complete.

Customers in more than 140 countries rely on the company's ability to supply leading edge technology of excellent quality. Service centers on all continents provide a broad base of knowledge and extraordinary customer support. All of this together with our strong network of sales partners is what has made our company a market leader in the electrical power industry.