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INCREASED OPERATON RELIABILITY THROUGH PD MONITORING OF STATOR WINDING

ZWIĘKSZENIE NIEZAWODNOŚCI POPRZEZ MONITOROWANIE WYŁADOWAŃ NIEZUPEŁNYCH W UZWOJENIU STOJANA

Abstract: In this article, the challenges in the application of continuous partial discharge (PD) monitoring of rotating machines are presented. A versatile partial discharge monitoring system is described that is applicable to different machines and can be connected to a vast range of sensors. The experience gathered from PD monitoring to assess the condition of turbo and hydro generator stator winding insulation is shown in the paper. The advantage of having a fully digital system, whose settings can be easily remotely adjusted is shown. The advanced features for noise and PD defects signal separation based on synchronous multi-channel techniques are also presented. Case studies are included, which indicate that critical defects can be detected early and their evolution can be monitored.

Streszczenie: W artykule opisano działanie uniwersalnego systemu ciągłego monitorowania wyładowań niezupełnych (wnz) w różnych typach maszyn wirujących. Przedstawiono doświadczenia wynikające z zastosowania tego systemu do oceny stanu izolacji wirnika turbo- i hydro- generatorów. Wskazano na zalety wynikające z posiadania systemu pomiaru cyfrowego wnz, którego zakresy pomiarowe mogą być łatwo dostosowywane do typu maszyny i poziomu sygnału zakłóceń. Wskazano na znaczenie automatycznego systemu do identyfikacji typu defektu w izolacji statora maszyny i na odróżnienie sygnałów wnz od sygnałów zakłóceń. Podano przykłady zastosowań, gdzie pokazano, że defekty krytyczne mogą być wcześniej wykryte, a ich ewolucja może być monitorowana w sposób ciągły.

Keywords: *rotating machines, stator insulation, partial discharge measurements, monitoring*

Słowa kluczowe: *maszyny wirujące, izolacja statora, pomiar wyładowań niezupełnych, monitorowanie*

1. Introduction

PD monitoring is nowadays a worldwide accepted method for the condition-based assessment of the stator insulation. Different solutions for sensors and acquisition techniques have been recommended, applied and lately acknowledged by international technical bodies [1-2]. Therefore, there is a strong need for a versatile PD monitoring system that can be applied to different types of rotating machines and which can be connected to a wide range of PD sensors. Moreover, the system should be able to provide all information requested in the relevant international documents. The sensitivity of the on-site PD measurements is strongly limited by the high noise level. The recommended systems should provide the hardware and software features able to diminish the noise influence on test results. Multi-channel and multi-

spectral techniques are used to increase the sensitivity of PD measurements [3]. The case studies described in this paper show that incipient defects can be detected and their evolution can be monitored.

2. Monitoring system concept

The large part of insulation defects develops over the lifetime of rotating machine. In order to detect such changes at an early stage, detailed information on the actual insulation condition is necessary. This information can be derived by monitoring PD during the operation of the equipment. Consequently, continuous PD monitoring is an essential tool for proper maintenance management to guarantee a high level of asset reliability [4].

2.1. Server and software architecture

The signals from sensors detecting partial dis-

charges are acquired by multi-channel data acquisition units. In case of PD signals, the acquisition unit performs advanced pre-processing of the raw data. The disturbances are removed and the main characteristics of the PD signal are determined and transferred to a server that enables long-term data storage.

The server receives data for analysis, display and storage. The acquisition units are configured and remote-controlled over TCP/IP by the monitoring system software. This allows operators to quickly react to detected problems and access the stored data from any remote location. The software is a highly modular, scalable distributed system. Its architecture consists of a Windows-based core part and a web-based control part (Fig. 1).

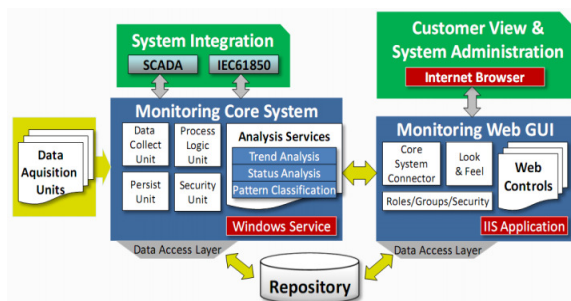


Fig. 1. Monitoring software architecture

The core part of the monitoring software is realized as Windows services and runs continuously without any direct user interactions. The core system includes: collection and persistence of measurement, data post-processing and analysis, security tasks for data access and system operations and external interfaces for data exchange over Ethernet or field bus.

The monitoring system provides data from each acquisition unit in two modes: Permanent and periodic mode. During the permanent mode, the data is acquired every second, compared with threshold values and displayed in the graphical user interface in real time. In case this data is within normal margins, it will be colored in green. If the values exceed thresholds for "warning" or "alarm" they are colored in yellow or red accordingly. Periodic measurements are initiated in equidistant time spans, e.g. every hour. The duration of the periodic measurement is normally one minute. During this time span all mentioned scalar values are calculated and PRPD (Phase Resolved PD) and 3PARD (3 Pulse Amplitude Relation Diagram) diagrams are acquired. This data is saved for later post-

processing and trend visualization. Unscheduled periodic measurements are triggered in case of one or more of the measured quantities exceed the threshold level.

2.2. Software tools for data evaluation

Each type of asset requires the use of specific tools that enable the localization and assessment of the defect type and its severity. The distinction between noise and internal PD defects should be performed by means of an automated identification system. To achieve this, synchronous multi-channel evaluation techniques (3PARD) are applied [3]. The 3PARD 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 a clearly distinguishable concentration of dots (clusters) in a 3PARD diagram (Fig. 2).

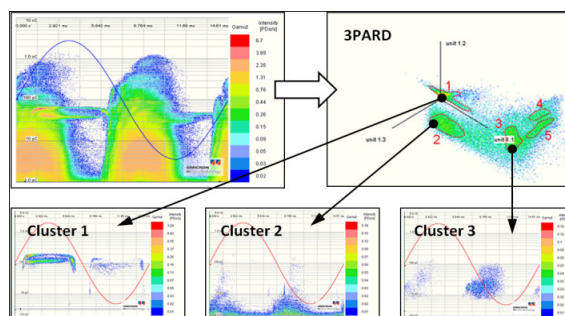


Fig. 2. Example of cluster separation using 3PARD

The monitoring system is configured for extended automated data evaluation - PD source classification on a regular basis (e.g. once per day) or triggered by alarm. In such a case, an automated separation of clusters in the 3PARD diagram is performed (Fig. 3).

For each cluster, the system automatically identifies the phase of signal origin and indicates PRPD related to this cluster as noise or PD. For PD clusters, the PD data set (streams) with all significant data is saved for additional expert analysis or future comparisons.

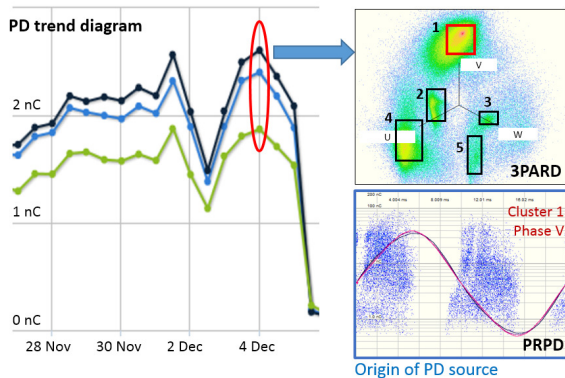


Fig. 3. Automated separation of clusters

In the case of monitoring rotating machines, an automated PD defect classification system has been developed to identify the type of stator winding insulation PD defect like, e.g.: delamination of insulation tapes, discharges in micro voids, end winding surface discharge etc. The automated defect classification is based on knowledge-based analysis designed as decision tree (Fig. 4).

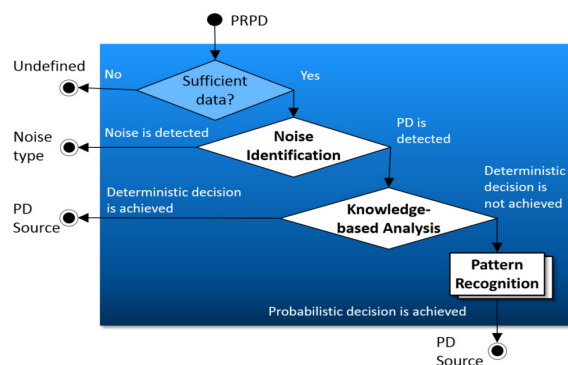


Fig. 4. Automated identification of PD defect

It gives a deterministic decision for clear cases. For unclear cases, where the PD signal can be assigned to more than one PD defect class, an additional pattern recognition procedure is applied which gives a probabilistic decision. There are several trained pattern recognition procedures specific to different groups of PD defect classes, each with unique statistical feature bases (Fig. 5). At the end, the report with a detailed analysis of PD defect classification is automatically generated.

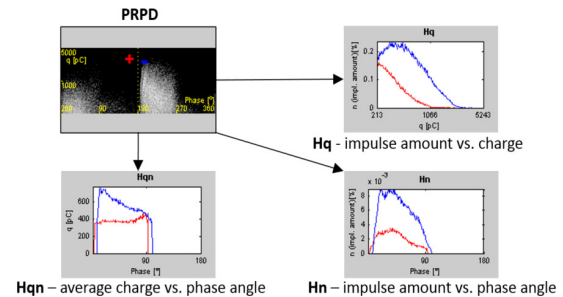


Fig. 5. Statistical evaluation of the PRPDs

3. Case studies

A huge progress has been made in the last 20 years and PD monitoring is now a practicable method for assessing the insulation condition of the stator winding in generators and motors. More than 12,000 machines have been equipped with on-line PD monitoring by various vendors [5]. The reasons is to monitor the condition of the equipment under normal operating electrical, thermal, and mechanical stresses. Better noise separation and interpretation methods have been developed to confirm the usefulness and effectiveness of PD monitoring [3, 6]. The examples of latest improvement in the monitoring technology are given in this chapter.

The selected cases studied show a practical application of insulation condition-based assessment within the context of complex monitoring systems. In order to highlight the flexibility of the monitoring platform for different types of rotating machines, examples of turbo and hydro generators have been chosen respectively.

Turbo and hydro generators are explicitly different in their construction. Even between turbo generators there are several solutions (i.e. cooling system and insulation technology), which can result in different PD activity. The direct comparison of results from different machines is not a meaningful way to evaluate data and can often lead to a wrong diagnosis. Instead, the possibility to compare data from similar machines stored in a common platform, is a powerful approach to achieve a reliable diagnosis and to build a solid in-house know-how of the insulation conditions to efficiently support company asset management.

The first two case studies show the advantage of having a fully digital system, whose settings can be easily adapted to environmental changes by remote adjustment of the monitoring settings. The third case represents instead a typical case

of how to proceed with the assessment of the stator winding conditions when clear PD activities are detected

3.1. Monitoring of turbo generators

Monitoring of a 180 MVA turbo generator

An example where preventive maintenance activity was triggered by the results from on-line PD monitoring of a 180 MVA turbo generator is shown in Figure 6 [7].

The three-phase PD trend diagram and the PRPD patterns saved during monitoring are given. An 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 pattern (Fig. 7), the increase of PD activity generated by surface discharge in the end winding area was identified. Consequently, the generator was taken out of service for further investigations. The high concentration of surface contaminants especially in the end section of the stator winding was confirmed during the maintenance activity.

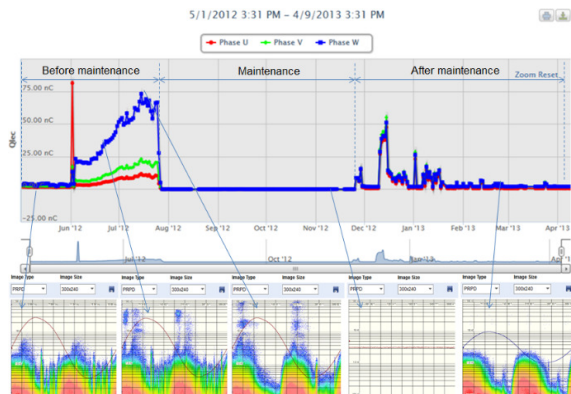


Fig. 6. Three-phase PD trend and PRPD patterns before and after maintenance

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.

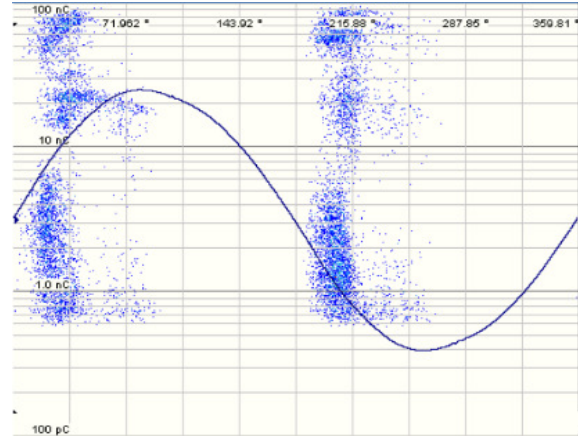


Fig. 7. PRPD pattern showing end winding surface discharges; the separation was performed using 3PARD feature

Monitoring of a 100 MVA air cooled turbo generator

The most efficient way to achieve a reliable insulation assessment of the stator insulation is by comparing the results from similar machines [8]. The graph in Figure 8 shows the combined trend from Generator 1 (Block 1 - PLTU 1) and Generator 2 (Block 2 – PLTU 2). PLTU 1 and PLTU 2, commissioned in 1981, are equipped with two twin 100 MW steam turbines coupled to 13.2 kV - air cooled generators .

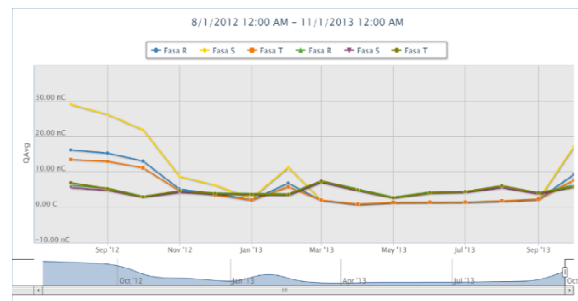


Fig. 8. Combined PD data trend in PLTU 1 & 2

After more than one year since the commissioning of the monitoring system, an increase of PD activity has been observed between September and October 2013 in PLTU 1 (blue, yellow and orange trends). The trend has been zoomed in order to investigate in detail the source of the steep increase in PD amplitude (Fig. 9). The increase is more evident in phase S (yellow) and has a fluctuating behavior on all the three phases, increasing in average since the 18th of October.

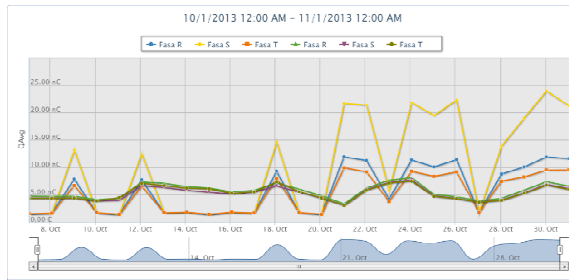


Fig. 9. Combined PD data trend in PLTU 1 and 2 related to the time period Sept – Oct. 2013

From the analysis of the recorded patterns, the cause of the increase has been identified in the appearance of a source of external noise or disturbances that periodically appears in the PRPD patterns. In order to restore the capability of the system to monitor PD exclusively, extra measurements have been performed by a team of PD monitoring specialists, with the target of evaluating an adequate system fine tuning.

The results from the tests, carried out via remote connection, showed that the monitoring band-pass filter central frequency can be moved from 2 MHz to 7 MHz, allowing the system to reject the noise while preserving adequate sensitivity to PD pulses.

In order to preserve the possibility to compare the results from PLTU 1 and PLTU 2 and validate the settings upgrade, the monitoring band-pass filter has been adjusted for both machines. The results, showed in Figure 10 confirm, both for PLTU 1 and PLTU 2, that:

- The capability to reject the noise has been improved.
- The sensitivity to the observed PD activity is preserved.
- The levels of PD activity are similar in the two machines, within an amplitude range of 200 -400 pC.

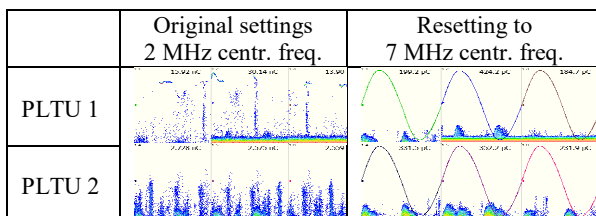


Fig. 10. PRPD diagrams in PLTU 1 and PLTU 2 for two different central frequencies of measurements: 2 and 7 MHz

3.2. Monitoring of hydro generator

A 126 MVA, 16.5 kV hydro generator (Unit 7) was installed in 1997, together with other three generators of the same design and provided by

the same manufacturer. The power plant delivers energy during the peak load hours and recover the regional electric system in case of black-out (Black Start-up PP). Installation of PD monitoring systems on all of the generators was completed in 2012.

Since the first months of trending the generator showed a steep increase of PD activity in phase S. As all generators have the same design and were commissioned in the same period, they can be considered comparable. The first action taken was to compare Unit 7 with its neighboring Unit 8 (Fig. 11).

From the trend diagrams of average charge for Unit 7 and Unit 8, it is possible to notice the deviation of Phase S - Unit 7. To confirm the activity in phase S, pattern acquisitions have been made periodically to identify the type of PD source and to confirm the phase location. In Figure 12, the results for Unit 7 and Unit 8 are presented, where each pattern is synchronized with its relevant phase voltage.

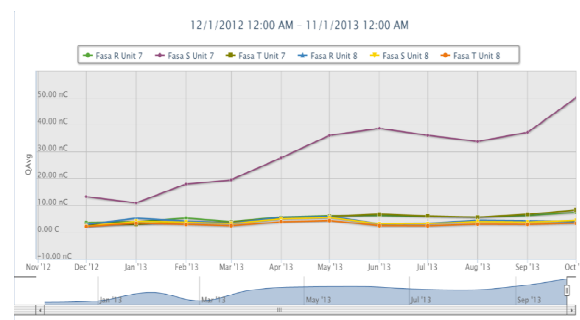


Fig. 11. PD trend in Unit 7 and Unit 8

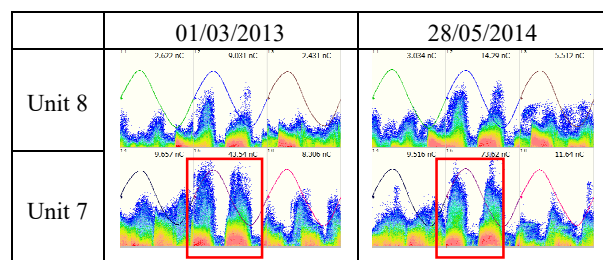


Fig. 12. PRPD patterns in Unit 7 and 8 acquired at different time

The next step of the evaluation aims to isolate the investigated PD source signal from the signals of other internal PD activity. This task is accomplished by means of the 3PARD separation technique (Fig. 13).

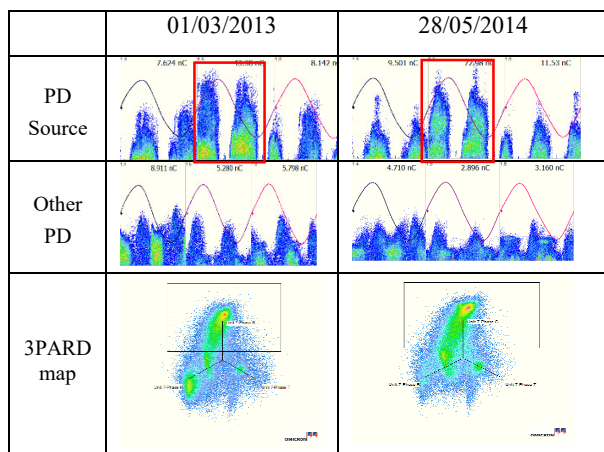


Fig. 13. Separated PRPD patterns of PD source and noise in Unit 7 acquired in different time

The investigated PD source, identified by the selected cluster in the 3PARD, can be associated with surface tracking located in phase S of Unit 7. Considering the other sources separately, it is possible to have an indication of the machine from the point of view of internal discharges, which can be considered uniform in the three phases and comparable with the values recorded in Unit 8 (twin of Unit 7).

The stator inspection confirmed the presence of surface PD activity in four slots, belonging to the investigated phase S (Fig. 14).

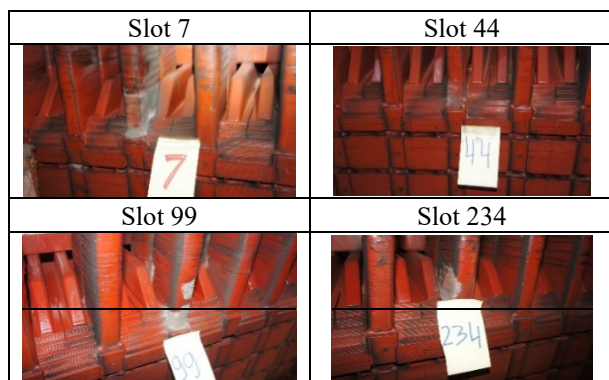


Fig. 14. Evidence of surface PD activity in four different slots of Phase S

4. Conclusion

- A versatile PD acquisition unit can be used for PD measurements on different type of rotating machines.
- A modular, distributed monitoring software system allows reliable long term storage of monitoring data and provides access via web interface for detailed data evaluation.
- Continuous PD monitoring of stator windings is proved to be an essential

diagnostic tool for condition-based maintenance of large generators, in order to increase their reliability. The examples of detection of surface discharges in stator windings are given in this article.

- Based on the PD monitoring results obtained before and after the maintenance of the machine, the effectiveness of the maintenance program can be evaluated and the maintenance can be properly scheduled.
- The main key to perform appropriate diagnosis of the insulation state is to accurately separate and identify different PD sources from noise and disturbances. To achieve this, synchronous multi-channel evaluation techniques – 3PARD techniques can be applied.

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