# Monitoring in Electrical Rotating Machines - Case Studies

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Expensive high-voltage (HV) apparatus tends to degrade during its service life. To balance this effect, various maintenance and refurbishment policies are applied during the life time of the equipment.

In asset management there is a clear trend to change from time based to more cost effective condition based maintenance. The continuous evaluation of equipment condition assures important information with regard to aging mechanism and is an essential tool for effective maintenance management. In particular:

- exact knowledge of the state of insulations at any time saves money, as maintenance schedules can be specifically optimised and an extended life of the assets can be reached
- monitoring answers questions about the present condition of the equipment and its future performance
- monitoring supports overall investment planning
- the large amount of real-time data gathered by monitoring systems can be used for precise insulation condition assessment
- effective comparison of historical data via an easy-to-use and extendable database solution

Partial discharge (PD) phenomena are a consequence of local electrical stress concentration in electrical insulations. PD activity can lead to failure and consequently to serious damage and finally to a fault in critical elements of the power network. Therefore it is mandatory to identify the presence of PD activities and monitor PD activity. The large variety of PD signals makes PD measurement and its detection a challenging task. Nevertheless, PD is a widely accepted measuring parameter for insulation diagnosis and the PD measurements are specified for type, routine and on-site tests for most HV assets. The introduction of digital technology created new opportunities for improving the sensitivity, significance and reproducibility of PD measurements by far exceeding the capabilities of older analogue systems [1].

## 1. About PLTA CIRATA

PLTA Cirata is one of the large hydroelectric power plant in Southeast Asia and the biggest hydroelectric power plant in Indonesia. PLTA Cirata's power house constructed underground with total capacity 1.008 MW consist of 8x126 MW generators with maximum energy production 1.428GWh per year.

PLTA Cirata consist of Cirata I with 4x126 MW generators those started in operation since1988 and Cirata II with 4x126 MW generators those started in operation since 1997. Cirata I and II are able to produce total energy approximately 1.428 GWh per year to be distributed through 500 kV extra high voltage transmission network towards interconnected system of Jawa-Madura-Bali.


*Fig. 1 PLTA Cirata (red circle) shown on PT Pembangkitan Jawa Bali (PJB) Business Unit Map*

PLTA Cirata power plant is operated by PT Pembangkitan Jawa Bali (PJB) a subsidiary of PT PLN (Persero). The main contribution of PLTA Cirata towards Jawa Bali system is providing the energy during the peak load hours. By using LCF (Load Frequency Control) operation mode, in which having line charging facility if Jawa Bali system is Black Out and Start up the operation/synchronous towards the network 500 kV which is relatively fast approximately in five minutes. [2]

## 2. Partial Discharge Monitoring for Rotating Machines

In course of operating lifetime, the rotating high-voltage machines are continuously and periodically faced with thermal, electrical, ambient and mechanical stress. According to failure statistics the second most common cause of outage of large rotating machines (generators and motors) is related to stator insulation faults.

A specific level of PD is allowed to occur in stator insulation of large high voltage rotating machine. Admittedly, degradation of stator insulation always produces increased PD activity in particular in the phase winding. It means that PD events, in dependence on their location of occurrence, represent certain symptoms or even causes of winding insulation accelerated.

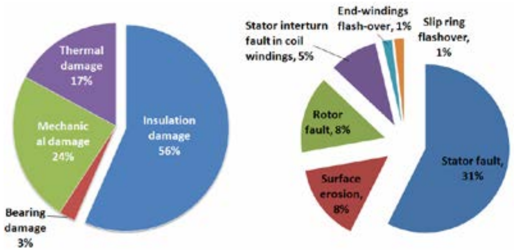


*Fig. 2 Occurrence of generator faults [CIGRE 2009 / Survey of Hydro Generator Failures]*

At least they can give a hint to the fact that the original design of the winding has changed e.g. by ageing. Hence the main challenge in PD measurement is to classify the PD events in a way to distinguish between their normal and harmful occurrences. Sensitive and selective PD measurement is suitable to discover potential defects in stator insulation before failure. Thus, periodic PD measurement is expected to provide warning for appropriate decisions and for actions to minimize the risk of failure in service.

PD-Monitoring solution for rotating machines is based on a high end acquisition unit, an appropriate set of sensors and a powerful server / software combination. The elements of a fixed / permanently installed PD-Monitoring system are illustrated in fig 3.

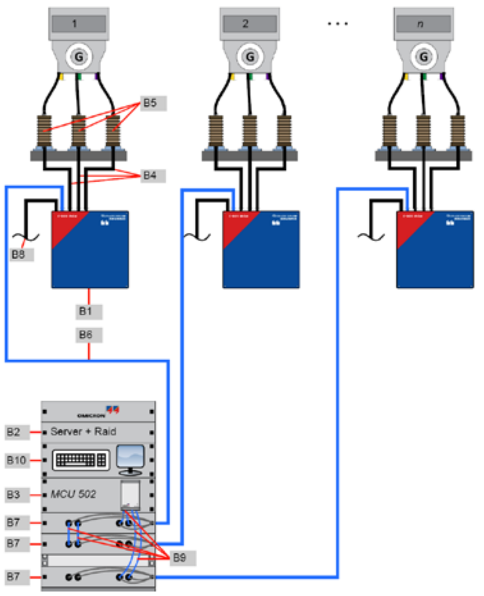


*Fig. 3 Continuous (permanent) Monitoring Systems (configuration Principle Example for 3 generator)*

## 2.1. PD Sensor

Three capacitive sensors are mounted within the generator's main terminal box to detect PD pulses. Such sensors can easily be integrated into the new, as well as to the machine already in service. The outputs of the capacitive sensors are connected to the PD input of the OMS600 system via double-screened coaxial cables in order to minimize the impact of external interferences.

*Fig. 4 PD Sensors installed at generator terminals*

## 2.2. Partial Discharge Signal Acquisition Unit

The OMS600 PD acquisition unit is a completely encapsulated 3 channels unit for the acquisition of PDs in the three phases of the generator. Each channel contains digital band-pass filter. The PD measurements in all channels are performed synchronously.

To detect PD events, each OMS600 PD acquisition unit receives data from its PD input, coupling capacitor connected to the HV phase terminal of the generator. Data from every single PD impulse like apparent charge value, polarity, time of PD occurrence and PD impulse relation to the phase voltage can be visualized, recorded and stored for further processing. The centre frequency and the bandwidth can be freely chosen in a wide range (centre frequency range from 50kHz to 20 MHz, bandwidth from 9 kHz to 3 MHz), which allows a proper adjustment of the measurement system to the device under test and the proper selection of frequency range in low disturbances region. All advanced technical features of PDM600 enable synchronous detection of PD on all three phases of rotating high voltage machine, suppression of noise signals and allows separation and individual evaluation of singular PD sources within the stator winding of each generator. Additionally, with 3 Phase Amplitude Relation Diagram (3PARD), PD sources can be separated, as well as noise and disturbances recognized and excluded.

Finally, the data are transmitted to the monitoring server via fibre optical cable providing complete electrical insulation.

### 2.3. Monitoring Server

The Monitoring Server receives PD data from the acquisition unit PDM 600 for analysis, display, and storage. The acquisition units PDM 600 is configured and remote-controlled by the Monitoring System Software.

The Software supports remote access over the TCP/IP (internet and the intranet). This allows operators to quickly react to detected problems and access the stored PD data from any remote location. A watchdog functionality integrated into the monitoring server system automates the process of starting and observing of the monitoring software. Once the watchdog application is started, it will automatically launch the monitoring software and periodically check whether the acquisition unit still receives and processes PD data.

### 2.4. Monitoring Software

The monitoring software is a highly modular application that supports multiple PD Monitors. The workspace of the Monitoring Software is divided into three major parts: a standard task menu displayed on top, status bar on the left and the visualization panel on the right.

A standard task menu provides access to software system settings which includes login administration, language selection and to user help.

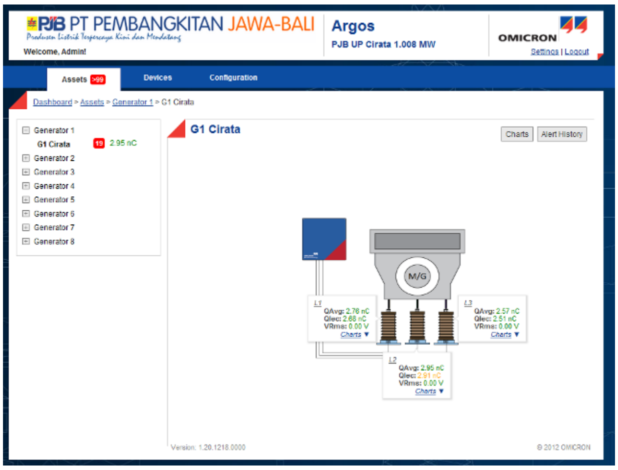


*Fig. 5 PD Monitoring Software Overview*

The status bar indicator provides information about the current status of monitored HV asset(s) and in lower part, the Condition of Monitoring System itself.

The visualization panel contains the schematic view of each HV asset and the setup of the monitoring system and sensors. Each element of the HV asset is clickable which will open another sub-window called "Current Status" showing the current measured quantities for each measuring location. Similar, the measured quantities can be displayed using drag-and-drop mouse function. The permanent measured values are continuously compared with signal levels. The measured quantities are coloured according to their value related to pre-seated warning or alarm threshold levels. This means, if the detected PD level on any channel on one assed exceeds a configurable threshold, the corresponding value will be drawn in yellow or red.

Three trend view diagrams show the history of measurement data over the time. Default values are PD levels measured on each of the phases of selected asset over the last 24 hours. These settings can be individually configured using two drop-down menus on the left side of each diagram. Also measuring locations as well as measured quantities are freely selectable.

The time selection is also free configurable using standard time selection menus in lower part of the window.

## 3. Case Studies of PD Monitor

PT Pembangkitan Jawa Bali (PJB) has installed Partial Discharge Monitor for power generators in Gresik, Paiton, Muara Tawar, Muara Karang and Cirata since 2012. Installation of partial discharge monitor aims to detect early failure of insulation on the stator.

In order to ensure safe and reliable energy supply, the insulation status of high-voltage equipment should be monitored continuously. Even a small inconsistency in the insulation can lead to partial discharge (PD) and considerably reduce the service life of the asset. The result is often unexpected power failures, which are associated with high costs. [3]

The measurement of partial discharges (PD) has been employed as a sensitive means of assessing the quality of new insulation as well as a means of detecting localized sources of PD in used electrical winding insulation arising from operational stresses in service. Compared with other dielectric tests (i.e. the measurement of dissipation factor or insulation resistance) the differentiating character of partial discharge measurements allows localized weak points of the insulation system to be identified. Especially on-line PD measurements are not only sensitive to partial discharges but also to various arcing and sparking phenomena. [4]

### 3.1. PD Monitor Cirata Unit 7

On-line partial discharge (PD) monitoring data analysis is performed for Unit 7 located in power plant Cirata. The necessity for a detailed investigation was triggered by the high PD values in the phase S visible in the trend diagram. The PD magnitude of phase S increases significantly from 20nC to 120nC during 9 months monitoring (fig.6).

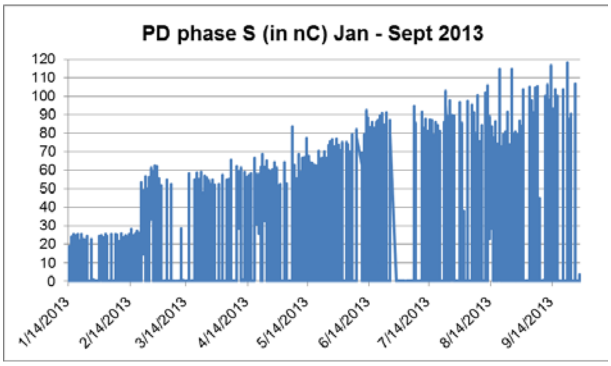


*Fig. 6 PD Monitoring data Cirata Unit 7 during 9 months*

It is also observed that PD on phase S can obscure monitoring on the other two phases (R and T) that slightly increase as cross-coupling of PD and noise on phase S (figures 7 and 8).

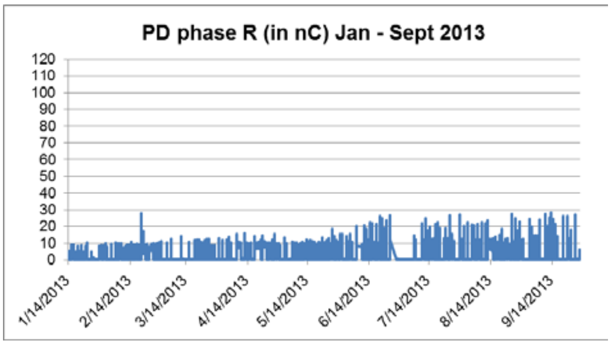


*Fig. 7 Cross-coupling of PD of phase S to phase R*

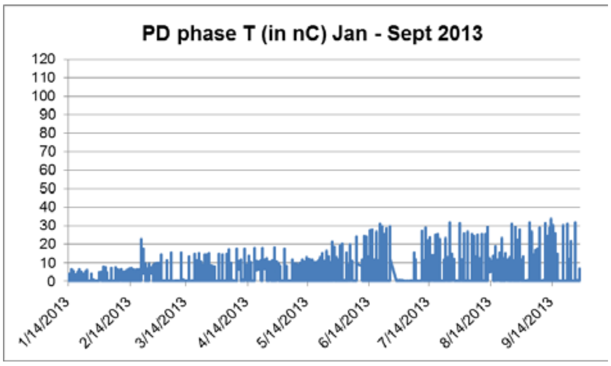


*Fig. 8 Cross-coupling of PD of phase S to phase T*

### 3.2. PD Data Analysis

Figure 9 depicts the phase resolved PD diagram (PRPD) of the PD signal acquired by the 3-channel synchronous system on Cirata Unit 7. The PRPD is a complex pattern with several PD sources visible.

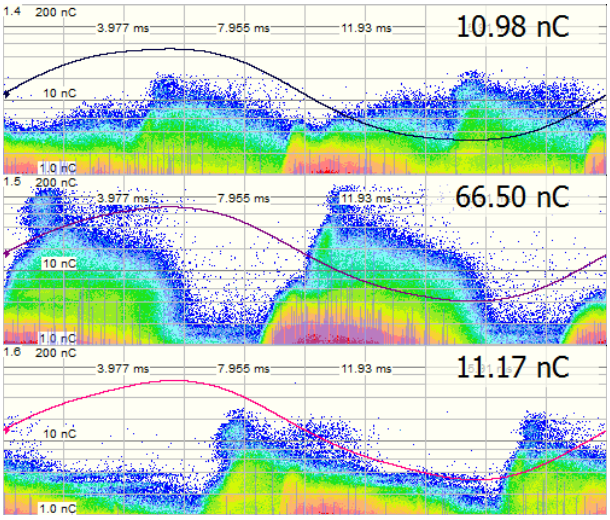


*Fig. 9 3 channels PRPD Pattern Cirata Unit 7*

In order to separate different PD sources, synchronous multi-channel technique was applied (3PARD). The 3PARD (star diagram) visualizes the relation among intensity 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 (clusters) in the 3PARD diagram (figure 10). In figure 10, eight clusters can be identified. By selecting each cluster a separation cross-coupling noise and other PD-like phenomena (clusters 1-8) is possible.

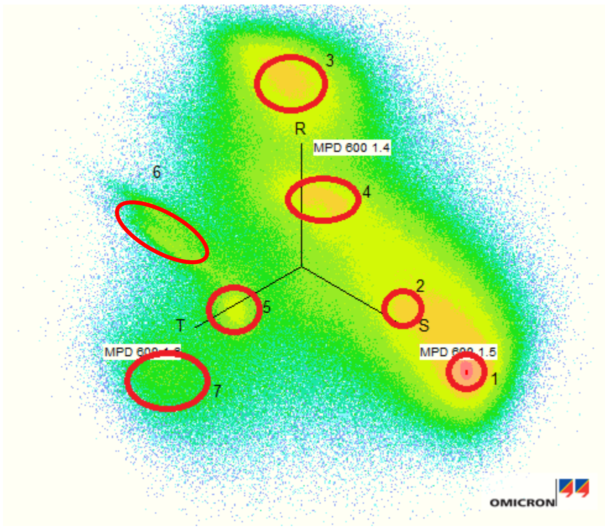


*Fig. 10 PD Sources separation using 3PARD*

The pulses generated by PD source located in one phase are visible in the other two phases because of the electromagnetic coupling inside the generator windings. Only the phases where these sources show highest amplitude are further investigated.

Phase S shows the highest PD value (56.40 nC) while other phases show five times lower values -

around 9 nC (fig.12). The dominant defect detected in phase S (cluster 1)is recognized as surface discharge with tracking, according to IEC-60037-27 guidelines.

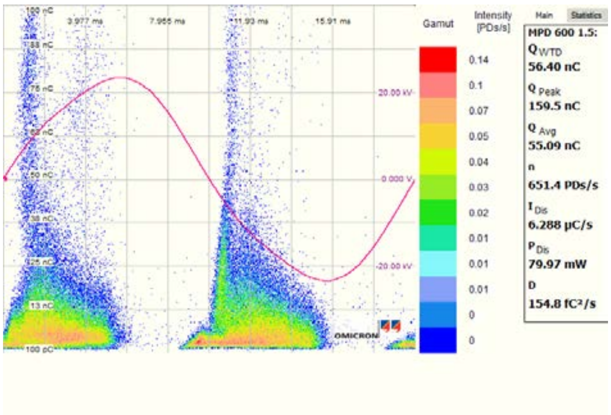


*Fig. 11 PRPD Pattern phase S of cluster 1*

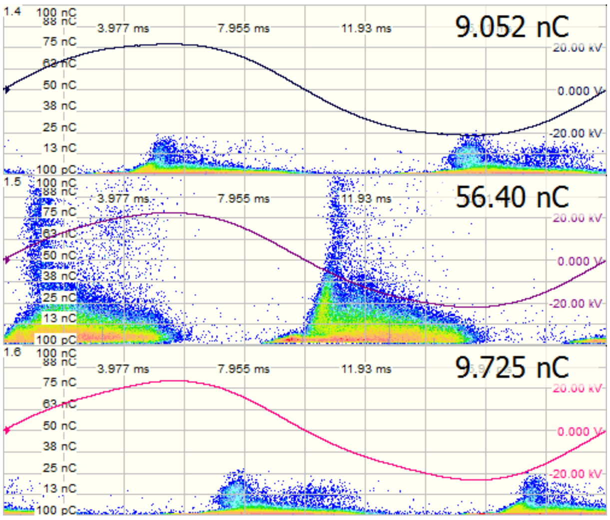


*Fig. 12 3-channels PRPD Pattern of cluster 1*

Phase S also shows the highest PD value (4.8 nC) while other phases show three times lower values - around 1,7 nC (fig.14). The dominant defect detected in phase S is recognized as gap type discharge (cluster 2).

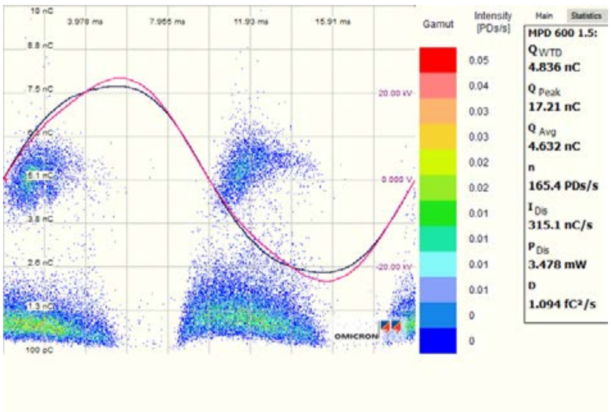


*Fig. 13 PRPD Pattern phase S of cluster 2*

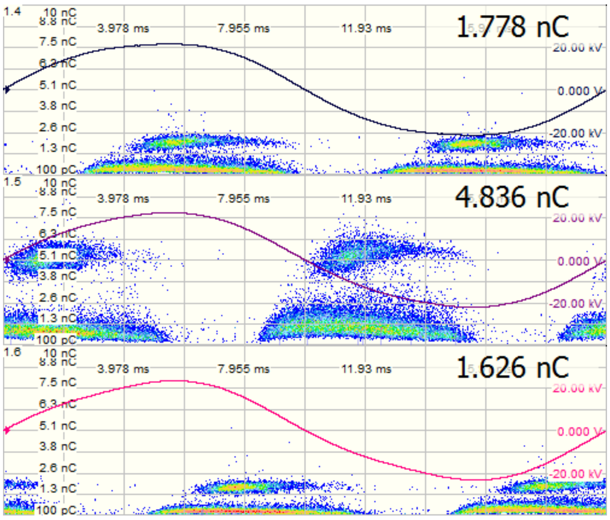


*Fig. 14 3-channels PRPD Pattern of cluster 2*

Cluster 3 is representing PD phenomena in phase R. Cluster 3 (figures 15 and 16) show PD-like phenomena because of the delamination of the slot insulation on phase R and its crosstalk generated signals in the other two phases.

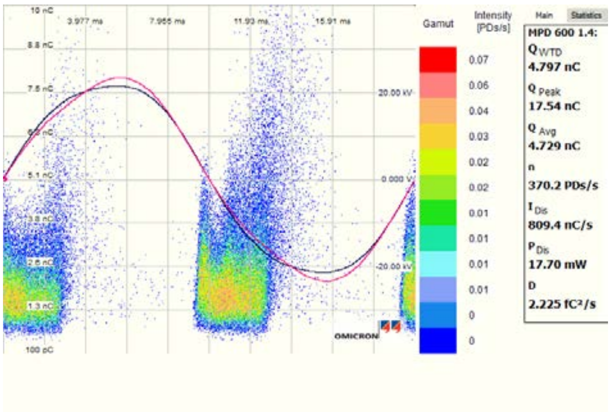


*Fig. 15 PRPD Pattern phase R of cluster 3*

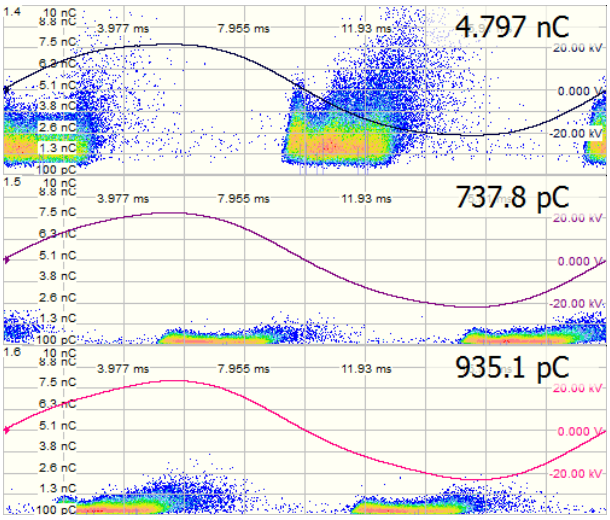


*Fig. 16 3-channels PRPD Pattern of cluster 3*

In cluster 4 shows PD-like phenomena of PD between phases. The PD is occurring between two phases and the PD detected in one phase will tend to be shifted right (closer the zero crossing of the AC cycle), whereas the same PD detected in the other phase will be shifted left (closer to the peaks of the AC cycle).

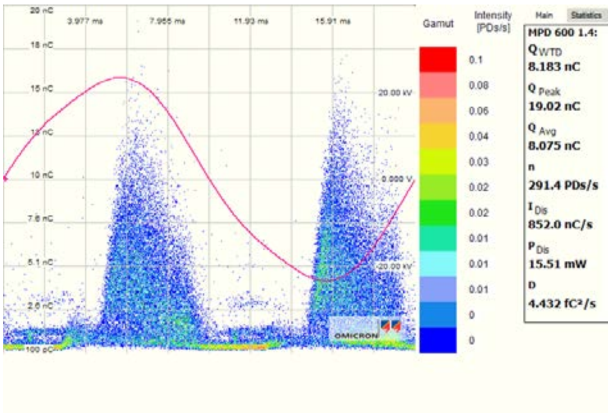


*Fig. 17 PRPD Pattern phase R of cluster 4*

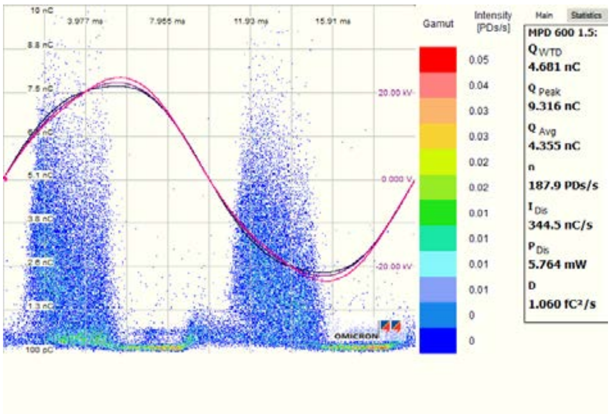


*Fig. 18 PRPD Pattern phase S of cluster 4*

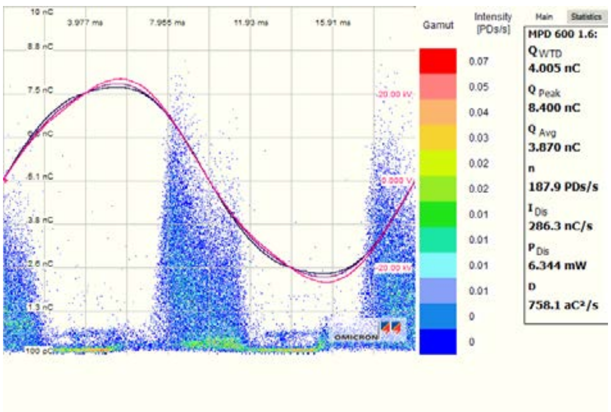


*Fig. 19 PRPD Pattern phase T of cluster 4*

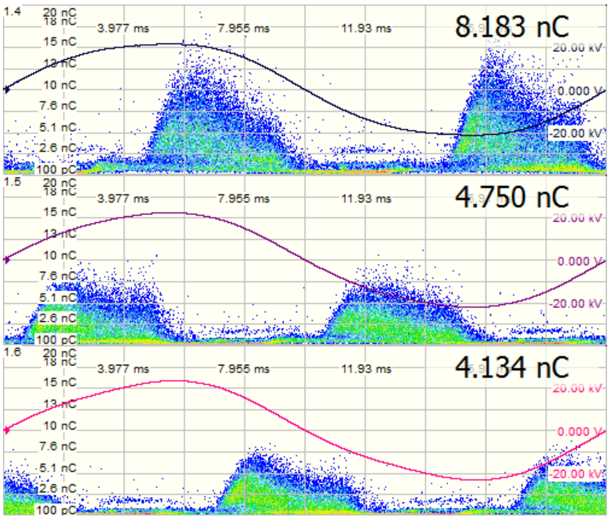


*Fig. 20 3-channels PRPD Pattern of cluster 4 (PD between phases)*

Cluster 5, 6, 7 and 8 are representing PRPD on phase T. Cluster 5 shows PD-like phenomena caused by gap type discharge. This activity will occur between bars in the winding overhang or between a bar and the press finger of the stator core but the PD magnitude relatively low in all phases.

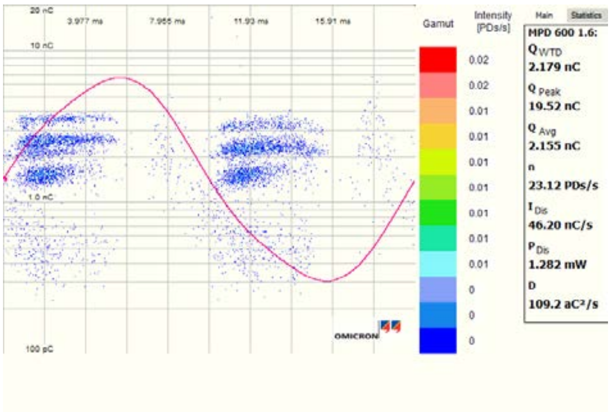


*Fig. 21 PRPD Pattern phase T of cluster 5*

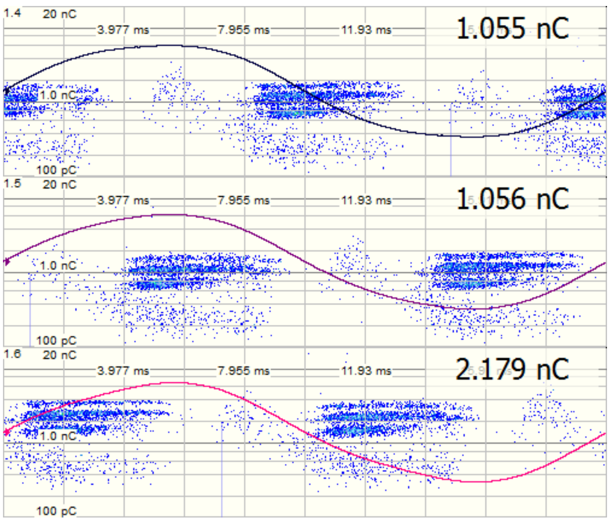


*Fig. 22 3-channels PRPD Pattern of cluster 5*

Similar to cluster 4, cluster 6 also shows PD-like phenomena of PD between phases. The PD is occurring between two phases and the PD detected in one phase will tend to be shifted right (closer the zero crossing of the AC cycle), whereas the same PD detected in the other phase will be shifted left (closer to the peaks of the AC cycle).

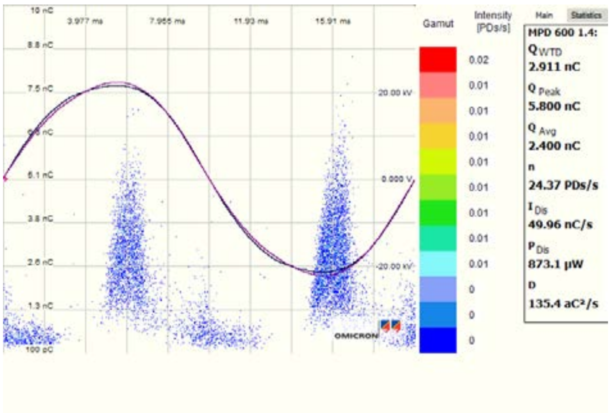


*Fig. 23 PRPD Pattern phase R of cluster 6*

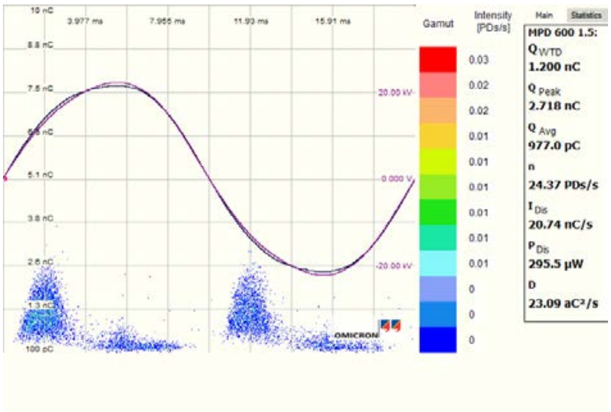


*Fig. 24 PRPD Pattern phase S of cluster 6*

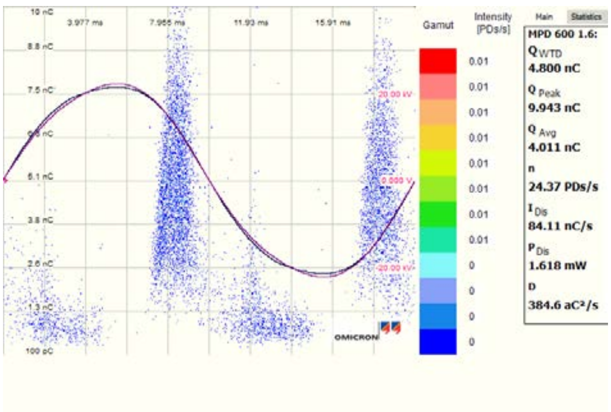


*Fig. 25 PRPD Pattern phase T of cluster 6*

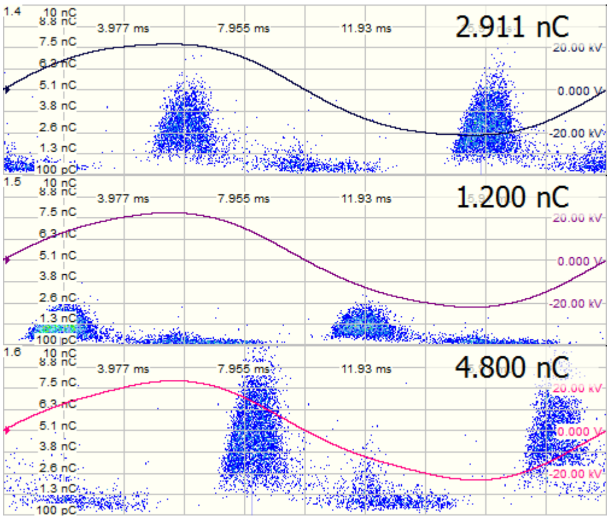


*Fig. 26 3-channels PRPD Pattern of cluster 6*

PD-like phenomena because of the delamination of the slot insulation is also discovered in phase T, but the value lower that phase S (cluster 7)

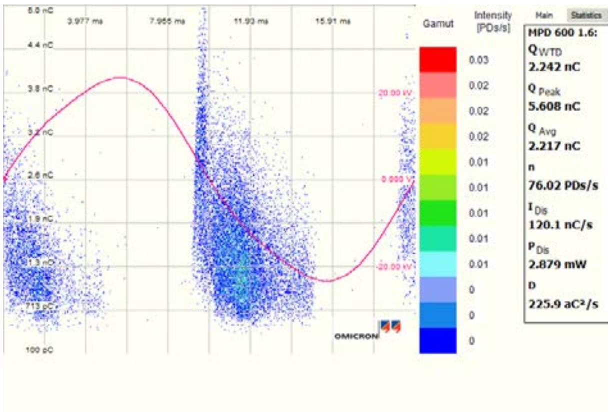


*Fig. 27 PRPD Pattern phase T of cluster 7*

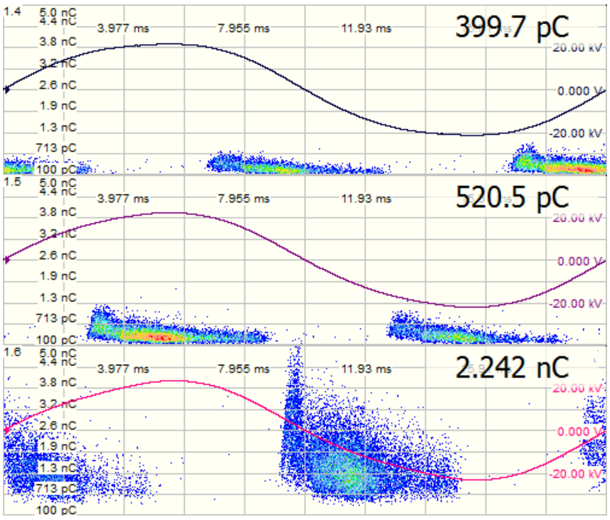


*Fig. 28 3-channels PRPD Pattern of cluster 7*

### 3.3. Visual Inspection Check

On September 27,2013 PT PJB UP Cirata has dcided to do visual inspection during annual shutdown and pull-out the stator winding.

*Fig. 29 Stator PLTA Cirata Unit 7 after pull-out*

During this visual inspection they found some evidences of partial discharge activities at least 6 spot of PDs as follows: slot no: 7, 44, 80, 99, 234 and 252.

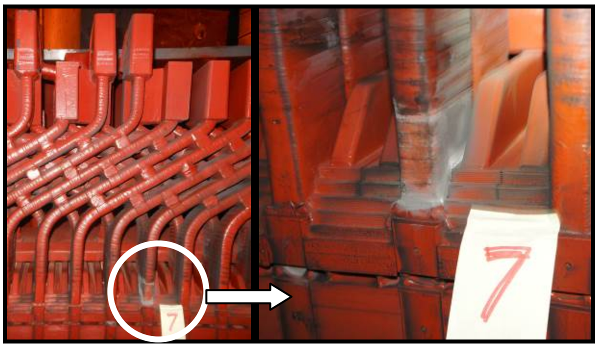


*Fig. 30 PD on Cirata Unit 7 slot no.7*


*Fig. 31 PD on Cirata Unit 7 slot no.44*

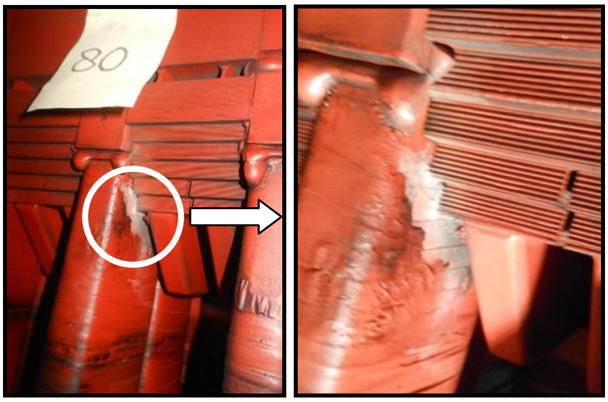


*Fig. 32 PD on Cirata Unit 7 slot no.44*


*Fig. 33 PD on Cirata Unit 7 slot no.99*


*Fig. 34 PD on Cirata Unit 7 slot no.234 (both on left side and right side)*


*Fig. 35 PD on Cirata Unit 7 slot no.252 (both on left side and right side)*

This fact finding on visual inspection and the trend data from the on-line partial discharge measurement will help PT PJB UP Cirata in order to determine the risk assessment of schedule for repair and its priority against unit 1. Also to determine the location of spare universal stator (now in procurement process) that in this case will be for unit 7 based on its condition.

## 4. Conclusion

The partial discharges measurement can provide information on points of weakness in the insulation system, degradation processes, maintenance measures and intervals between overhauls.

Online PD measurement also provide PD trend evaluation and comparisons with machines of similar design and similar insulation system measured under similar conditions, using the same measuring equipment has an advantage to ensure reliable assessment of the condition of the stator winding insulation.

By using continuous on-line PD monitoring, the PD data can be continuously trended in real-time and thus changes of the PD behaviour can be detected and the risk of losing important information on the PD activity can be minimised. This allows a detailed PD analysis to be implemented on an event basis, rather than a traditional fixed time interval basis.

The separation of PD sources and noise is required for clear PD analysis. By utilizing synchronous multi-channel PD measurement system as well as 3PARD software analysis is a powerful tool for reliable discrimination of different PD sources during three-phase measurements for optimum gating of unwanted signals, such as noise, multiple PD sources and external discharges.

## Literature


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## About the Author

**Constant** is with PT Citra Wahana Sekar Buana since 2001. He works as board director but actively involves as sales and application engineer for electrical testing and monitoring products, conducting trainings, on site testing support, installation and commissioning of partial discharge monitoring for generators. He studied electrical engineering at Institut Sains dan Teknologi Nasional (ISTN) Jakarta.