

Article

Defects Classification of Hydro Generators in Indonesia by Phase-Resolved Partial Discharge

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Abstract: This paper proposed a phase-resolved partial discharge (PRPD) shape method to classify types of defect generator units by using offline partial discharge (PD) measurement instruments. In this paper, the experimental measurement was applied to two generators in the Inalum hydropower plant, located in North Sumatera, Indonesia. The recorded PRPD using the instrument MPD600 can illustrate the PRPD patterns of generator defects. The proposed PRPD shape method is used to mark auxiliary lines on the PRPD patterns. Moreover, four types of defects refer to the IEC 60034-27 standard, which are microvoid (S1), delamination tape layer (S2), slot defect (S3), and internal delamination (S4) and are used to classify the defect types of the generators. The results show that the proposed method performs well to classify types of defect generator units.

Keywords: partial discharge (PD); phase-resolved PD (PRPD); rotating machine; stator coil

MSC: 35Q68



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1. Introduction

Partial discharge (PD) phenomena are produced from the concentration of the local electrical stresses in electrical insulation [1–3]. PD activity may deploy to failure resulting in serious damage. Eventually, it would undermine the essential elements of the power network [4]. Therefore, it is compulsory to check, identify, and monitor the PD activity of the main rotating machine, motors, or generators [5,6]. Detection, measurement, and interpretation of PD are great challenges due to the large variety and complexity of PD signals [7–9]. However, PD measurements are still a widely accepted method for insulation diagnosis, and they are specified for the type, routine, and on-site tests for the highest voltage (HV) assets [10,11].

Generally, PD can be developed at locations where the dielectric properties of insulating materials are inhomogeneous. The local electric field strength may be enhanced in such locations [12]. This may lead to a local partial breakdown regarding local electrical overstressing. This partial breakdown does not result in the total breakdown of the insulation system [13]. Although the stator winding insulation system in HV machines normally has some PD activity, it is inherently resistant to PD regarding the inorganic mica components [14]. The significance of PD in these machines generally can be said as a symptom of insulation deficiencies, such as manufacturing problems or in-service deterioration, that finally become a direct cause of failure [15]. In conclusion, PD occurrences in machines may directly damage the insulation, hence influencing the aging process, which depends on the machine processes [16]. The failure time may not correlate with the PD levels, but we are significantly looking at other factors, e.g., site operating temperature, condition of the wedging, level of contamination, etc. [17].

The developments of digital technology, both for the equipment and software, have created innovative solutions for improving the sensitivity, significance, and reproducibility

of power systems. For example, Li et al. developed an adaptive virtual synchronous generator (VSG) controller. This controller can implement optimal control policies in a no-expert or model-free manner [18]. Zhang et al. proposed an event-triggered decentralized hybrid control scheme for the economic cost of an integrated energy system (IES) composed by a cluster of energy hubs (EHs) [19]. Gopinath et al. demonstrated a hybrid method for predicting the insulation state of stator windings using an artificial neural network (ANN) and an optimization algorithm [20]. Nair et al. successfully found slot discharges at low frequencies, which, in practice, can significantly reduce the size and cost of test sources [21]. The developments are, by far, exceeding the capabilities of old analog systems to make it easier both for analyzing and interpreting insulation conditions in rotating machines [22].

PD measurement from stator coil windings can be conducted in two ways [23]—(1) online measurement [24]: the rotating machine is normally operated and connected to the power system; and (2) offline measurement [25]: the stator winding is separated from the power system by giving a power supply to energize the winding during the standstill of the machine.

Indonesia Asahan Aluminum Co. Ltd, hereinafter called Inalum, is an aluminum company in Indonesia, which has two hydropower stations that use water flow from the Asahan River to produce electricity for the Inalum Smelting Plant. One of the power stations is called Siguragura Power (SGP) with a capacity of 4×71.5 MW with a voltage of 11 kV, and another one is called Tangga Power (TNP) with a capacity of 4×79.2 MW with a voltage of 11 kV; this together is called the Inalum Power Plant (IPP), as shown in Figure 1 [26]. The routine maintenance of the main machines in the IPP has been properly conducted to keep power without any stoppage to fulfill the load demand at the smelting plant, i.e., maintenance of the water turbine, generator, and equipment.



Figure 1. Location of Inalum Hydropower Plant, Paritohan, North Sumatra, Indonesia.

PD measurement at the generator intends to assess the stator coil insulation system condition [27]. This PD measurement is applied for the first time to Inalum's generator since its operation in 1983, 37 years ago, to assess the stator coil of generator TNP units 2 and 3. Furthermore, the intention of this paper was to compare the PD result of two rotating machines with similar ratings and designs [28].

The paper is organized as follows: PD measurement for rotating machines is discussed in Section 2. PD measurement connection is presented in Section 3. Case studies of partial discharge measurement are discussed in Section 4. Discussion is provided in Section 5, and the conclusions are given in Section 6.

2. Partial Discharge Measurement for Rotating Machines

In relation to the operating lifetime, the rotating HV machines continuously and periodically face thermal, electrical, ambient, and mechanical stress. Conseil International des Grands Reseaux Electriques (CIGRE), also called the International Council on

Large Electric System, conducted an interesting and important statistic by observing hydro generators. CIGRE observed 1199 units of generators, then recorded and analyzed 69 incidents, and found that 56% of the failed machines are related to insulation damage. The top 3 root causes leading to insulation damage are aging (31%), contamination of winding (25%), and internal PD (22%). The others are shown in Table 1 [29].

Table 1. Root cause of insulation damage.

Root Cause of Insulation Damage	Percentage of Failures (%)
Aging	31
Contamination of winding	25
Internal PD	22
Loosing of bars	10
Thermal cycling of overloading	7
Defective corona protection	3
Overvoltage	2

Some machines have been designed to be able to withstand an appreciable level of discharge without significantly affecting the insulation properties based on the mica–epoxy insulation system. For instance, the internal discharge in small volumes and some other PD activities are even strongly detrimental to the insulation system. Moreover, the PD in HV can be used to detect the insulation aging and evaluate the insulation condition [30].

A specific level of PD is allowed to occur in the stator insulation of a large HV rotating machine. Admittedly, degradation of stator insulation always increases PD activity, particularly in phase winding. It means that PD events represent certain symptoms or even causes of winding insulation defects, depending on their location of occurrence on the winding [31].

PD measurement can identify stator coils that have insulation problems and evaluate the condition of stator coil insulation systems. The rotating machines that do not have specific acceptable PD levels are unusual among high-voltage equipment [32] because the mica-based insulation can tolerate the large magnitudes and huge difference in acceptable magnitude to different types of PD sources in the stator insulation. PD measurement has been used for many years as a powerful tool to detect and interpret the signs of locally confined insulation defects.

The factors that affect the insulation such as corona can be described based on the research of hydro generator damage samplings. At least, the data give a hint that the original design of the winding has changed, e.g., by aging. Hence, the main challenge in PD measurement is to classify the PD events to diagnose a damaged one. A sensitive and selective PD measurement is suitable to discover a potential defect in stator insulation before failure. Therefore, periodical PD measurement is expected to provide warning for appropriate decisions and actions to minimize the possibility of risk failure in service. Many methods are available to detect the PD activity for motors and generators. This paper used MPD600 and its acquisition unit as the tool to measure, collect, and analyze the PD data from the generators.

PD measurement detects most, but not all, of the common manufacturing and deterioration problems in the form-wound stator windings, including the following [33]:

- (1) Overheating or deterioration of thermal cycling in the long term;
- (2) Poor impregnation of the epoxy inside;
- (3) Improper coating of the semiconductive;
- (4) Insufficient spacing between coils in the end-winding area;
- (5) Looseness of coils in the slot;
- (6) Contamination of winding by dust, dirty oil, moisture, etc.;
- (7) Cycling problems of the load;

(8) Improper electrical connections.

Normally, a PD pattern is viewed as a PD distribution map, in which the specific PD quantity is correlated in a scatter plot, in obtaining information on the PD activity and its sources. Usually, the PD distribution is in two dimensions for visualization. A PD pattern consists of three items, ϕ , q , and n . The pattern is recommended to identify the causes of PD in the stator winding insulation, where ϕ is the phase of occurrence, q is the PD magnitude, and n is the frequency of PD occurrence. The frequency of PD occurrence normally is put in the scatter plot within each phase-magnitude window, and it should be displayed by a suitable color type whose scale can be visualized on the right side of the plot. The PD measurement shows the three-item ϕ - q - n pattern as the output of the phase-resolved partial discharge (PRPD) pattern, which sometimes is called the fingerprint ϕ - q - n diagram. In addition, PD characteristics can be displayed in bipolar patterns to show the characteristic of PD (symmetrical or asymmetrical) by displaying the PD events during interval time recording versus discharge magnitude [34].

2.1. Definitions

The PD activity in the generator usually occurs in the stator coils. The stator coils have many parts protecting the core winding. This paper did not include every type of fault, e.g., mechanical faults such as broken strands. The assembly of a stator coil is simplified with the aim to show the PD detected location found in the stator coil, as shown in Figure 2. The simplified signs marked as S1 are microvoids, S2 is the delamination of tape layers, S3 is the slot discharge-semiconductive paint abrasion, and S4 is the delamination of winding from the main insulation of the conductor. The purpose of signs S1, S2, S3, and S4 is to make the recognition and interpretation of PRPD patterns easier [35].

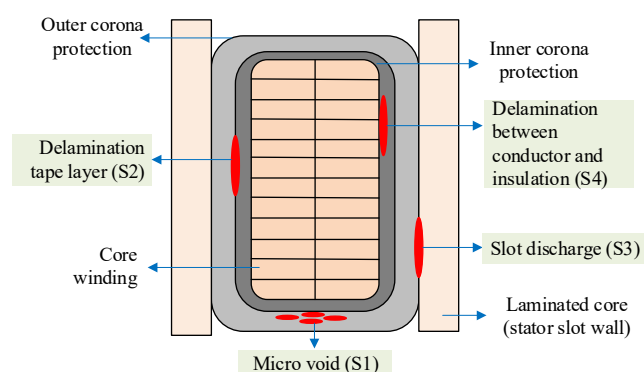


Figure 2. Stator coil part and typical PD faults.

Table 2 refers to the nature of PD in rotating machines and displays some basic ideas regarding the risk associated with some major PD sources. The risk assessment is stated based on experience with modern resin-impregnated mica tape-based HV insulation systems and may vary depending on the insulation material, surface conditions, location of the PD source, etc. [36].

PD parameters, such as apparent charge, pulse repetition rate, current discharge, etc., should be recorded at each voltage as stated and defined in the standard and the PRPD diagram; the so-called fingerprints ought to be recorded as well. Limitations for the meaning of apparent charge levels are not defined in any standard. Evaluation for the rotating machines is a more complex procedure based on several results, such as the number of measured PD magnitudes, PRPD pattern, Q_{Peak} , etc. The condition of the background environment is important for evaluation.

The PD pulse repetition rate, n (kPDs/s), is the ratio between the total number of PD recorded in the interval time selected and the duration of this certain time interval, t [16]. Q_{IEC} , which is expressed in pC or nC, is an apparent charge, which is measured according to the IEC standard, sometimes called Q of an individual PD. An apparent charge is not

equal to the amount of charge locally involved at the site of discharge and cannot be directly measured [23].

Table 2. Basic risk assessment of PD fault.

PD Source	Risk	Remarks
Microvoid (S1)	Low	Does not indicate aging factors, whereas normal circumstances do not lead to remarkable aging.
Delamination tape layer (S2)	High	Internal delamination or tape layer commonly results from overheating and extreme mechanical forces, which can lead to separation of large areas of these layers.
Slot discharge (S3)	High	Generated by poor, missing, contact between field-grading layer and stator slot wall.
Delamination between conductors and insulation (S4)	High	Commonly results from overheating and extreme mechanical forces, which can lead to separation of large areas of these layers.

The number of charges can be measured as in (1) for testing and measuring the void of the test object.

$$Q = \Delta V_1 \times C_F = \int_{t_0}^{t_m} i(t)dt \quad (1)$$

where Q is the apparent charge, ΔV_1 is the instantaneous applied voltage to the test object, C_F is the capacitance inside the void of the test object, t_0 is the starting time, t_m is the completion time, and m is the number of the final pulse during t .

Q_{Peak} is the PD magnitude of the largest absolute discharge of any PD event seen during the evaluation interval. Q_{Avg} is the average Q_{IEC} value during the evaluation interval. I_{Dis} is the average discharge current over the evaluation interval. The statistical computation of MPD600 shows the I_{Dis} value, which refers to the IEC standard [6], by adopting the formula as shown in (2).

$$I_{Dis} = \frac{Q_1 + Q_2 + \dots + Q_m}{t_m - t_0} = \sum_{j=1}^m \frac{Q_j}{t_m - t_0} \quad (2)$$

where I_{Dis} is the average discharge current; and Q_1, Q_2 , until Q_m are the apparent charges, transferred in PD pulse 1 through m [4].

P_{Dis} is the average discharge power, which is discharge current times instantaneous AC voltage over the evaluation interval. The statistical PRPD pattern result of MPD600 shows the values of P_{Dis} and D as calculated from the formulas shown in (3) and (4), respectively.

$$P_{Dis} = \frac{1}{t}(Q_1 V_1 + Q_2 V_2 + \dots + Q_i V_i) = (1/t) \sum_{i=1}^m Q_i V \quad (3)$$

$$D = 1/t(Q_1^2 + Q_2^2 + \dots + Q_m^2) \quad (4)$$

where P_{Dis} is the discharge power, t is the time period, Q_i is the magnitude of the i -th pulse in terms of the charge transfer at the system terminals, and V_i is the instantaneous value of the applied test voltage in volts at which the i -th pulse happens. D is the quadratic rate over the evaluation interval of the sum of the individual discharge magnitudes [5]. The quadratic rate is expressed as coulombs square per second.

2.2. PRPD Pattern of Microvoids (S1)

Microvoid discharge refers to the internal discharges that occur within the insulation ground wall, inside small voids. Internal activity always occurs on HV machines, for example, measured at 13.8 kV generators under normal operating conditions [6]. During offline measurement, it is normal that the activity appears at the lowest voltage, except in the presence of severe problems such as slot discharge activity or severe damage of the stress-grading paint. Microvoid activity is characterized by symmetry in the maximum amplitude and in the number of discharge pulses when the activity occurring in both voltage half-cycles is compared. Figure 3 shows a typical PRPD pattern of the microvoid activity. In addition, this microvoid pattern shows the symmetry of the positive discharges, occurring during the negative cycle of the voltage, and the negative discharges, occurring during the positive cycle of the voltage, which has long been recognized as a characteristic of microvoid discharges [28].

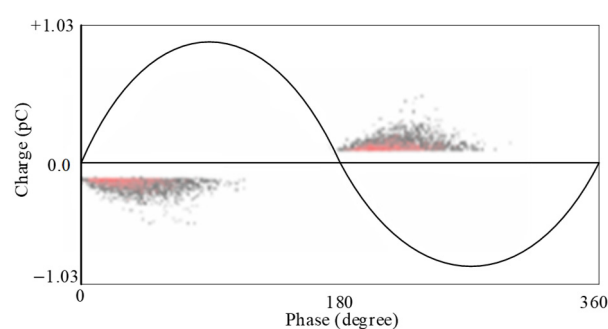


Figure 3. PRPD pattern of microvoid measured on stator bar (S1).

2.3. PRPD Pattern of Delamination Tape Layer (S2)

Delamination discharge is the discharge that occurs between conductors and an insulation layer generated within air or gas filled in the longitudinal direction, which is embedded between the main insulation and field-grading material [6].

This phenomenon is often created by overheating or extreme mechanical forces that lead to the separation of large areas between two layers. Although a distinctive asymmetry was recorded for this defect, it disappeared after a short exposure time to HV as shown in Figure 4.

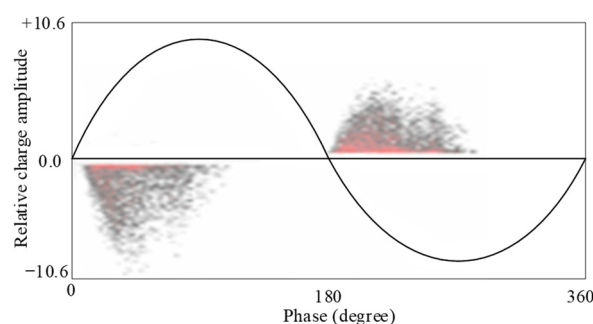


Figure 4. PRPD pattern of delamination tape layers (S2).

The asymmetrical PRPD pattern, followed by a sickle or bow shape as shown in Figure 5, is an important attribute for the PRPD analysis of delamination discharges. In many cases, the sickle shapes stick out of bigger symmetrical inner microvoids [6].

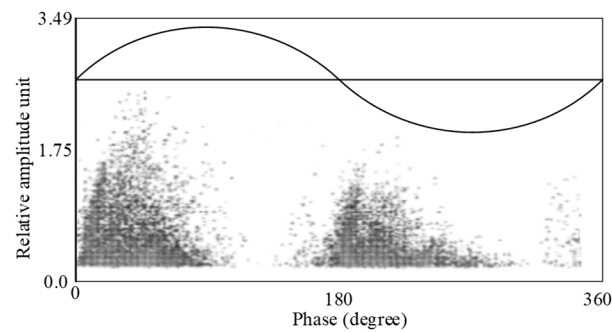


Figure 5. Another PRPD pattern of delamination tape layers (S2).

2.4. PRPD Pattern of Slot Defect (S3)

In the presence of slot discharge, the PRPD pattern is completely different from what is seen in the internal PD. A typical PRPD pattern that resulted from slot discharges exists in the air gap between the magnetic core and the side of stator bars [28] as shown in Figure 6. The occurrence of slot discharge activity obviously increases the risk of in-service failure.

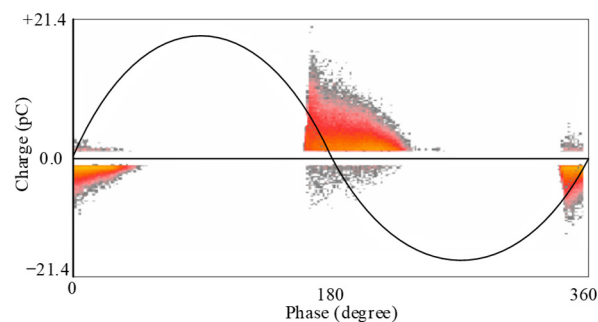


Figure 6. PRPD pattern of slot discharge (S3).

This activity manifested a PRPD pattern stated as slot discharge at the slot area of the stator coil. It can break the insulation gap of the stator. In comparison with the internal PD, the PRPD pattern results from an asymmetrical shape with a magnitude of charges at the negative cycle that is larger than the positive cycle, combined with a triangular shape [6,28]. Moreover, another feature of this PRPD pattern is typical of slot discharge marked with a steep edge in front of a triangular pattern.

2.5. PRPD Pattern of Internal Delamination Discharge (S4)

Internal delamination is generated within air or gas filled in a longitudinal direction that is embedded within the main insulation. This activity often results from overheating of the main insulation or extreme mechanical force that leads to the separation of large areas between insulation layers. The delamination tape layer pattern is an asymmetric pattern with a higher PD reading in the negative half-wave in the AC voltage as shown in Figure 7. The delamination reduces thermal conductivity and accelerates aging [23,28].

Large voids potentially develop over a large surface resulting in discharges of relatively high energy, which may significantly attack the insulation. Particularly, delamination reduces the thermal conductivity of the insulation, which might lead to accelerated aging or even a thermal runaway. Thus, delamination needs deep attention when PD activity is being assessed [6].

Delamination is located between copper strands and the ground-wall insulation found on the generator bars with a resin-rich mica-epoxy insulation system. This delamination is associated with the resin decomposition area that was caused by the PD activity in this delamination [36]. The appearance of the decomposed resin can be figured as a white powder. Specifically, the resin was found totally decomposed at the edges.

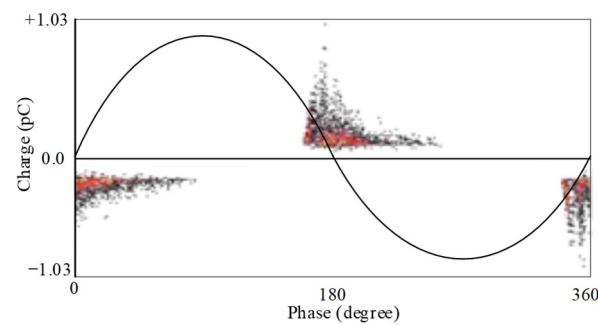


Figure 7. PRPD pattern at internal delamination discharges (S4).

3. Partial Discharge Measurement Connection

The PD measurement in this paper was conducted in offline condition. Firstly, both generators were completely shut down and separated from the system before measurement (see Figure 8a). After the generators were completely shut down, the HV controller and its HV-source 12 kV transformer were set up and connected to a compensating reactor that needed the test source to deliver the impedance part of the current (see Figure 8b,c). The test voltage was gradually stepped up by this HV controller. Then the output of the HV controller was connected to all three HV phase terminals R, S, and T of the generator as the test object was synchronously performed, and the channel had a digital band-pass filter [35] (see Figure 8d).

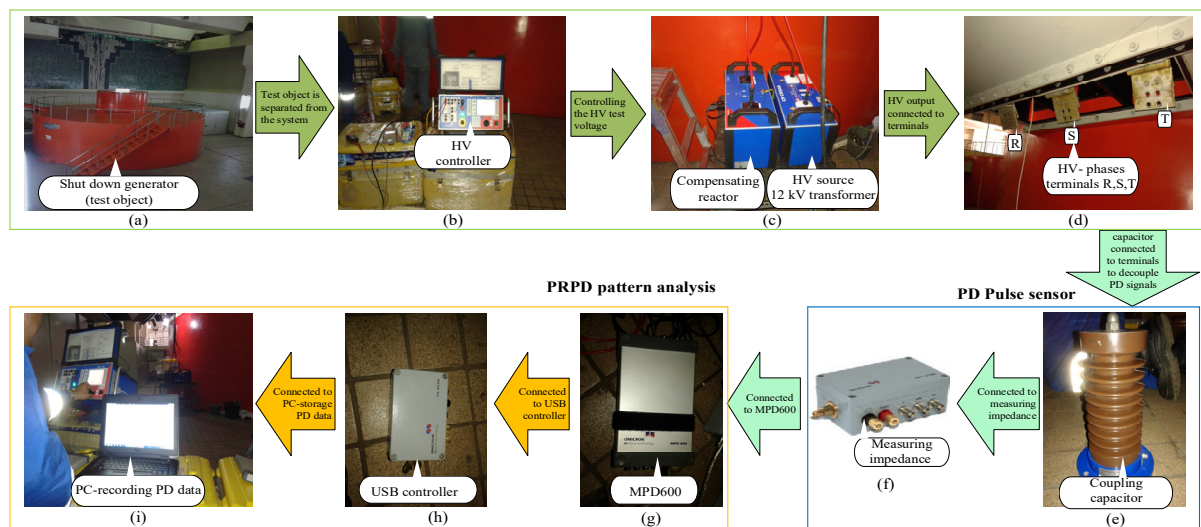


Figure 8. PD measurement instrument and equipment connection to the generator as test object. (a) Test object. (b) HV controller. (c) Compensating reactor and transformer. (d) Three phases' terminals. (e) Coupling capacitor. (f) Measuring impedance. (g) MPD600. (h) USB controller. (i) Recording data.

The measurement used a coupling capacitor as the sensor. Coupling capacitor MCC124 was used as the mounted sensor within the generator's terminals R, S, and T to decouple the PD signal and connected to measuring impedance (see Figure 8e). The sensor was easily integrated into the old machine as a test object after being separated from the power system. The MPD600 PD acquisition unit completely encapsulated components without any control element. The impedance was measured as the input was connected to MPD600 (see Figure 8f). Then MPD600 was connected to a USB controller. The USB controller and all connected MPD600 units were restarted, and the software continued to perform measurements (see Figure 8g).

The collected data were transmitted to a server via cable providers. A PC received the recording PD data from the acquisition unit MPD600 by using a USB controller (see Figure 8h). PD data were displayed, recorded, and analyzed through a PRPD streamer that had been stored at the PC for every stage of the test voltages (see Figure 8i). The PD measurement equipment connection can be seen as shown in Figure 8.

The principal difference between the various PD measuring systems is the bandwidth. The PD pulses arriving at the terminals have a frequency spectrum characterized by the transmission function of the machine winding. Following IEC 60270, PD measurement systems are defined as a wide band if their bandwidth exceeds 100 kHz [6].

The range of the bandwidth for the PD record is from 100 kHz to 400 kHz, which is the PD measurement instrument specification of MPD600. This setting follows the IEC standard for PD setting measurement [23].

The test circuit instrument requires calibration using the CAL542D charge calibrator by 10 nC by a calibration factor before performing measurement [5,6]. The aim of the calibration is to compare various influences of the test circuit, e.g., power supply connection, stray capacitance, coupling capacitance, and test object capacitance, by injecting a better value-defined reference at the terminal after the test circuit is completely connected [23].

The lower cutoff frequency should be in the range of dozens of kilohertz following the IEC standards [23]. It should be noted that resonance phenomena that are in the frequency range of the PD measuring device may occur and, therefore, may also influence the PD results depending on the winding design and measurement arrangement used.

4. Case Studies of Partial Discharge Measurement

The PD measurement uses the frequency integration at $250 \text{ kHz} \pm 300 \text{ kHz}$ from 100 kHz to 400 kHz referring to the specification of MPD600 to follow the IEC standards [23,35]. The testing voltage for the PD measurement is carried out by gradually injecting the voltage to the test objects, initially from 20%, 40%, 60%, 80%, to 100% of the phase-to-phase voltage 6.35 kV, which is obtained by dividing 11 kV by $\sqrt{3}$ and hereinafter called the Un [5,23]. The voltage of the test procedure gradually stepped up from 1.27 kV to 6.35 kV including the following stages: 1.27 kV–2.54 kV–3.81 kV–5.08 kV–6.35 kV–5.08 kV–3.81 kV–2.54 kV–1.27 kV, as shown in Figure 9.

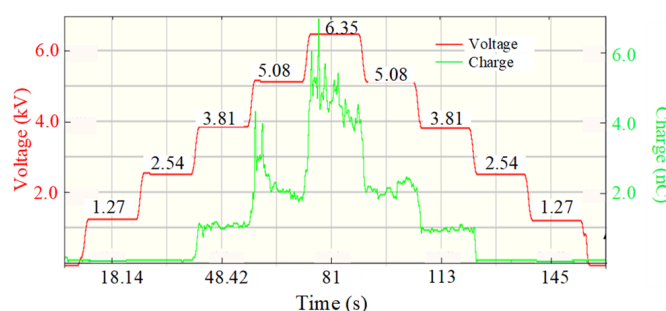


Figure 9. Gradual step-up test voltage for offline PD measurement on rotating machines.

Offline PD measurement was conducted with the system presented above using MPD600 on hydropower generator units 2 and 3 with a capacity of 79.2 MW with a voltage of 11 kV as test objects located in TNP, IPP, North Sumatera, Indonesia. There are four units of generators at TNP as shown in the single-line diagram of TNP in Figure 10 [26].

This paper focused on units 2 and 3 for PD data measurement. The purpose was to assess and compare the stator coil insulation condition by PRPD analysis of the PD level in the stator coil [27]. The main objective of the purpose of the PD measurement is to interpret the result. The PD measurement is a powerful tool for detecting and diagnosing the locally confined insulation defects in rotating machines [35]. The minimum magnitude of the PD quantities that can be measured in a particular test is, in general, limited by disturbances. These can effectively be eliminated by suitable techniques by choosing the appropriate

coupling capacitor sensor; additional limits are obtained by the internal noise levels of the measuring instruments and systems, physical dimensions and layout of the test circuit, and values of the test circuit parameters.

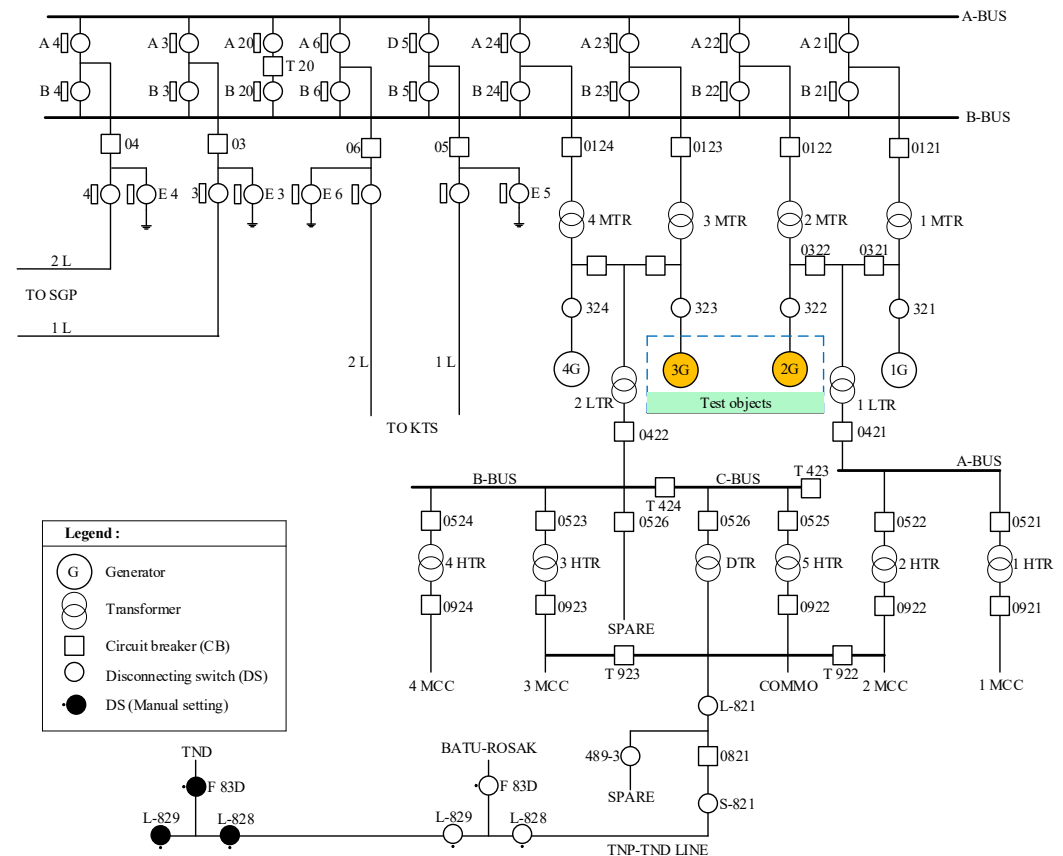


Figure 10. Single-line diagram of TNP, Inalum Power Plant, Indonesia.

Another consideration and limit for the measurement of a minimum PD quantity are set by the capacitance ratio of C_t/C_C and the optimal values for the input impedance of the coupling device and its matching to the measuring instruments used. C_t is the capacitance of the test objects, and C_C is the capacitance of the coupling capacitor. The highest sensitivity would be realized if C_C is greater than C_t ; this condition is generally inconvenient to satisfy due to the additional loading of the HV supply. Thus, the nominal value of C_C is limited for the actual tests, but acceptable sensitivity is usually achieved with C_C being about 1 nF or higher [23]. The coupling capacitor as a sensor in this offline PD measurement uses the coupling-capacitor-type MCC124, 24 kV, with the capacitance 1.1 nF and Z_m C542: 30 μ F, 0.5 A, with the frequency bandwidth of PD measurement of MPD600 100–400 kHz following the IEC standards. Sometimes, the PD measurement uses a coupling capacitor with a capacitance of 80 pF with reference to the IEEE 1434 standard.

The test objects are connected to the offline PD measurement equipment. The test voltage is increased until reaching the maximum test voltage of 6.35 kV. The PRPD pattern, partial discharge inception voltage (PDIV), partial discharge extinction voltage (PDEV), and the largest repeated occurrences of PD magnitude referred to as Q_{Peak} are the basic results to interpret from any offline PD measurement on the stator, recorded during the interval time of measurement [6]. The values of the PDIV and PDEV are influenced by many constraints, including the rate where the voltage gradually increased as well as the history of the voltage applied in the winding or other components thereof. In most cases of the PD measurement, the PDIV is larger than the PDEV, which is related to the following factors: statistical time lags of the availability of the initial electron, oxidation

for the consumption of oxygen, and residual voltage [5,23]. Both the PDIV and PDEV may define the limit of permissible background noise.

The PD detector obtains several important parameters from the PD measurement, such as the PDIV, PDEV, and PD magnitude in pC. The advantages of the PD measurement are given as follows [4]:

- (1) Getting the series prediction and an indication of the insulation degradation in advance prior to failure;
- (2) Avoiding unexpected in-service failures of the equipment, furthermore, can extend uptime between outages;
- (3) Avoiding service that is not important and repairing old equipment by maximizing the operating hours;
- (4) Finding a problem and repairing it before it has a chance to fail the equipment;
- (5) Finding a problem with new equipment that is still under warranty;
- (6) Evaluating the quality of maintenance and repairing whether to rewind it before and after testing;
- (7) Comparing the results of similar equipment to decide on maintenance on those with higher levels of PD;
- (8) Identifying the root cause of the failure mechanism in the equipment to determine the action prior to an outage;
- (9) Improving the overall reliability of the equipment.

4.1. PD Measurement Test Procedures

The PD measurement for generator units 2 and 3 was conducted on 27 January 2016 and that for unit 3 on 28 January 2016. The balance power generation unit is properly regulated during the measurement to fulfill load demand at the smelting plant. These procedures are briefly described as shown in Figure 11 and applied to both generator units 2 and 3 as test objects for the PD measurement. The generators are shut down and separated from the power system network. The HV source test equipment should be well-prepared after the generators are completely stopped. The step procedures of the PD measurement for generator units 2 and 3 are briefly described as follows [35]:

- Step (1) Preparing the HV source test equipment (see Figure 11a);
- Step (2) Connecting the HV power output to the stator winding (see Figure 11b);
- Step (3) Connecting the HV return to the ground (see Figure 11c);
- Step (4) Connecting the PD sensor and coupling capacitor to stator winding (see Figure 11d);
- Step (5) Connect the output from the PD sensor to the measurement unit (see Figure 11e);
- Step (6) Connecting the PD measurement unit to the USB controller using fiber optic cable (see Figure 11e);
- Step (7) Connecting the USB controller to the PC for measurement (see Figure 11f);
- Step (8) Selecting the test voltage 20% U_n (see Figure 11g);
- Step (9) Operating the HV output button, making sure to observe safety rules (see Figure 11g);
- Step (10) Recording the test voltage and PD stream as the PRPD output (see Figure 11h);
- Step (11) Discharging the test object using the ground device after finishing the test (see Figure 11i);
- Step (12) Following steps (8) to (12) for the test voltage 40%, 60%, 80%, and 100% U_n .

The complete offline PD measurement procedures can be seen as shown in Figure 12. The first step is to completely shut down the generator and prepare the circuit of the PD equipment, and the last step is to record and analyze the PD data and then compare them with the ideal kind of PD defect provided by the standards IEC 60034-27 and IEC 60270.

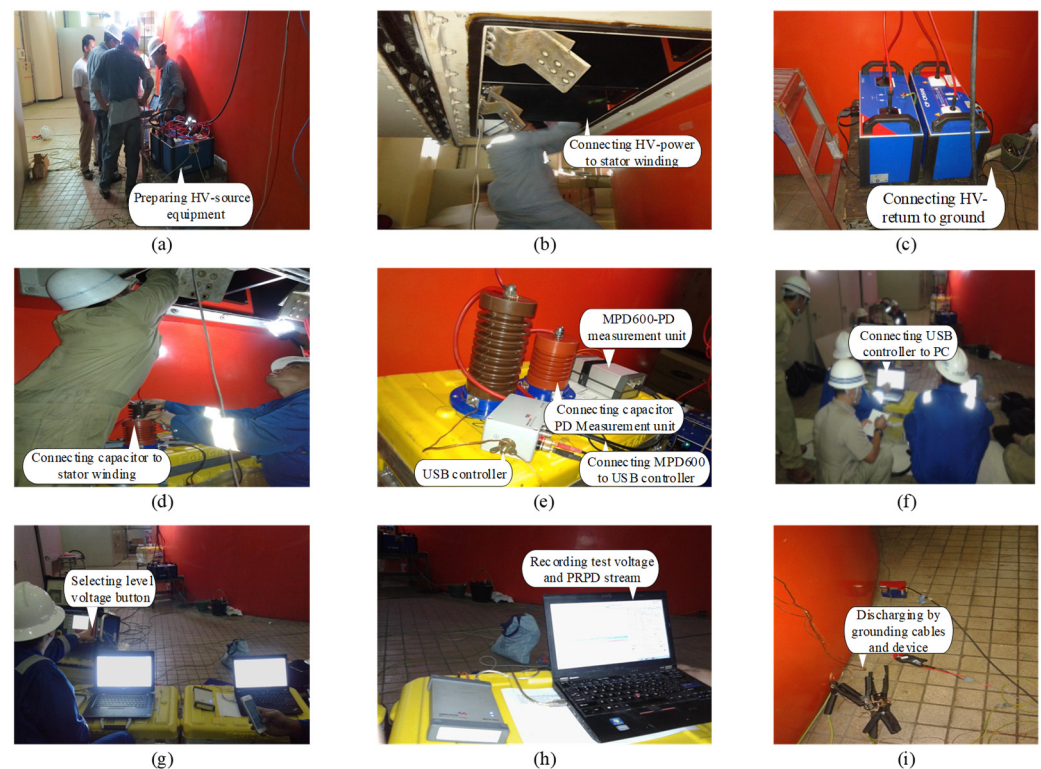


Figure 11. Test procedures for offline PD measurement on generator units 2 and 3 Inalum hydro generators at TNP. (a) HV source test equipment. (b) Connecting HV output to stator winding. (c) Connecting HV return to the ground. (d) Connecting PD sensor capacitor to the stator winding. (e) Connecting output from PD sensor to PD measurement unit and PD measurement unit to USB controller. (f) Connecting USB controller to PC. (g) Selecting test voltage–HV output level. (h) Recording test voltage and PD stream. (i) Discharging test object using grounding device.

4.2. PD Test Result of Phase R + S + T- Unit 2

The PD stream has been recorded from stator coil unit 2 and analyzed by the PRPD pattern method. PD activities recorded in the range of bandwidth frequency from 100 to 400 kHz refer to the specification of the PD measurement instrument, MPD600 [23]. PRPD pattern results are recorded during the interval time for every stage of the test voltage. The maximum scale setting discharge on MPD600 during the test is set to 8 nC to capture the appropriate PRPD pattern.

- (1) PRPD pattern result of 20%, and 40% U_n : The initial testing voltage was applied by injecting 20% U_n , 1.27 kV, to the stator coil with interval duration time. The value of the voltage is 1.27 kV, which gradually increased during a specific interval time. This pattern is recorded without knowing the kind of PD fault during this setup voltage. After recording the PD stream, the test voltage is increased to 40% U_n , 2.54 kV. The PRPD patterns in these two stages, 20% and 40% U_n , are still flat and small as shown in Figure 13a,b, respectively.
- (2) PRPD pattern result of 60%, 80%, and 100% U_n : The next step is voltages are set up to 60%, 80%, and 100% U_n . The higher voltage obtains the higher PD magnitude as well. The PRPD pattern is shaped like a bowl and is asymmetric. The clearest pattern and largest PD magnitude are found in 100% U_n . The recorded PRPD pattern has a triangular shape and is asymmetric since the positive charge magnitude is higher than the negative charge on 60%, 80%, and 100% U_n as shown in Figure 13c–e, respectively. Hence, the PD fault from this PRPD pattern can be categorized as slot discharge (S3) as in the IEC standards [6,7,23]. The highest PD magnitude of the PRPD pattern result is during 100% U_n .

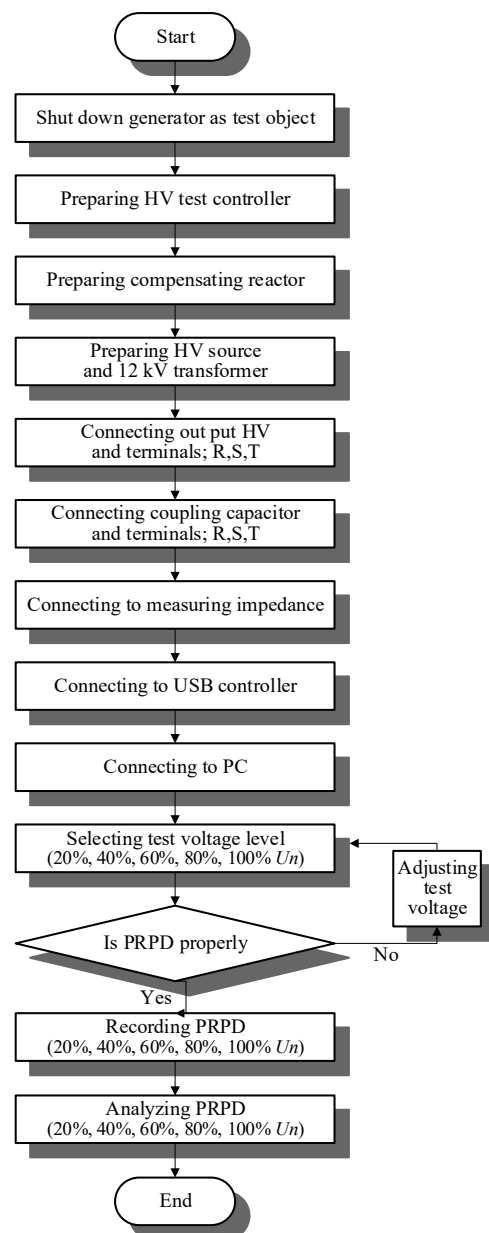


Figure 12. Flow chart of offline PD measurement.

The PD magnitude is set with a threshold of 50 PD/s pulse repetition and 3.5 nC with the PD magnitude maximum found at Q_{Peak} of 8098 pC and relatively can be categorized as a low PD magnitude, as shown in Figure 13f, for a service aged generator [26].

Data resulting from the measurement of all the levels of test voltage were collected for further analysis. The fingerprint data, PRPD pattern, were collected during the interval time testing. The output of the PD detector MPD600 is displayed in the PRPD pattern graph. The data result of the discharge magnitude of Q_{Peak} and Q_{Avg} , n , I_{Dis} , P_{Dis} , and D is higher when the voltage is set up higher. The maximum value of each variable resulted when the test voltage is 100% Un . The value for each level of voltage test can be seen as shown in Table 3.

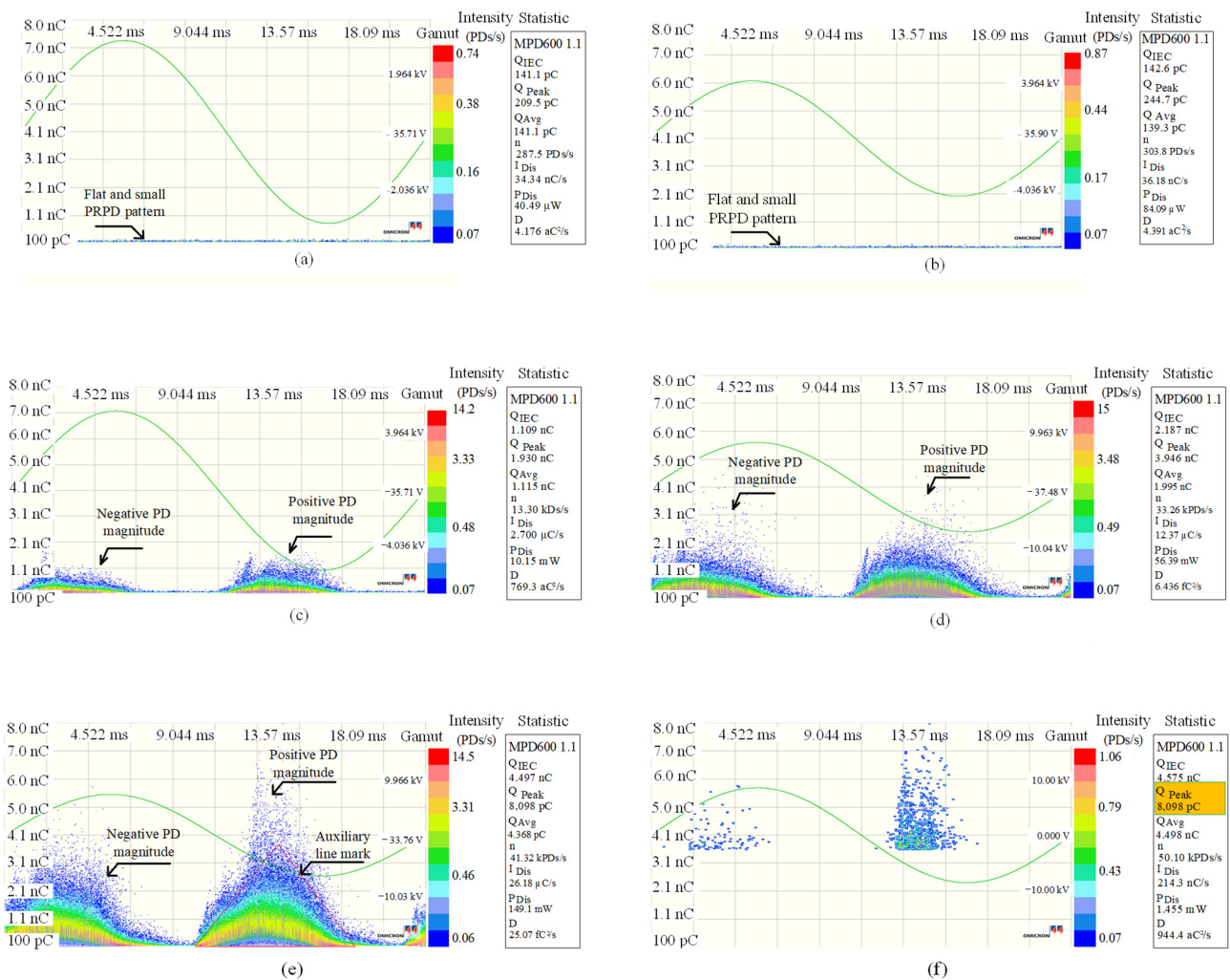


Figure 13. PD test result on generator unit 2, (a) PRPD pattern at 20% U_n , (b) PRPD pattern at 40% U_n , (c) PRPD pattern at 60% U_n , (d) PRPD pattern at 80% U_n , (e) PRPD pattern at 100% U_n , and (f) PD threshold 50 PD/s pulse repetition.

Table 3. PRPD parameter result on unit 2.

U_n (%)	Q_{Peak} (pC)	Q_{Avg} (pC)	n (kPDs/s)	I_{Dis} (nC/s)	P_{Dis} (μ W)	D (aC^2/s)
20	209.5	141.1	0.3	34.3	40.5	4.2
40	244.7	139.3	0.3	36.2	84.1	4.4
60	1930.0	1115.0	13.3	2,700.0	10,150.0	769.3
80	3946.0	1995.0	33.3	12,370.0	56,390.0	6436.0
100	8098.0	4368.0	41.3	26,180.0	149,100.0	25,070.0

The common representation of the PD events versus discharge value can display the analysis and interpretation of the PD fault from unit 2. The display is in bipolar shape from both negative and positive discharges [34]. It is easy to differentiate the slot discharge and internal PD from the phase-resolved representation, and over the last decade, it has replaced other types of representation such as bipolar or unipolar shape [7]. The level of discharge patterns at low voltage, 20% and 40% U_n , is lower compared with that at 60%, 80%, and 100% U_n . The bipolar shape patterns from 20% and 40% U_n are not clear since the total amounts of PD events are 4131 and 4483 PDs as shown in Figure 14a,b in the maximum event scale of approximately 5000 PDs.

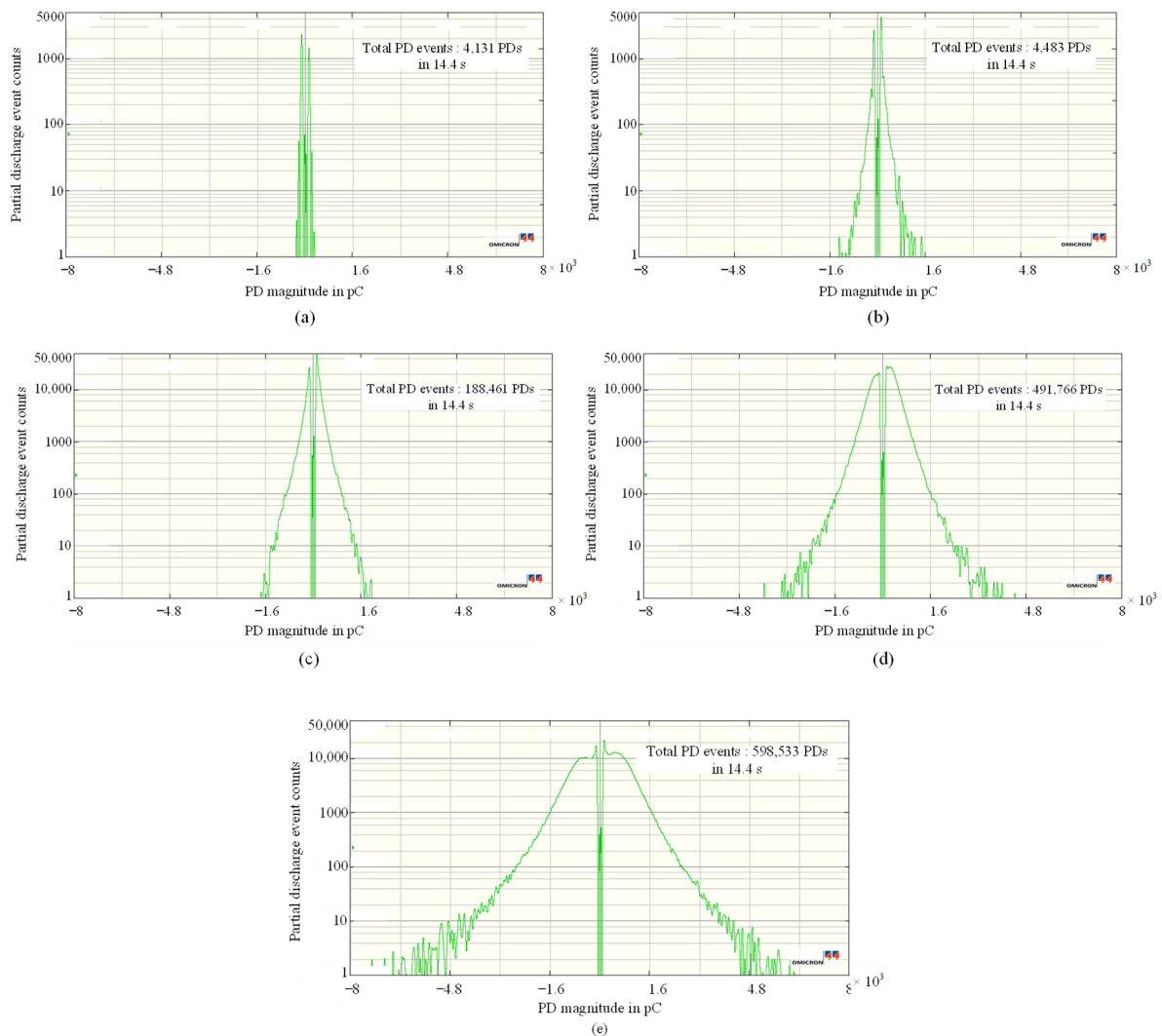


Figure 14. Bipolar pattern of PD events on generator unit 2, (a) 20% U_n , (b) 40% U_n , (c) 60% U_n , (d) 80% U_n , and (e) 100% U_n .

The time duration for recording is 14.4 s. The bipolar shapes for higher voltage 60%, 80%, and 100% U_n are more rounded with the total amount of PD events larger than that of 20% and 40% U_n , i.e., 188,461 PDs, 491,766 PDs, and 598,533 PDs within the same duration recording time of 14.4 s with the maximum events scale approximately 50,000 events as shown in Figure 14c–e, respectively. The bipolar patterns have triangular shapes and similar asymmetric patterns. The PD events in the positive cycle are larger than those in the negative cycle. The bipolar pattern is in asymmetric shape, which shows as the slot discharge referring to the IEC pattern [23,34].

The PD fault on stator coil unit 2 as slot discharge can be indicated from the frequency spectrum of PD pulses as shown in Figure 15. The frequency spectrum is viewed for a wider bandwidth up to 32 MHz to compare with the slot discharge spectrum in the IEC standard as shown in Figure 16. PD activities are recorded in the range of bandwidth frequency from 100 to 400 kHz to refer to the specification of the PD measurement instrument MPD600 [23]. Slot discharge was detected along the frequency test during the measurement. It happened along the frequency bandwidth, even though the trend is not similar for all the percentages of U_n as shown in Figure 17.

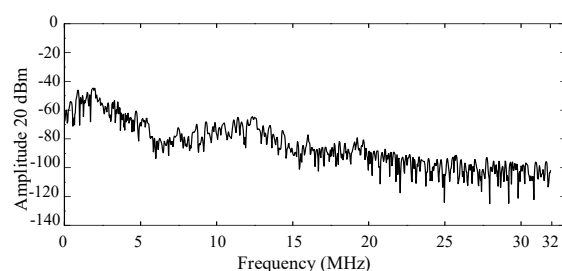


Figure 15. Frequency spectrum pattern of slot discharge pulses on unit 2.

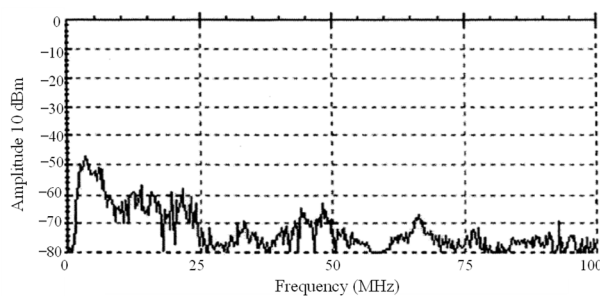


Figure 16. Frequency spectrum of slot discharge in IEC standards.

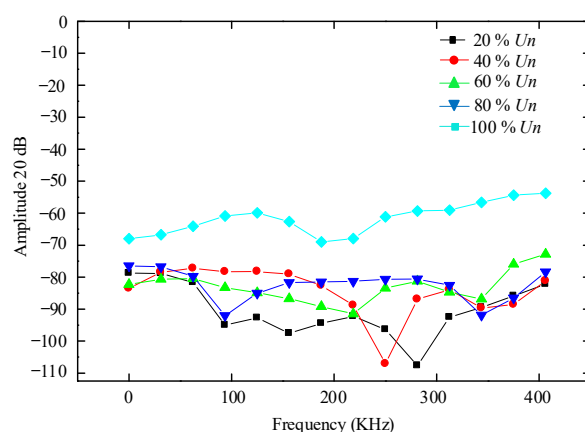


Figure 17. Frequency spectrum of slot discharge MPD600 on unit 2.

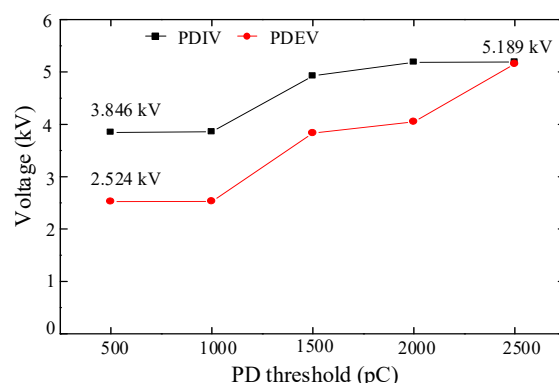
Through the PRPD pattern, PD bipolar characteristic, and PD spectrum frequency analysis, the PD defect on generator unit 2 was analyzed and interpreted as slot discharge (S3). Slot discharge in high machines develops when the conductive slot portion coating is damaged due to the stator bar–coil movement in the slot or the slot exit area, e.g., by loss of wedging pressure due to settlement, erosion of the material, abrasion, chemical attack, or manufacturing deficiencies [5,23]. The high-energy discharge develops when serious mechanical damage or void occurs [4,16]. It can result in additional damage to the main insulation and eventually cause an insulation fault. The level of risk of insulation damage is high since the stator coil has slot discharge (S3).

The initial threshold of 500 pC set to determine the PDIV of unit 2 obtains a voltage of 3.846 kV. This value is 60.57% U_n , and the PDEV is obtained at 2.524 kV. The highest PDIV and PDEV occur when the threshold is at 2500 pC, since the PDIV is 5.189 kV, which is about 81.72% U_n . The PDIV and PDEV are recorded with various thresholds rather than recording the PRPD patterns during the PD measurement, as shown in Table 4 [5,16]. The recording can be figured out in the graph since the PDIV is larger than the PDEV, as shown in Figure 18.

Table 4. PDIV and PDEV with various thresholds on unit 2.

PD Threshold (pC)	PDIV (kV)	PDEV (kV)
500	3.846 (60.57%)	2.524
1000	3.857 (60.74%)	2.528
1500	4.926 (77.57%)	3.831
2000	5.185 (81.65%)	4.046
2500	5.189 (81.72%)	5.155

Note: PD threshold 3000 pC result is PDIV < PDEV (not typical), Un base is 6.35 kV.

**Figure 18.** PDIV and PDEV with various thresholds on unit 2.

4.3. PD Test Result of Phase R + S + T- Unit 3

The PD stream that has been recorded from stator coil unit 3 is analyzed by the PRPD pattern method in the same way as that carried out in unit 2. PD activities recorded in the range of bandwidth frequency from 100 to 400 kHz refer to the specification of the PD measurement instrument MPD600 [23]. PRPD pattern results were recorded during the interval time for every stage of the test voltage. The maximum discharge setting on MPD600 during the test is set to 14 nC to capture the appropriate PRPD pattern since the unit 3 charge magnitude is higher than the unit.

- (1) PRPD pattern result of 20% and 40% U_n : The initial testing voltage was applied by injecting 20% U_n , 1.27 kV, to the stator coil with interval duration time. The value of the voltage is 1.27 kV, which gradually increased during a specific interval time. This pattern is recorded without knowing the kind of PD fault during this setup voltage. The PD magnitude during this voltage stage is small. After recording the PD stream, the test voltage is increased to 40% U_n , 2.54 kV. The PRPD pattern and magnitudes of 40% U_n are still small but larger than those of 20% U_n . During this stage, there are not enough PRPD pattern results to recognize the kind of PD defect. However, the result is still higher than unit 2 since the maximum scale of the discharge was set to 14 nC compared with 8 nC for unit 2. The PRPD patterns and magnitudes of 20% and 40% U_n are recorded as the output of MPD600 for further analysis as shown in Figure 19a,b, respectively.
- (2) PRPD pattern result of 60%, 80%, and 100% U_n : The next step is the voltages are increased to 60%, 80%, and 100% U_n , with the maximum scale of discharge set to 14 nC. The higher voltage obtains the higher PD magnitude. The pattern is shaped like a bowl and asymmetric since the negative charge magnitude is higher than the positive charge. The PRPD patterns and magnitudes for 60%, 80%, and 100% U_n are larger than those for 20% and 40%. PRPD pattern results can be recognized for the kind of PD defect. The patterns have triangular shapes, are asymmetric, and have sickle shapes before having a bowl shape, as shown in Figure 19c–e, respectively. Referring to the PRPD pattern result, the PD defect can be indicated as delamination

(S2) and slot discharge (S3), which also refers to the IEC standards and experiences of PD measurements [7,23].

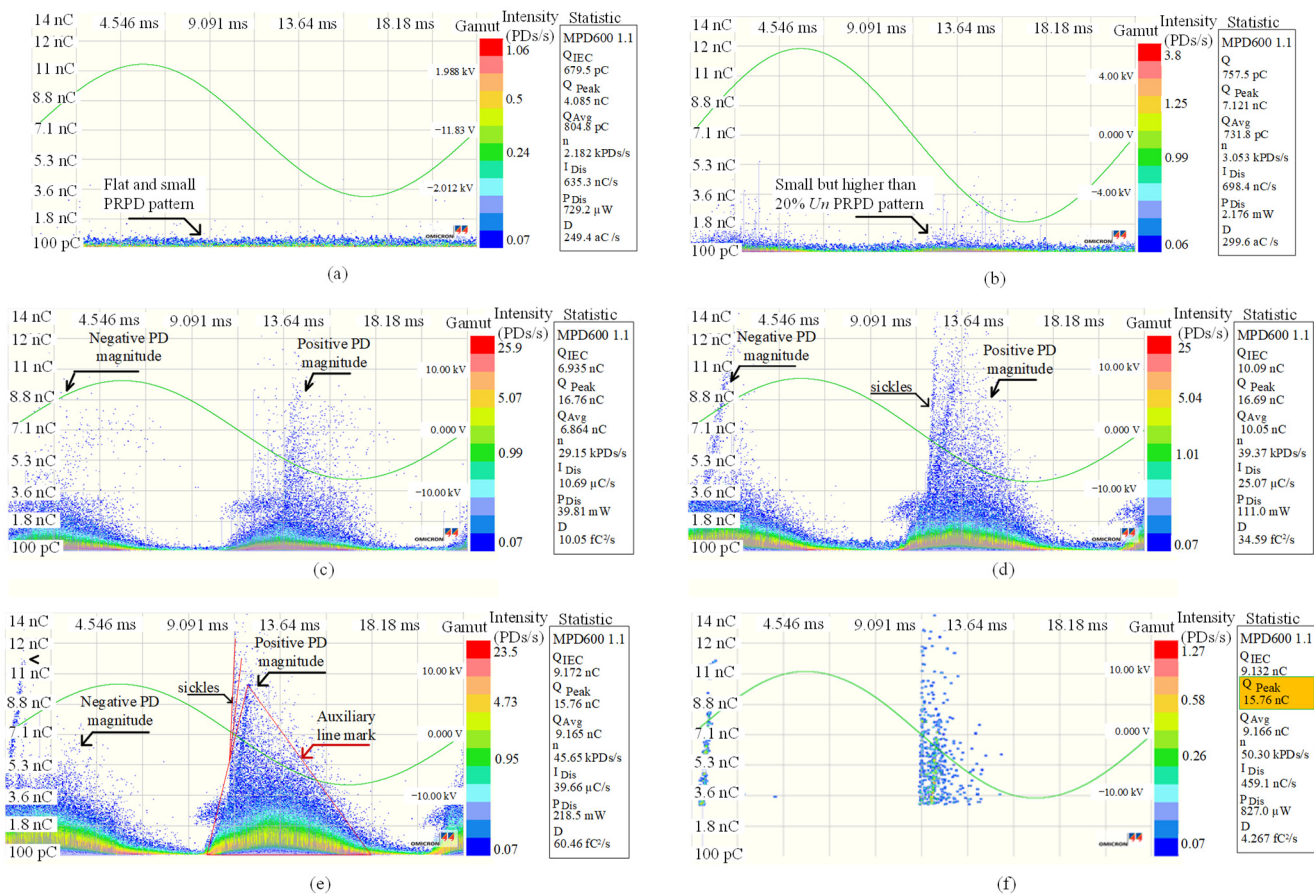


Figure 19. PD test result on generator unit 3, (a) PRPD pattern at 20% U_n , (b) PRPD pattern at 40% U_n , (c) PRPD pattern at 60% U_n , (d) PRPD pattern at 80% U_n , (e) PRPD pattern at 100% U_n , and (f) PD threshold 50 PD/s pulse repetition.

The PD magnitude with a threshold at 50 PD/s pulse repetition is 7.65 nC with the PD magnitude maximum Q_{Peak} of 15,760 pC detected as shown in Figure 19f and relatively can be categorized as the medium PD magnitude for the 33-year operation of the generator.

Similar with the treatment in unit 2, the data resulting from the measurement of all the levels of test voltage were collected for further analysis. The PD stream data were collected in PC software. This PD stream is the PRPD pattern, and the value is displayed on the statistics of the MPD600 result, on the right side of the PRPD pattern. The fingerprint data, PRPD pattern, are collected during the sine-wave cycle. The output of the PD detector MPD600 is displayed in the PRPD pattern graph. Similar with unit 2, the data result of the discharge magnitude of Q_{Peak} and Q_{Avg} , n , I_{Dis} , P_{Dis} , and D is higher when the voltage is set up higher. The maximum value of each variable resulted when the test voltage is 100% U_n . The value for each level of test voltage is shown in Table 5.

The analysis and interpretation of the PD fault from unit 3 can be displayed by the common representation of the PD events versus discharge [34]. The display pattern from MPD600 is bipolar. The level of slot discharge is low at 20% and 40% U_n . The bipolar patterns have triangular shapes with the total amount of PD events being 25,168 PDs and 29,583 PDs, during the duration interval of 14.4 s with maximum event scales of approximately 5000 and 10,000 events as shown in Figure 20a,b, respectively. Anyhow, the asymmetrical shape is not clear during this stage. However, the bipolar patterns for 60%, 80%, and 100% U_n have a more rounded and triangular shape asymmetrically. The total amount of PD events in the negative cycle is larger than that in the positive cycle, i.e.,

418,894 PDs, 563,461 PDs, and 698,192 PDs during the interval time of 14.4 s as shown in Figure 20c–e with a maximum PD event scale of approximately 50,000 events, respectively. The bipolar pattern of PD events has an asymmetrical shape since the negative cycle is larger than the positive cycle, and the triangular shape can be indicated as the PD defect on the slot area also has delamination at the tape layer and is referred to as the IEC standard pattern [23,34].

Table 5. PRPD parameter result on unit 3.

Un (%)	Q_{Peak} (pC)	Q_{Avg} (pC)	n (kPDs/s)	I_{Dis} (nC/s)	P_{Dis} (μ W)	D (aC^2/s)
20	4085	804.8	2.2	635.3	729.2	249.4
40	7121	731.8	3.1	698.4	2176.0	299.6
60	16,760	6864.0	29.2	10,690.0	39,810.0	10,050.0
80	16,690	10,050.0	39.4	25,070.0	111,000.0	34,590.0
100	15,760	9165.0	45.7	39,660.0	218,500.0	60,460.0

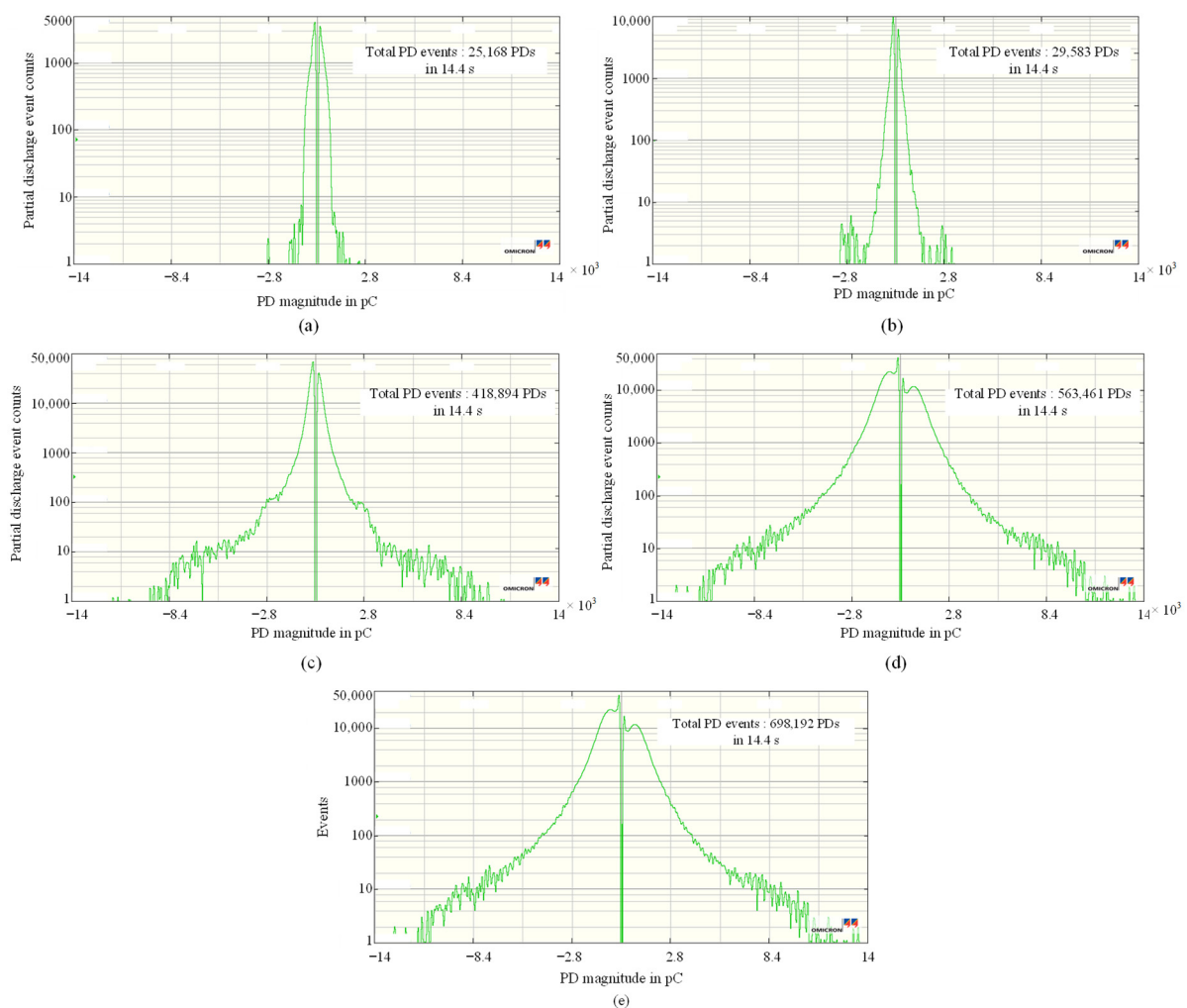


Figure 20. Bipolar pattern of PD events on generator unit 3, (a) 20% Un , (b) 40% Un , (c) 60% Un , (d) 80 % Un , and (e) 100% Un , respectively.

Delamination discharge can be explained through PRPD, and the bipolar pattern as above refers to the experiences of such PD measurements [7,23]. The frequency spectrum can be viewed for a wider bandwidth up to 32 MHz from PD pulses to compare with the standard since the pattern is like the slot discharge pattern in the IEC standards, as

shown in Figure 21. The recorded frequency spectrum refers to the bandwidth of MPD600 in the range of 100–400 kHz. The slot discharge happened even though the magnitude is randomly not similar, but it could be seen along the frequency setting, as shown in Figure 22. The PD pulse was recorded higher than the spectrum in unit 2. It cannot be distinguished whether the pulse is slot discharge or delamination through this spectrum, but the pulse has been detected along the frequency test. The other important parameters that needed to be recorded during the PD measurement are the PDIV and PDEV. The initial threshold, 500 pC, is set to determine the PDIV of unit 3 and obtain the voltage of 1.262 kV. This value is 19.87% U_n , and the PDEV is obtained at 1.216 kV. The highest PDIV and PDEV occur when the threshold is at 11,500 pC and the PDIV is 5.731 kV, which is about 90.25% U_n . The PDIV and PDEV are recorded with various thresholds rather than recording the PRPD patterns during the PD measurement, as shown in Table 6 [5,16]. The recording data are figured out in the graph since the PDIV is larger than the PDEV as shown in Figure 23.

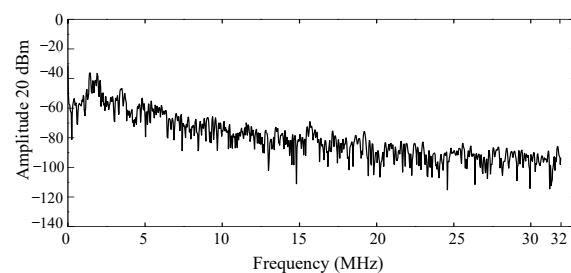


Figure 21. Frequency spectrum pattern of slot discharge pulses on unit 3.

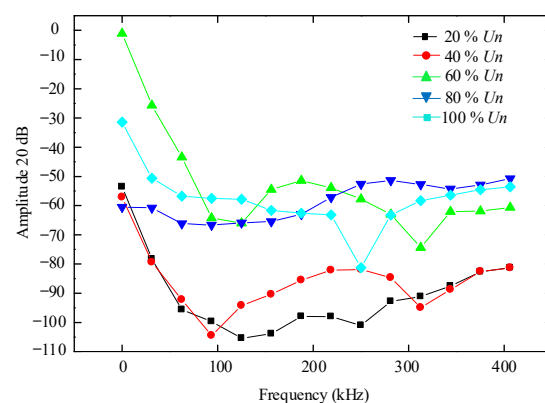


Figure 22. Frequency spectrum of slot discharge MPD600 on unit 3.

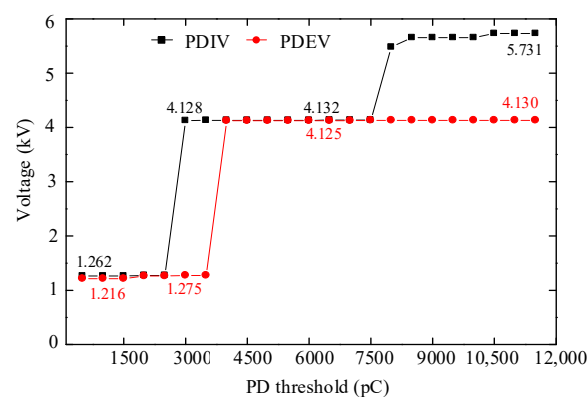


Figure 23. PDIV and PDEV with various thresholds on unit 3.

Table 6. PDIV and PDEV with various thresholds on unit 3.

PD Threshold (pC)	PDIV (kV)	PDEV (kV)
500	1.262 (19.87%)	1.216
1000	1.262 (19.87%)	1.216
1500	1.262 (19.87%)	1.216
2000	1.275 (20.08%)	1.263
2500	1.275 (20.08%)	1.263
3000	4.128 (65.01%)	1.275
3500	4.132 (65.07%)	1.275
4000	4.132 (65.07%)	4.124
4500	4.132 (65.07%)	4.124
5000	4.132 (65.07%)	4.124
5500	4.132 (65.07%)	4.125
6000	4.132 (65.07%)	4.125
6500	4.133 (65.08%)	4.125
7000	4.133 (65.08%)	4.125
7500	4.133 (65.08%)	4.130
8000	5.481 (86.32%)	4.130
8500	5.657 (89.08%)	4.130
9000	5.657 (89.08%)	4.130
9500	5.657 (89.08%)	4.130
10,000	5.657 (89.08%)	4.130
10,500	5.731 (90.25%)	4.130
11,000	5.731 (90.25%)	4.130
11,500	5.731 (90.25%)	4.130

Note: PD threshold 12,000 pC result is PDIV < PDEV (not typical), $U_n = 6.35$ kV

4.4. PD Defect Measurement Found

Based on the PRPD pattern, PD bipolar characteristic, and PD spectrum frequency analysis, the PD defect on generator unit 3 was analyzed and interpreted as the combination of thermal aging or delamination (S2) and slot discharge (semicon paint abrasion, S3). The internal delamination within the main insulation can be caused by imperfect curing of the insulation system during manufacturing or by mechanical and thermal overstressing during operation. The level of risk of insulation damage for both S2 and S3 is high based on the PRPD pattern results [6,23].

Delamination, which is located at the interface of the copper conductor and the main insulation, mostly results from excessive thermal cycling and is harmful, and the delamination can cause the turn or strand of the insulation's conductor to be severely broken. Therefore, this delamination phenomenon must be paid attention to and should be firstly maintained to avoid more severe damage.

The PD data results show that the values of Q_{Peak} and Q_{Avg} in unit 3 are not rapidly increasing similar with those in unit 2. Data show that in 100% U_n , Q_{Peak} and Q_{Avg} are lower than those in 80% and 60%. This condition is probably caused by contamination occurring on unit 3; hence, at that stage voltage, the PD is decreased. Since PD is a symptom affected by many parameters, such as contamination, manufacturing issues, and incorrect design, there are thermal and mechanical stresses in operation. By considering this phenomenon, generator unit 3 should be put in priority to check the stator coil condition in the maintenance plan schedule.

4.5. Actual Experimental Inspection Found

The intention of this research was to compare the PD fault result from two generators with similar rates and designs by using the same testing methods, equipment, and characteristics as well, and it was found that there are different PD faults on generator units 2 and unit 3 of the Inalum hydro generator. Therefore, the maintenance plan should be stipulated for unit 3 as the priority while keeping the monitoring of the PD activity by periodically measuring, for instance, every six months [30].

Slot discharges in HV machines develop when the conductive portion coating is damaged when there is bar or coil movement in the slot exit area, e.g., by loss of wedging pressure due to settlement, erosion of material, abrasion, chemical attack, or manufacturing deficiencies. These are the root causes of producing slot discharge [6]. The fault typically appears during the operation of the machine and is caused by electromechanical forces, resulting in arcing, which can be measured as slot discharge [35].

A typical delamination tape layer develops when there is a separation of large areas between two insulation layers in a longitudinal direction. It often results from overheating, extreme mechanical force, or imperfect curing of the insulation system. Delamination is dangerous since the turn or strand insulation of the conductors can be severely damaged [6].

Based on inspection experience as evidence, slot discharges in generator stator coil units 2 and 3 at TNP were found, as shown in Figures 24 and 25. Maintenance treatment is carried out for the stator coil as countermeasures after conducting the inspection, such as

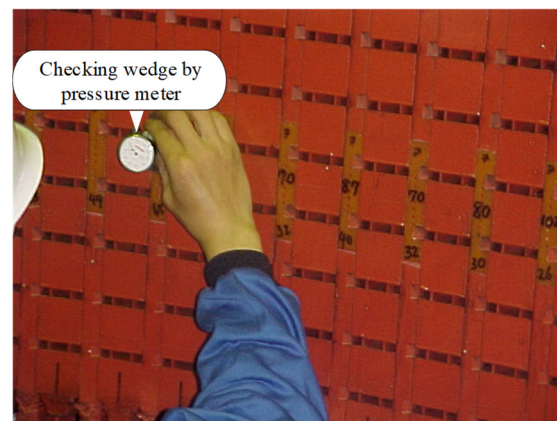
- (1) Checking the wedges of the stator coil for each stator slot as shown in Figures 24a and 25a, overheating areas for units 2 and 3, respectively;
- (2) Marking the loosened wedges for every slot so that they can be replaced by appropriate new wedges as shown in Figure 24b, wedge at slot no. 86, and Figure 25b for units 2 and 3, respectively.
- (3) Inspecting and marking the loosened wedges for every slot number of the stator coil, as shown in Figure 24c, wedge at slot no. 126, and Figure 25c, wedge at slot no. 47 for units 2 and 3, respectively.

Loose and wounded wedges were found during the routine maintenance work on 27 January 2016. In the inspection procedure, pressure meters were used to obtain the pressure magnitude to realize the status of wedges, as shown in Figures 24a and 25a for units 2 and 3, respectively. In the measurement, loose and wounded wedges were found at slot nos. 126 and 86, as shown in Figures 24b and 25b for units 2 and 3, respectively. Meanwhile, other loose and wounded wedges were inspected at slot nos. 126 and 47 as shown in Figures 24c and 25c for units 2 and 3, respectively. The locations of the wedges are almost similar with the locations of the conductor partial discharge nearby.

Some countermeasures need to be applied to the stator coil after collecting data such as

- (1) Tightening the loosened wedges by adding the pieces of wedges;
- (2) Replacing broken wedges with new ones, with the same dimension as well;
- (3) Cleaning the slot area of the stator coil by smoothly scrubbing it;
- (4) Re-taping the stator coil bar for the slightly broken stator bar;
- (5) Replacing the broken stator coil with a new one since there is a spare in the warehouse;
- (6) Renew all the total stator coils with new ones by conducting a precise inspection or major overhaul of the whole parts of the generator machine including turbine parts.

The last part of this countermeasure was not included in this paper, since the intention is to compare the PD magnitude of two rotating machines with a similar rating and design only.



(a)

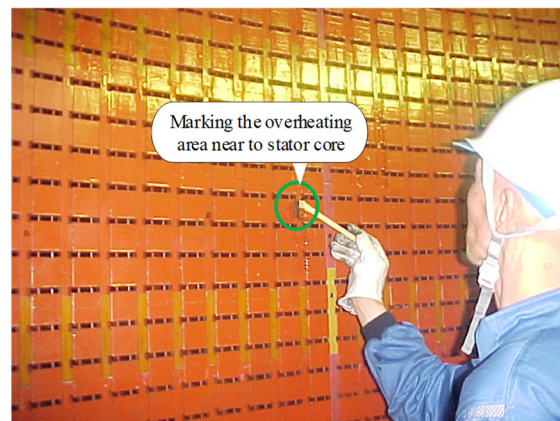


(b)

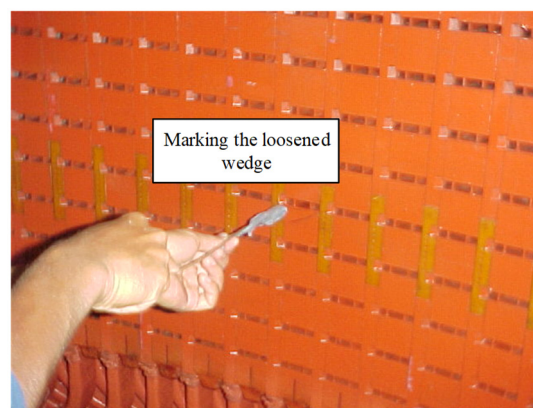


(c)

Figure 24. Visual checking on stator slot of generator unit 2. (a) Engineer checking the wedge by gauge pressure. (b) Loosening of the wedge in slot no. 86. (c) Loosening of the wedge in slot no. 126.



(a)



(b)



(c)

Figure 25. Visual checking on stator slot of generator unit 3. (a) Engineer checked and found marking such as overheating. (b) Marking the loosened wedge. (c) Loosening of the wedge in slot no. 47.

5. Discussion

The PD measurement methods can bring a new point of view and contribution to other similar rotating machines. The stator coil with the greatest activity should be subjected to further inspections instead of the other. To summarize, the advantages of applying PRPD pattern analysis can be listed for several types of discharge in the rotating machine as follows:

- (1) Knowing the stator coil condition: The PD measurement can be stated as the preliminary checking of the condition of the stator coil without pulling out the rotor of

the generator. The interpretation of PRPD analysis is necessary to indicate the stator coil condition prior to being inspected. The results of the PRPD pattern analysis in this research found that the defect on the stator coil on unit 2 is slot discharge (S3) with a high-risk level; unit 3 has delamination (S2) and slot discharge (S3) with a high-risk level.

- (2) Early detection for stator coil treatment: The PD measurement of units 2 and 3 shows the result condition of the stator coil insulation system. The result contributes to early detection for the future planning of the stator coil treatment by finding out whether to re-tape it or replace it with a new stator coil.
- (3) Priority maintenance plan of the generator: The PD fault interpreted by the results of the PRPD analysis can explain which unit of the generator has more PD activity. Then, the stator with the highest PD magnitude should be subjected to further inspection. Based on the result of this research, generator unit 3 should be planned to be inspected first rather than generator unit 2 since the former has a higher peak Q_{Peak} . The PD measurement is suggested to be periodically conducted to see the trend of PD activity on the stator coil.

6. Conclusions

PD measurement that has been conducted in hydropower generators was presented in this paper. The intention is to compare the PD magnitude and pattern from two rotating machines that have similar ratings and designs. The measurement result shows that the two generators have different PD fault on the stator coil.

The measurement results show that the stator coil defect of unit 2 is slot discharge (S3), and unit 3 has delamination (S2) and slot discharge (S3). Based on the PRPD analysis, the PD fault of the generator unit on generator unit 2 is a slot defect caused by stator coil–bar movement in the slot area, but unit 3 has not only a slot defect but also delamination at the tape layer, which is caused by mechanical overstressing during operation. Moreover, due to the higher peak Q_{Peak} of unit 3, inspections should be scheduled first. Finally, after a maintenance inspection, the stator coils of TNP generator units 2 and 3 were found to have loose and damaged wedges. The location of the wedge is almost the same as the location of the partial discharge from nearby conductors.

The benefit of the PRPD analysis on the offline PD measurements was shown in this thesis. It certainly can provide more clear information and reference to other similar rotating machines about PD activity. For future work, some studies are of great interest: for instance, the new identification method of delamination and slot discharge could be verified for the insulation condition of the stator coil for other rotating machines.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Koltunowicz, W.; Badicu, L.-V.; Broniecki, U.; Belkov, A. Increased operation reliability of HV apparatus through PD monitoring. *IEEE Trans. Dielectr. Electr. Insul.* **2016**, *23*, 1347–1354. [\[CrossRef\]](#)
2. Cavallini, A.; Montanari, G.; Puletti, F.; Contin, A. A new methodology for the identification of PD in electrical apparatus: Properties and applications. *IEEE Trans. Dielectr. Electr. Insul.* **2005**, *12*, 203–215. [\[CrossRef\]](#)
3. Seo, I.-J.; Khan, U.A.; Hwang, J.-S.; Lee, J.-G.; Koo, J.-Y. Identification of Insulation Defects Based on Chaotic Analysis of Partial Discharge in HVDC Superconducting Cable. *IEEE Trans. Appl. Supercond.* **2015**, *25*, 5402005. [\[CrossRef\]](#)
4. Omicron Energy Monitoring Solution Brochure. *Partial Discharge Monitoring of High Voltage Assets*; Omicron: Asotin, WA, USA, 2015.
5. *IEEE Std. 1434-2000 (R2005)*; IEEE Guide to the Measurement of Partial Discharges in Rotating Machinery. IEEE: New York, NY, USA, 2005.
6. *IEC60034-27*; Rotating Electrical Machines - PD Measurements of Rotating Machinery. IEC Std.: Worcester, MA, USA, 2006.
7. Hudon, C.; Belec, M. Partial discharge signal interpretation for generator diagnostics. *IEEE Trans. Dielectr. Electr. Insul.* **2005**, *12*, 297–319. [\[CrossRef\]](#)
8. Baug, A.; Choudhury, N.R.; Ghosh, R.; Dalai, S.; Chatterjee, B. Identification of single and multiple partial discharge sources by optical method using mathematical morphology aided sparse representation classifier. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 3703–3712. [\[CrossRef\]](#)
9. Lee, S.B.; Naeini, A.; Jayaram, S.; Stone, G.C.; Šašić, M. Surge Test-Based Identification of Stator Insulation Component With Partial Discharge Activity for Low Voltage AC Motors. *IEEE Trans. Ind. Appl.* **2020**, *56*, 2541–2549. [\[CrossRef\]](#)
10. Johnson, J.S.; Warren, M. Detection of Slot Discharges in HV Stator Windings During Operation. *Trans. AIEE* **2009**, *70*, 1998–2000.
11. Renforth, L.A.; Giussani, R.; Dodd, L.; Mendiola, M. On-line partial discharge insulation condition monitoring of complete high voltage (HV) networks. *IEEE Trans. Ind. Appl.* **2019**, *55*, 1021–1029. [\[CrossRef\]](#)
12. Mondal, M.; Kumbhar, G.B.; Kulkarni, S.V. Localization of Partial Discharges inside a Transformer Winding Using a Ladder Network Constructed from Terminal Measurements. *IEEE Trans. Power Deliv.* **2018**, *33*, 1035–1043. [\[CrossRef\]](#)
13. Petr Mraz, I. Aspect of Partial Discharge Activity Evaluation. Ph.D. Dissertation, Pilsen University, Pilsen, Czech Republic, 2014.
14. Lwin, K.-S.; Park, N.-J.; Kim, H.-D.; Ju, Y.-H.; Park, D.-H. Off-line PD Diagnosis for Stator Winding of Rotating Machines using a UWB Sensor. *J. Electr. Eng. Technol.* **2008**, *3*, 263–269. [\[CrossRef\]](#)
15. Stone, G.C.; Sasic, M.; Dunn, D.; Culbert, I. Recent Problems Experienced with Motor and Generator Windings. In Proceedings of the Petroleum and Chemical Industry Conference, Industry Applications Society 56th Annual, Anaheim, CA, USA, 14–16 September 2009.
16. Wang, X. Partial Discharge Analysis of Stator Insulation at Arbitrary Voltage Waveform Stimulus. Ph.D. Dissertation, KTH Electrical Engineering, Stockholm, Sweden, 2015.
17. Altenburger, R.; Heitz, C.; Timmer, J. Analysis of phase-resolved partial discharge patterns of voids based on a stochastic process approach. *J. Phys. D Appl. Phys.* **2002**, *35*, 1149. [\[CrossRef\]](#)
18. Li, Y.; Gao, W.; Huang, S.; Wang, R.; Yan, W.; Gevorgian, V.; Gao, D.W. Data-driven Optimal Control Strategy for Virtual Synchronous Generator via Deep Reinforcement Learning Approach. *J. Mod. Power Syst. Clean Energy* **2021**, *9*, 919–929. [\[CrossRef\]](#)
19. Zhang, N.; Sun, Q.; Yang, L.; Li, Y. Event-Triggered Distributed Hybrid Control Scheme for the Integrated Energy System. *IEEE Trans. Ind. Informat.* **2022**, *18*, 835–846. [\[CrossRef\]](#)
20. Gopinath, S.; Sathiyasekar, K.; Padmanaban, S.; Chokkalingam, B. Insulation Condition Assessment of High Voltage Rotating Machines Using Hybrid Techniques. *IET Gener. Transm. Distrib.* **2019**, *13*, 171–180. [\[CrossRef\]](#)
21. Nair, R.P.; Sumangala, B.V.; Rao, N.B. Identification of slot discharges in rotating machine insulation system using variable frequency PD measurement. *IET High Volt.* **2018**, *3*, 179–186. [\[CrossRef\]](#)
22. CIGRE Technical Brochure 258, Application of On-Line Partial Discharge Tests to Rotating Machines. 2015. Available online: <https://e-cigre.org/publication/258-application-of-on-line-partial-discharge-tests-to-rotating-machines> (accessed on 1 September 2022).
23. *IEC 60270*; High-Voltage Test Techniques—Partial Discharge Measurements. 3rd ed. IEC Std.: Worcester, MA, USA, 2000.
24. Parent, G.; Rossi, M.; Duchesne, S.; Dular, P. Determination of Partial Discharge Inception Voltage and Location of Partial Discharges by Means of Paschen's Theory and FEM. *IEEE Trans. Magn.* **2019**, *55*, 7023504. [\[CrossRef\]](#)
25. Stone, G.C.; Sedding, H.G.; Chan, C. Experience with online partial-discharge measurement in high-voltage inverter-fed motors. *IEEE Trans. Ind. Appl.* **2018**, *54*, 866–872. [\[CrossRef\]](#)
26. Nippon Koei Co., Ltd. *Project Completion Report, Vol. III Main Text (3)*; PT. Indonesia Asahan Aluminium: Jakarta Selatan, Indonesia, 1984.
27. Nelson, J.K. *Assessment of Partial Discharge and Electromagnetic Interference On-Line Testing of Turbine-Driven Generator Stator Winding Insulation Systems*; EPRI: Palo Alto, CA, USA, 2003; p. 1007742.
28. Rotating Electrical Machines—Part 27-2: On-Line Partial Discharge Measurements on the Stator Winding Insulation of Rotating Electrical Machines, IEC/TS60034-27-2:2012-03. Available online: <https://webstore.iec.ch/publication/131> (accessed on 1 September 2022).
29. Edin, H. Partial Discharges Studied With Variable Frequency of the Applied Voltage. Ph.D. Dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, 2001.

30. Kurtz, M.; Lyles, J.F.; Stone, G.C. Application of partial discharge testing to hydro generator maintenance. *IEEE Trans. Power Appar. Syst.* **1984**, PAS-103, 2148–2157. [[CrossRef](#)]
31. Stone, G.C.; Goodeve, T.E.; Sedding, H.G.; McDermid, W. Unusual PD Pulse Phase Distributions in Operating Rotating Machines. *IEEE Trans Dielectr. Electr. Insul* **1995**, 2, 567–577. [[CrossRef](#)]
32. Yue, B.; Chen, X.; Cheng, Y.; Song, J.; Xie, H. Diagnosis of stator winding insulation of large generator based on partial discharge measurement. *IEEE Trans. Energy Convers.* **2006**, 21, 387–395. [[CrossRef](#)]
33. Stone, G.C.; Warren, V. Objective Methods to Interpret Partial-Discharge Data on Rotating-Machine Stator Windings. *IEEE Trans. Ind. Appl.* **2006**, 42, 195–200. [[CrossRef](#)]
34. Yazici, B. Statistical Pattern Analysis of Partial Discharge Measurements for Quality Assessment of Insulation Systems in High-Voltage Electrical Machinery. *IEEE Trans. Ind. Appl.* **2004**, 40, 1579–1594. [[CrossRef](#)]
35. MPD600 User Manual, Omicron Service Centers, www.omicronusa.net, a Publication of Omicron Electronics GmbH. 2013. Available online: http://www.ucaiug.org/Meetings/CIGRE_2014/USB%20Promo%20Content/OMICRON/Presentations/OMICRON-magazine-volume4-issue2-ENU.pdf (accessed on 1 September 2022).
36. Sumereder, C.; Weiers, T. Significance of Defects Inside In-Service Aged Winding Insulations. *IEEE Trans. Energy Convers.* **2008**, 23, 9–14. [[CrossRef](#)]