Diagnostic of generator partial discharge and acoustic imaging scheme for monitoring winding health condition and repair

Riyo Purnomo
Unit Maintenance Repair and Overhaul
PT PLN Nusantara Power
Surabaya, Indonesia
rio71@pln.co.id

Triyadi Nugraha Syaputra
Unit Maintenance Repair and Overhaul
PT PLN Nusantara Power
Surabaya, Indonesia
triyadi.nugraha@pln.co.id

Rian Suryadiningrat
Unit Pembangkitan Cirata
PT PLN Nusantara Power
Purwakarta, Indonesia
suryadiningrat88@pln.co.id

***Abstract*—Partial discharge in a generator is a phenomenon of electrical discharge that occurs in the generator winding insulation. This phenomenon, if it continues, will cause the generator winding insulation failure. Therefore, partial discharge needs to be monitored, both on-line and off-line. Currently, partial discharge monitoring equipment has been installed at the Cirata Hydroelectric Power Plant (PLTA Cirata), and routine off-line partial discharge testing has been carried out. With this data, it can be used as a reference for the necessary generator maintenance. If the partial discharge trending value increases 2 times in a year, maintenance is required. During maintenance, acoustic imager testing is carried out to map the location of the partial discharge. By combining the three types of testing, a good generator monitoring system will be obtained, and the right type of maintenance will be determined according to the partial discharge mapping results. The analysis begins by conducting on-line and off-line partial discharge trending. If the trending has exceeded the limit, mapping is then carried out with an acoustic imager during maintenance, and repairs are made according to the location and type of damage. Analysis of maintenance results is carried out by comparing the magnitude of the partial discharge value before and after maintenance. The maintenance results based on the test results of the three methods proved effective, this was indicated by a decrease in the off-line PD value from 751,3 nC to 3,792 nC and on-line PD from 23,92 nC to 1,059 nC.**

Keywords—partial discharge, pd on-line, pd off-line, acoustic imager, stator generator

I. INTRODUCTION

A generator is a conversion machine that converts mechanical energy into electrical energy. One of the important parts of a generator is the coil bars, where the generator voltage is generated and distributed. Fig. 1 shows the construction of the coil bars.

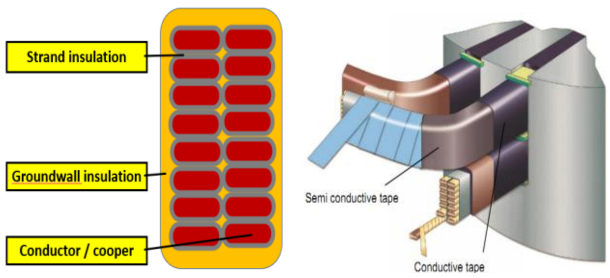

Fig. 1. Coil bar construction [1-2]

The explanation of the coil bars construction is as follows:

1) Conductor a formed from smaller strands of copper, so that it is easy to bend and shape according to what is needed.
2) Insulation consists of strand insulation which functions as insulation between strands, and ground wall insulation which functions as insulation between conductors and ground.
3) Anti-corona which functions to prevent surface discharge on the coil bar. The location of the anti-corona is in two areas, namely the slot area which is conductive, and the end winding area which is semiconductive.

With good coil bar construction and manufacturing process, it is expected that the emergence of PD can be minimized. However, over time, and the influence operation thermal, electrical, ambient, and mechanical stresses, the winding will experience degradation accompanied by increased PD activity [1]. Therefore, a PD monitoring system is needed, in order to see the increasing trend and type of PD, as a basis for carrying out proper maintenance. The problem to be discussed is the increase in the on-line PD value at the Cirata Hydroelectric Power Plant (PLTA Cirata), where the increase has exceeded 2 times in a year an inspection needs to be carried out [3]. With this increase in PD value, corrective action is needed to reduce the PD value so that it can prevent the occurrence of isolation failure. The use of on-line PD, off-line PD and corona imager to monitor motor condition and identify PD location as a basis for getting the right type of maintenance [4]. On-line PD is used to monitor PD while the generator is operating and verified with off-line PD [5]. Corona imager is used to determine the location of PD occurrence, as a follow-up to on-line and off-line PD analysis to determine the location of PD, while there are various PD detection methods, including ultrasound sensors [6], this study specifically employs acoustic imaging due to its ability to visually display PD sources using the FLUKE ii910 acoustic imager. This tool was selected because of its availability in the field and its demonstrated accuracy in detecting corona and surface discharge. Both acoustic imaging and corona imaging, both have the same accuracy related to corona and surface discharge [7]. But, Acoustic imager, it can also detect internal void PD that already has

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significant cavity. Image of the FLUKE ii910 also good in PD visualization.

In this study, using on-line PD to see the increase in PD value and verified with off-line PD for further analysis as a basis for maintenance planning. To identify the location of the coil bar experiencing PD using an acoustic imager, and continued with repairs according to the type of damage. To see the results of the repair, a comparison of test values before and after repair was carried out. For PD problems that arise in the Cirata Hydroelectric Power Plant (PLTA Cirata), many occur in the end winding area. Environmental factors, where high humidity levels can be a trigger for PD [8]. In addition, mechanical factors also have an effect, especially related to end winding vibration, which has an impact on generator winding insulation failure [9]. For winding repairs can be done by cleaning, replacing, and repairing winding insulation. End winding insulation repair is done by tapping insulation and re-coating anti-corona layer with Vonroll P8001 for end winding area and P8003 for slot and slot exit area [2,10]. With the right test and repair methods, it is expected that the generator PD value will decrease so that the unit can operate safely and reliably. For information, the hydroelectric generator on this study case, PLTA Cirata Unit 6 was made in 1996.

II. Methods

The research method starts from collecting PD value data during unit operation, analyzing it and conducting the necessary tests during off-line to obtain the right repair method according to the type and location of PD. The flow of the research process is shown in Fig. 2. The testing and data collection process is carried out during operation, shut down (without dismantling the generator) and overhaul.

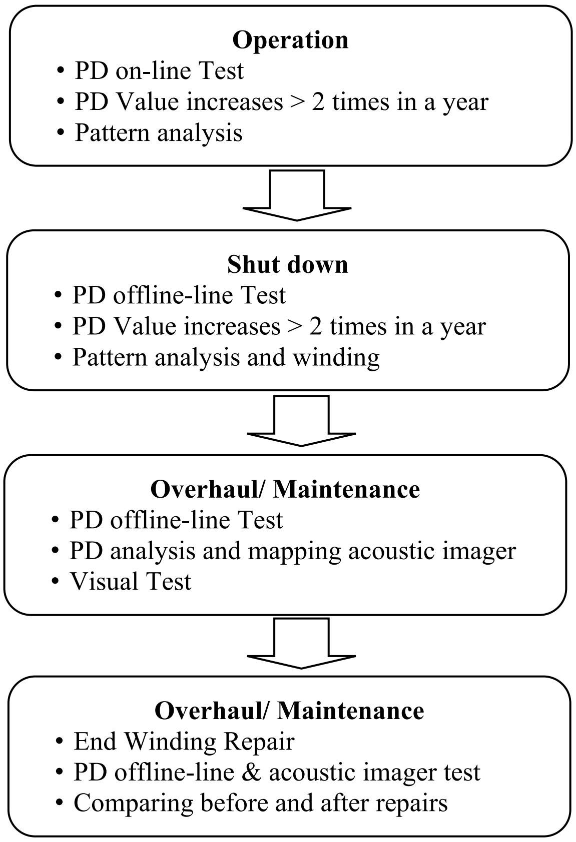
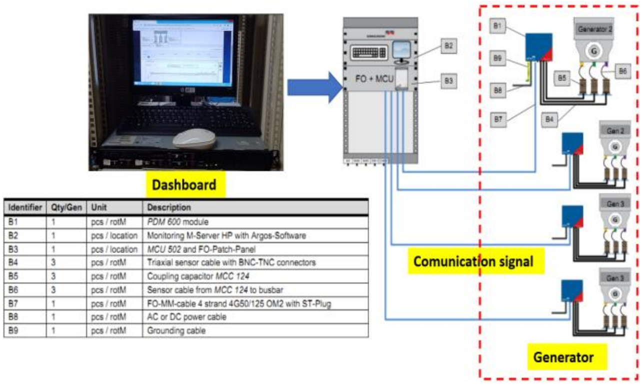


Fig. 2. Research process flow

The explanation of each process is as follows:

Operating conditions at Cirata Hydroelectric Power Plant (PLTA Cirata), an on-line PD monitoring device has been installed using the omicron MPD600. The configuration of on-line PD monitoring is shown in Fig. 3.



Identifier	Qty/Gen	Unit	Description
B1	1	pcs / rotM	*PDM 600* module
B2	1	pcs / location	Monitoring M-Server HP with Argos-Software
B3	1	pcs / location	*MCU 502* and FO-Patch-Panel
B4	3	pcs / rotM	Triaxial sensor cable with BNC-TNC connectors
B5	3	pcs / rotM	Coupling capacitor *MCC 124*
B6	3	pcs / rotM	Sensor cable from *MCC 124* to busbar
B7	1	pcs / rotM	FO-MM-cable 4 strand 4G50/125 OM2 with ST-Plug
B8	1	pcs / rotM	AC or DC power cable
B9	1	pcs / rotM	Grounding cable

Fig. 3. PD on-line monitoring configuration [11].

MPD600 uses bus coupler detection with digital filter, where this method is effectively used in hydrogenator which has little internal noise [12-13]. With this on-line PD, PD (Qm) and pattern values will be obtained continuously, so that trending can be done. Trending and evaluation are done by [3]:

1) PD trends on the same machine and the same PD tool over time

2) Comparing PD trends between phases on the same machine and PD tool

3) Comparing PD trends on machines with the same PD design and tools.

With PD (Qm) value trend data and patterns, information can be obtained regarding the condition of the insulation during operation as well as a rough picture of the source and location of PD. Trending should be done under the same operating conditions (Load, temperature, ambient, etc.). An increase in PD value 2 times a year indicates that damage is occurring, and off-line and visual PD testing is required.

Shutdown condition is done by off-line PD measurement as a follow-up test related to the results of on-line PD. This test is done when the unit is off and the generator is not dismantled. The configuration of the off-line PD test is shown in Fig. 4 [14-15]. For the maximum generator voltage injection line to neutral (Umaks) is UN / √3, where UN is the nominal generator voltage. This process is done in stages per 0.2 Umaks. Trending PD values and their evaluations off-line are done as explained in ref. [14] as follows:

1) PD value trend on the same stator winding and the same PD device over time

2) Comparing the trend of PD values between phases on one stator winding and the same PD device

3) Comparing the trend of PD values in Stator Windings with the same PD design and tools.

In addition to trending and comparison, pattern interpretation is also done to see the PD type and rough estimate of PD sources. Many studies are related to the identification and analysis of Phase Resolved Partial Discharge (PRPD) patterns [16-19]. This is related to the identification of patterns that occur in generators, where several PD sources can occur simultaneously, so a more complex analysis is needed. If the on-line and off-line PD patterns show the same PD type and point to end winding discharge or surface discharge, then acoustic imager testing can be performed to obtain precise location details.

Overhaul / maintenance conditions are carried out after PD test data is obtained and leads to end winding discharge/ surface discharge, then a generator pull-out is carried out, in order to obtain maximum visualization. Additional testing during off-line is an acoustic imager, which is carried out simultaneously with off-line PD testing. The test configuration is shown in Fig. 4. The Acoustic imager equipment used is the Fluke ii910. This tool is equipped with a digital filter that can be adjusted, so that it can eliminate unwanted noise in the ultrasonic PD signal. The Fluke ii910 can also provide a visible-light image of the object being tested. The data obtained from this acoustic imager is in the form of ultrasonic signal magnitude in decibels (dB), PD type and visible light which shows where the PD occurs [20].

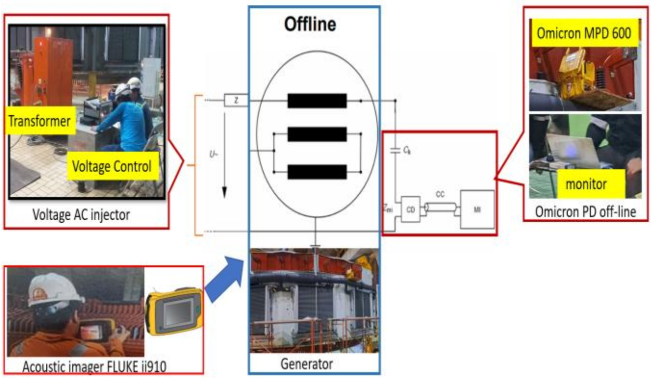


Fig. 4. Schematic of PD testing offline and acoustic imager

With the testing process according to Fig. 4, it is expected that the identification process of problematic coil bars can be faster and more accurate, considering that the hydro generator stator winding has a large area. To see the effectiveness of this method on maintenance results, it is done by comparing the values of on-line PD, off-line PD, and acoustic imager, before and after maintenance.

III. Results and Discussion

A. PD online

Fig. 5. shows the trend graph of PD values from June to December 2023 taken from the ARGOS Monitoring System [21]. From the graph, it can be seen that the PD value has increased 2-fold over 6 months. The highest increase trend occurred in December 2023 in the S phase from 13 nC to 26 nC.

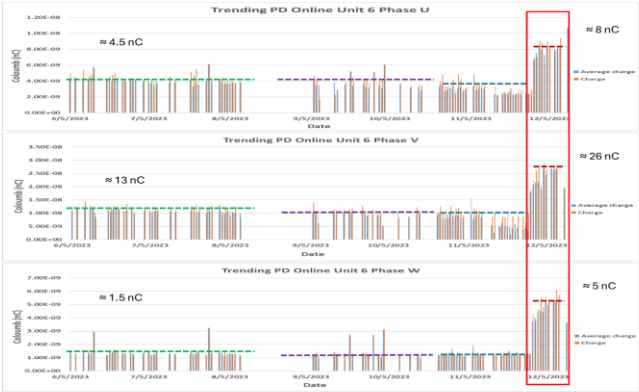
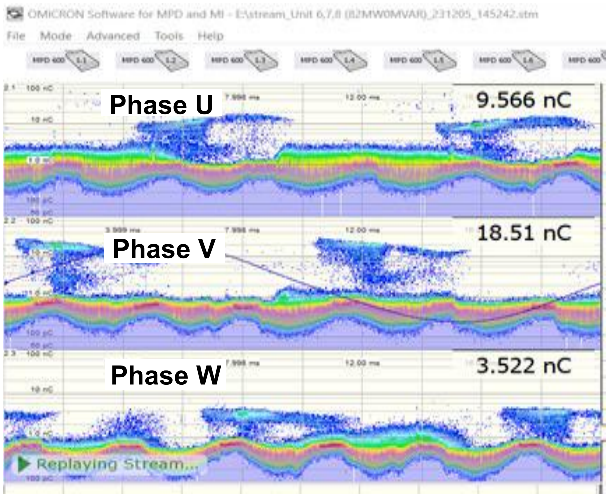
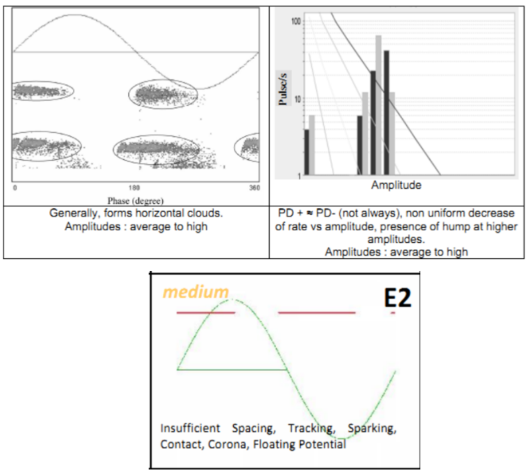


Fig. 5. Trending PD online June – December 2023

To find out the cause of the increase in PD value, it can be seen from the PRPD pattern. Fig. 6 shows the PD pattern taken from the MPD600 streaming. Based on the PRPD pattern, the increase in PD value occurs in the end winding area of the generator stator winding [22-23]. The cause of this increase in PD can be caused by humidity, contaminants and end winding vibration [8-9]. If it lasts for a long time, it can cause deterioration of the winding insulation. Therefore, it is necessary to conduct an off-line PD test and visual inspection of the generator winding to verify the results of the on-line PD.



(a)



(b)

Fig. 6. (a)Streaming PRPD pattern MPD600 (b)Typical PRPD pattern [22-23]

B. *PD offline*

As a follow-up to the increase in the PD on-line value, in December 2023, PD off-line was carried out when the unit was shut down with the results as per Table I:

TABLE I. PD OFF-LINE DECEMBER 2023

No	Test. Volt (LN)	Frequency	Qiec max (C)
1	Phase U = 9.5 kV	250 kHz ± 150 kHz	7.642 nC @ 9.4 kV
2	Phase V = 9.5 kV	250 kHz ± 150 kHz	751.3 nC @ 9.4 kV
3	Phase W = 9.5 kV	250 kHz ± 150 kHz	12.56 nC @ 9.4 kV

From Table I it is concluded that the V phase experienced a very significant increase compared to other phases. This is in accordance with the results of on-line PD, where the PD value of the V phase is higher than the other phases. However, for the U and W phases, the off-line PD value of the W phase is higher than the U phase, this is inversely proportional to the on-line PD results. This can occur because the test conditions during operation and shutdown are different, especially related to the voltage level received by the coil bar [22]. Fig. 7 shows the PRPD pattern of the off-line PD of the U, V and W phases.

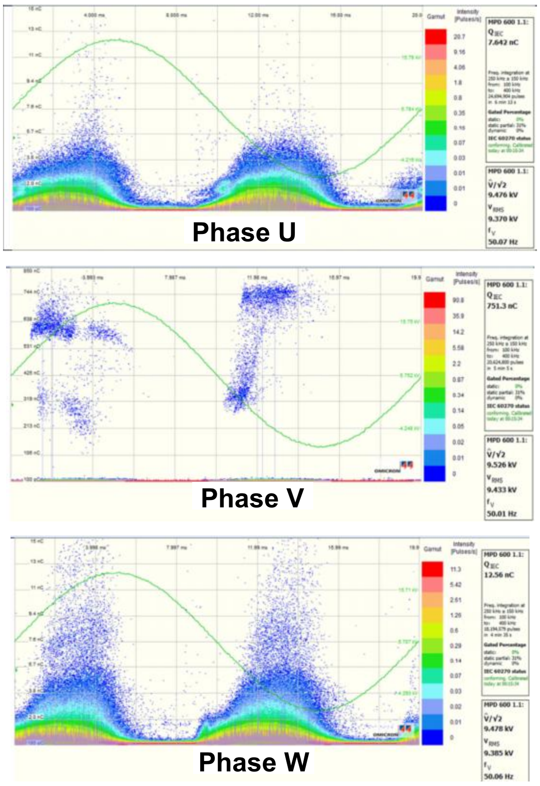


Fig. 7. PRPD Pattern

From the PD pattern in Fig. 7, phase V has the highest PD value and the typical pattern indicates end winding discharge. This result is in accordance with the indication produced by the on-line PD pattern. With the on-line and off-line PD results indicating an increase in PD value and the same pattern, it is necessary to plan maintenance / overhaul actions. In June 2024, an overhaul was carried out and an off-line PD test was carried out with the condition that it had been cleaned and heated. This test was carried out before the end winding repair was carried out. The PD values obtained are shown in Table II.

TABLE II. PD OFF-LINE DURING OVERHAUL AND BEFORE END WINDING REPAIR

No	Test. Volt (L-N)	Frequency	Q_{iec} max (C)
1	Phase U = 9.5 kV	250 kHz ± 150 kHz	3.127 nC, discharge slot
2	Phase V = 9.5 kV	250 kHz ± 150 kHz	652.2 nC, end winding discharge
3	Phase W = 9.5 kV	250 kHz ± 150 kHz	2,761 nC, end winding discharge

From Table II, it can be seen that there is a significant decrease in the U and W phases, while the V phase is still high so that corrective action is needed. In order for the repair to be right on target, an acoustic imager test was carried out to map the PD location points that occurred.

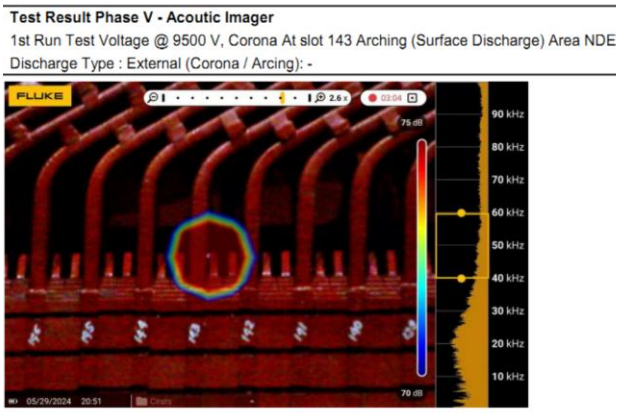
C. *Acoustic imager*

Acoustic imager testing was conducted during the June 2024 overhaul, along with off-line PD testing. The mapping results are shown in Table III. According to the mapping results, the high intensity point is in phase V (75 dB), slot number 143.

TABLE III. RESULTS OF PD MAPPING WITH ACOUSTIC IMAGER

Phase	Number of dots	Slot	Information
U	13	172, 244, 246, 237, 30-31, 84-85, 101, 102, 109, 119, 127, 138, 201,	Intensity 28 – 47 dB
V	6	161, 152-153, 126, 90, 143, 233-234,	5 points intensity 28-32 dB, 1 point 75 dB
W	7	86-87, 94, 122, 140-141, 239, 23-24, 166	5 points of intensity 28-40 dB, 2 points 46 and 49 dB

The PD type in slot 143 based on the corona imager results is external (corona, arching), as seen in Fig. 7.a. After knowing the discharge point, verification is carried out with visual inspection. In Fig. 7.b, the insulation condition is starting to deteriorate, so repairs need to be made.



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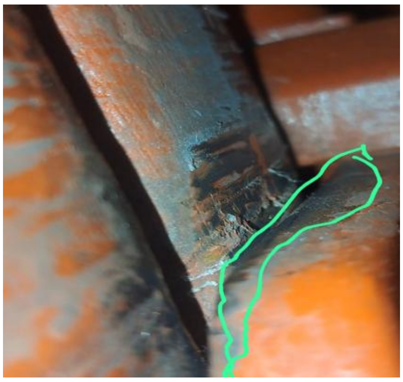


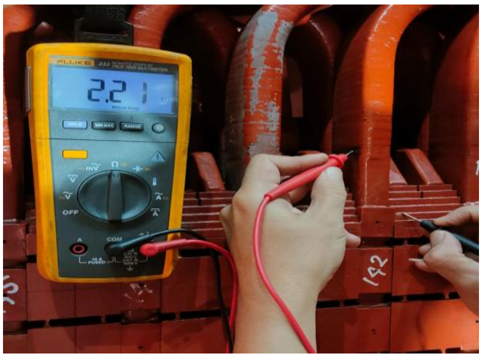
(b)

Fig. 7. Slot 143 inspection (a).Visible light from the acoustic imager, (b).Visual inspection

D. Repair

Repair methods caused by moisture and contaminants are carried out by cleaning and heating [8]. The handling of insulation damage was as follows:

1) **Cleaning and Resealing of Insulation**: The first step was to clean the insulation and perform resealing (rearranging) of the insulation. This was important to remove moisture and contaminants that could have damaged the insulation, as well as to ensure that the insulation continued to function well after the repairs.
2) **Corona Resistant Coating (Vonroll P8003)**: After cleaning, a corona-resistant coating, Vonroll P8003, was applied to the insulation. This coating was applied with a thickness of 0.2–0.5 mm [2]. The purpose of this process was to protect the insulation from corona phenomena, which could have further damaged the insulation. Next, coupling resistance measurements were performed, which should not have exceeded 6 KΩ or complied with the manufacturer's standards (Fig. 8).



(a)

(b)

Fig. 8. Maintenance activities, (a) Coupling resistance test, (b) Anti-corona paint coating

3) **Vonroll P8001 Coating and Conductive Paint**: After the corona-resistant coating, Vonroll P8001 was applied along with a conductive paint layer (20mm). This coating had a specific length, which was calculated using the formula provided in Equation (1) [10]:

$$L = V_{test\ max} / 2 \quad (1)$$

Where L is layer length measured from the exit slot in cm, while $V_{test\ max}$ is maximum test voltage ($2U_N+1$) in kV

4) **Offline PD Testing, Acoustic imager, and Other Electrical Tests**: These tests were carried out to verify whether any disturbances or damages remained in the insulation after repairs. Perform off-line PD and acoustic imager tests, and other electrical tests.
5) **Corona-Resistant Red Varnish Coating**: The final step was to apply a corona-resistant red varnish to the insulation. This varnish provided an additional protective layer against damage caused by corona phenomena.

Several literatures mention that the composition of the material and the area of the anti-corona coating have an effect on the effectiveness of reducing partial discharge [24-25].

E. Testing after repair

The test parameters used as the basis for the end winding repair results are the off-line PD value, on-line PD and acoustic imager. Table IV and Table V show a comparison of PD values before and after maintenance. From Table IV and Table V, it is concluded that there has been a decrease in PD values after maintenance, both from the side of off-line PD, on-line PD, and acoustic imager. Until October 2024, the PD value has not increased relatively.

TABLE IV. COMPARISON OF OFF-LINE PD AND ON-LINE PD RESULTS

Phase	PD Off-line		PD On-line	
	Before	After	Before	After
U	7.642 nC	3.56 nC	11.76 nC	1.582 nC
V	751.3 nC	3.792 nC	23.92 nC	1.059 nC
W	12.56 nC	3.784 nC	4.03 nC	0.902 nC

TABLE V. COMPARISON OF ACOUSTIC IMAGER RESULTS

Phase	Before	After	dB before	dB after
U	13	8	Intensity 28 – 47 dB	Intensity 30 – 46 dB
V	6	7	5 points intensity 28-32 dB, 1 point 75 dB	Intensity 29 - 45 dB
W	7	11	5 points of intensity 28-40 dB, 2 points 46 and 49 dB	Intensity 27 - 36 dB

IV. CONCLUSION

The performance of the generator stator is greatly influenced by several factors including the manufacturing process, operation and maintenance, then over time degradation and damage can occur on the generator stator side. To mitigate this, it is necessary to monitor and implement appropriate maintenance actions. Monitoring of the online PD system, offline PD and acoustic imager has proven effective in identifying PD trends and types, so that the right maintenance method is obtained. The application of these three PD test methods, with a case study on the stator generator of Cirata Unit 6 hydroelectric power plant (PLTA Cirata Unit 6), has proven effective in identifying damage so that the maintenance process is more precise and effective, and has succeeded in reducing the PD value. The off-line PD value of phase V decreased from 751.3 nC to 3,792 nC, where this value is close to the same as the other phases. The on-line PD value of phase V decreased from 23.92 nC to 1,059 nC.

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