Repair of High Partial Discharge Value due to End-Winding Stator Generator Vibration: a case study

Edo Radita, Sendy Putra, Sujadi Sujadi and Putu Utama

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Edo Angga Radita
(MSU) Maintenance Service Unit
PT. Indonesia Power
Jakarta, Indonesia
edo.angga@indonesiapower.co.id

Sendy Nugrahatama Putra
(MSU) Maintenance Service Unit
PT. Indonesia Power
Jakarta, Indonesia
sendy.nugrahatama@indonesiapower.co.id

Sujadi
(MSU) Maintenance Service Unit
PT. Indonesia Power
Jakarta, Indonesia
sujadi@indonesiapower.co.id

Putu Tedy Pradyana Utama
(MSU) Maintenance Service Unit
PT. Indonesia Power
Jakarta, Indonesia
putu.utama@indonesiapower.co.id

***Abstract*— Damaging factor which often occurs in stator winding is located in its end winding. Stator end winding is vulnerable toward vibration on double frequency of electromagnetic field grid system. Looseness symptom on end winding generator in unit 2.3 Priok Power Plant is marked by compound greasing finding and bump test result showed that mostly of end winding natural frequency stayed on the range of 95-115 Hz. Its looseness problem can bring serious impact toward winding insulation because it can develop an abrasion. The result of insulation abrasion was shown by its x-ray diffraction test. The other finding was corona discharge in overhang end winding area. There were efforts to resolve the looseness of end winding and corona discharge to increase generator age, such as repairing existing ties and adding new end winding ties to increase its rigidity. Bump test result after retying showed that natural end winding frequency shifted from its natural frequency. To repair partial discharge in end winding area, repairing anti corona coating in different voltage connection phase was done. Offline partial discharge test result after repair showed that this method was effective to reduce partial discharge magnitude value to safety level. This method was also effective and adding asset owner's confidence to operate unit 2.3 generator safely. It could give reference to other power plants facing the same problem.**

Keywords: end winding, vibration, natural frequency, partial discharge

I. PREFACE

This paper will discuss about a case study of corona discharge and end winding ties looseness problem of gas turbine generator unit 2.3 Priok Power Plant when 2018 major inspection was taken place. The problems which was found were:

- Spacer block crack between turbine side and exciter side of end cap which is shown in figure 1.1.

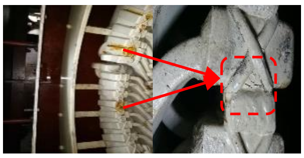

Figure 1.1 Insulation end cap crack

- Greasing compound in end winding stator generator which is shown in figure 1.2.

Figure 1.2 Greasing compound in end winding ties

- Corona discharge tracing in generator end winding area which is shown in figure 1.3.

Figure 1.3 Corona discharge tracing in overhang end winding

Bump test and offline partial discharge test was done to validate those visual findings.[1] The result was beyond the standard limit. It gave warning sign for owner to repair in order to prevent potential catastrophic damage of generator if it is going to operate again.

There were some research that has discuss about end winding generator vibration and corona protection stress grading separately. But, there is no research that discuss about the correlation of end winding vibration causing corona protection insulation damage in end winding area. This particular matter can cause offline partial discharge test result on unsafe level to operate. This research focus on repairing and solving that problem specifically.

II. LITERATURE REVIEW

A. *End Winding Area Vibration*

This decade, the usual problems of stator generator is not strong enough winding support in end winding area. Current flows between two generator pole will generate frequency around 100 Hz or twice of frequency power which induced magnetic force toward its winding.[2,3] Vibration force will be equal to the square value of flowing current. The amount of force generated can be seen in this equation:

$$F = \frac{8\pi x 10^{-7}}{w} im^2[1 - cos2\omega t]$$

F : coil force

I : current

w : coil slot wide.[2]

At the beginning, starting current will generate 36 times higher magnetic force. If the support bracket end winding ties (figure 2.1) was not good to hold, the force will make end winding ties loose and vibrate. The ties and support bracket looseness will generate insulation ties friction in end winding which is usually identified by the finding of white powder or grease compound.

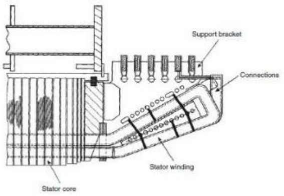

Figure 2.1 End winding support system

B. *Impact of End Winding Ties Looseness*

End winding looseness will reduce end winding structure power gradually. The looseness will increase when end winding natural frequency stays between 95 to 115 Hz. Operating generators at this condition is dangerous. Generator which often undergoing start stop operation and having external problem will have bigger risk to fail.
Generator failure because of end winding looseness such as:

- Insulation damage generating phase to phase short circuit.
- Stranded conductor (coil) crack.
- Brazing or winding connection damage which can generate heat developing short circuit.[1]

C. *Outer Corona Protection Damage in Stress Grading Area*

When semi-conductive coating or silicon carbide undergoes degradation, there will be partial discharge on the surface of stator winding insulation. In air cooled generator, partial discharge will produce ozone (O_3). Ozone is a reactive chemical gas which can be blend with nitrogen and humidity to become nitric acid (HNO_3). Nitric acid will destroy anti-corona coating which consist of semi-conductive and conductive coating, expanding the destruction of anti-corona corona.[4] Figure 2.2 shows the coating damage.

Figure 2.2 Surface PD destroys anti-corona coating

Partial discharge which continue developed in insulation coating surface will destroy main insulation epoxy or usually called ground wall insulation. Small hole might be developed because of ground wall damage which can generate a short circuit.

D. *Role of Corona Protection In Stator Winding Insulation*

Corona protection coating is an insulation component which has function to prevent partial discharge on stress grading (overhang). Partial discharge is developed when insulation breakdown voltage is higher that 3kV/mm.[5] This breakdown voltage is caused by huge electric stress in overhang area. It is caused by thin conductive coating which generate pointed conductive coating tip. The pointed tip will develop non-uniform electric field which its value is opposite with conductive coating radius. The smaller radius or the thinner conductive coating, the bigger electric stress. Electric stress in overhang area can be seen in this equation:

$$E = \frac{2V}{r \ln(\frac{4d}{r})}$$

E : electric stress of electric field power (kV/mm)

V : overhang line-ground voltage (kV)

d : main insulation thickness (mm)

r : conductive coating radius (mm).[3]

To reduce electric stress in the pointed conductive coating, it needs to overlap with semi-conductive coating. Semi-conductive coating consist of silicon carbide (SiC) which has non linier characteristic. If electric stress occurs or voltage is high in overhang, SiC resistance will become brake in order to generate uniform electric field. By the development of uniform electric field, the electric stress will be very low in end core.

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III. REPAIR OF LOOSENESS AND CORONA DISCHARGE IN END WINDING AREA

Based on some of the abnormal condition findings, we suggested that the condition were caused by looseness of end winding structure which cause insulation friction and corona discharge tracing. To prove this hypothesis, some tests to find the main problem was needed. Those tests were:

1. X-ray diffraction (XRD) analyze test was used to analysis grease compound.
2. End Winding Generator Bump Test was used to find end winding generator natural frequency ties structure. It was important to make sure that there is no resonance frequency in the end winding ties structure.
3. Electrical tests were used to analyze corona discharge tracing. Those tests were isolation resistance, polarization index (PI), tangent delta test, and offline partial discharge.

A. *Test Before Repair*

- X-Ray Diffraction Test

Based on foreign material test of grease compound in generator GT 2.3 PLTGU Priok, three main compounds were found. Those were:

a) Muscovite, KAl2(AlSi3O10)(OH)2, the amount was 16.6%.

Muscovite is phyllosillicate mineral (silica oxide structure) from aluminum and potassium. On the industry, muscovite is widely used to make electrical appliances and thermal resistance materials. The presence of muscovite in grease compound generator might come from insulation winding.[6]

b) Silica-Carbida (SiC), C17 Si17, the amount was 47,1%.

Significant amount of Si-C was found in generator grease compound, which is 41,7%. It indicated that Si-C base material machines was damaged. One of machines that might use Si-C material is generator winding anti corona.

c) Adamantane, C10H16, the amount was 11,7%.

Adamantane is organic chemical compound from carbon aromatic cluster. It is one of the component which form petroleum. Based on XRD test, significant amount of C10H16 was found, which is 11,7%. It might tell that there was bearing oil element entering stator generator.

- Bump Test

Bump test was done on the turbine side and exciter side of end winding (figure 3.1). The test was done on axial, radial, and tangential direction of every single end-turn winding ties with total of 60 slots.

Figure 3.1 Bump Test End Winding Generator

The test was done to identified natural frequency (resonance) around 95 Hz to 115 Hz. Bump test result before repair is shown in table 3.1.

Table 3.1 Bump Test Result Before Repair

Parameter	Direction	Exciter side	Turbine side
Measurement point total with Fn = 95 Hz-115 Hz	Axial	30	37
	Radial	5	43
	Tangensial	1	36
Looseness percentage		48%	85%

From the test result, we can see that there are a lot of end winding ties structure looseness. This condition will affect insulation lifetime. Loose ties will make winding in end-winding position rubbing against each other and scraping away insulation coating.

- Electrical Test Before Repair

a) Insulation Resistance Test and Polarization Index Result

Insulation resistance test and polarization index result before repair can be seen in table 3.2. Based on IEEE 43-2000 standard, insulation resistance value of AC winding manufactured after 1970 should be above 100 MΩ and PI value should be above 2.[7]

Table 3.2 IR Test and PI Result

Minute	Phase to Ground			Phase to Phase		
	U - Ground	V - Ground	W - Ground	U - V	V- W	U -W
1	1.33 GΩ	1.2 GΩ	1.36 GΩ	3.03 GΩ	2.21 GΩ	2.71 GΩ
10	5.40 GΩ	4.49 GΩ	6.64 GΩ	10.38 GΩ	8.61 GΩ	11.20 GΩ
PI	4.03	3.72	5.08	3.42	3.89	4.10

b) Tangent Delta Test Result

The purpose of dissipation factor or tangent delta measurement is to find insulation quality of electrical appliances. Tangent delta test result of new electrical appliance is needed to become reference for the next periodic tangent delta test in order to give clear vision of insulation resistance degradation graph. Other than periodically used, tangent delta test result can be analyze using IEC60034-27-3 standard.[8] Stator winding insulation condition can be explained from the data analysis. Tangent delta test result before repair can be seen in table 3.3.

Table 3.3 Tangent Delta Test Result

Analysis Method	Before Repair			Standard
	U Phase (%)	V Phase (%)	W Phase (%)	
Tanδ 0,2Un	0.6	0.64	0.63	≤ 2 %
Δ Tan δ increments at each voltage 0.2 Un level	0.45	0.47	0.45	≤ 0.5 %
Tanδ tip-up between 0.6UN and 0.2UN	0.36	0.37	0.37	≤ 0.5 %

c) Partial Discharge Offline Test Result

When we found visual result of corona discharge tracing in end winding area, we need to do offline partial discharge test to make sure of that condition. The result of partial discharge test can be seen on table 3.4, 3.5, and 3.6. Based on best practice from Mitsubishi Electric Companies in their "Site Test Procedure for Generator and Auxiliaries, MELCO,"ART-T-7219" standard, partial discharge value is categorized into warning category with magnitude discharge test value above 15 nC. It is said to be critical value if the value is above 22 nC.

Table 3.4 Offline PD U Phase Test Result before Repair

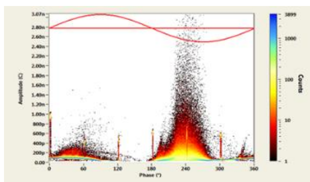
U Phase

Qm = 0.88 nC

Table 3.5 Offline PD V Phase Test Result before Repair

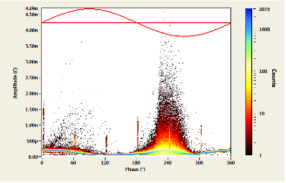
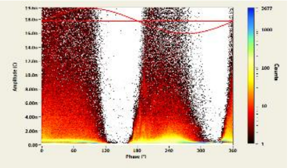
V Phase

Qm = 1.18 nC

Table 3.6 Offline PD W Phase Test Result before Repair

W Phase

Qm = 135.68 nC

The result of the test and best practice analysis based on literature pattern was discharge in end winding.[9] There was exceeded best practice standard partial discharge on T phase which is counted on 135,68 nC magnitude.

B. *Problem Repair*

After doing several test, there were visual result and test data result that make us clear that the problem of gas turbine generator unit 2.3 PLTGU Priok was because of excessive vibration. It can scrape away insulation coating especially ant-corona protection coating. The damage can cause corona tracing activity in end winding stator generator. Based on those two factors, the repair was divided into two different repairs, which are: end winding ties looseness repair and end winding corona discharge repair.

- End Winding Ties Repair

To solve end winding generator looseness of Unit 2.3 PLTGU Priok, natural frequency in end winding needs to be move farther from 95 Hz - 115 Hz. The principle is how to add mass so that the natural frequency can be shifted. Adding coil mass is impossible to be done because coil never change. The possible way is to add the coil stiffness. It can be done by repairing loose old ties and adding ties on end winding area close to end cap. Adding ties was an easy step to do because we had the material and the team.

Before repairing old ties and adding whole ties, the test was done to ensure the properness of this method. One of the loose end winding was taken as a sample. Then, it was smeared in epoxy resin. The ties material was insulation material which have thermal resistance and mechanical power.

Figure 3.2 Old Ties Repair

Figure 3.3 New Ties Addition

After binding all of the ties in turbine side and exciter side of end winding area, we heated up ties to harden epoxy resin. Then, bump test was done again to calculate affectivity of the repair. The result is seen on table 3.7.

Table 3.7 Comparison between Before and After Repair

Paramater	Arah	Exciter Side		Turbine Side	
		Before	After	Before	After
Measurement point total with Fn = 95 Hz-115 Hz	Axial	30	24	37	6
	Radial	5	1	43	20
	Tangensial	1	8	36	7
Looseness Percentage		48%	23%	85%	37%

Frequency Response Function curve of end winding test result on turbine side and exciter side can be seen in figure 3.4 and 3.5. On the figure, we can see there are two natural frequencies in turbine side, which are 92,25 Hz and 119,75 Hz. There are also two in exciter side, which are 69 Hz and 102,75 Hz. Both of natural frequencies in turbine side was beyond 95 – 115 Hz range, and only one natural frequency in exciter side was on the range, with 102,5 Hz.[10]

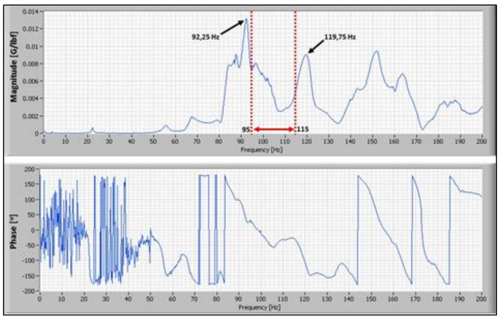


Figure 3.4 FRF Test Curve of End Winding Turbine Side

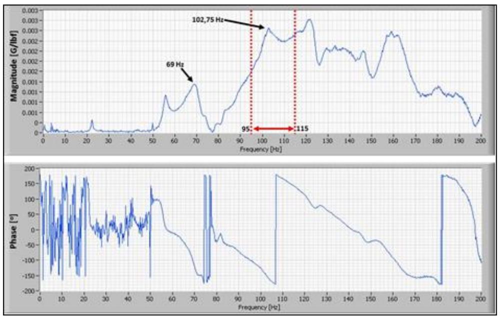
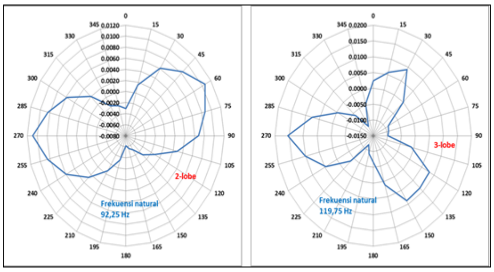


Figure 3.5 FRF Test Curve of End Winding Exciter Side

Because generator 2.3 has two poles, so its electromagnetic field will generate excitation modes in ellipse shape (two lopes) with excitation frequency of 100 Hz (twice RPM). In order to avoid resonance phenomenon, the ellipse shape end winding vibration modes needs to be beyond 95 -

115 Hz range. Vibration modes on each natural frequency can be seen in figure 3.6 and 3.7.We can see that ellipse shape end winding vibration modes is under or beyond 95 - 115 Hz range. It means that there is only small chance of end winding resonance phenomenon which can add looseness is formed. After tightening the end winding ties, we can amplify the conclusion that generator 2.3 is safe to operate.



. Figure 3.6 End Winding Turbine Side Vibration Modes

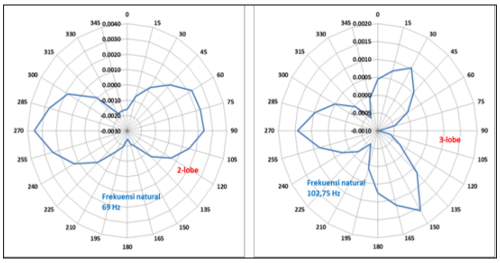


Figure 3.7 End Winding Exciter Side Vibration Modes

- High Offline PD Test Result

We found that there were corona discharge tracing and higher PD offline test result than standard. We planned to repair corona protection coating in end winding area. First step to do was wiping out varnish in face to face connection phase which is seen in figure 3.8. Connection phase is an area in end winding which has high difference potential voltage. The purpose of wiping out varnish were to see gradient design of corona protection coating from manufacture and to make new corona protection coating sticking perfectly in corona protection coating for long time.

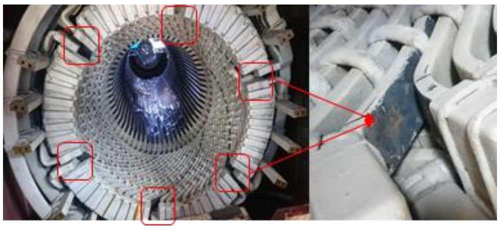


Figure 3.8 Connection phase without varnish

There were two anti-corona coating, the first was conductive varnish which is located in the tip of slot core end stator showing in figure 3.9. The second was semi conductive coating which is located after conductive coating until end cap showing in figure 3.10. We need to pay attention to critical point which is around 2 cm between conductive coating and semi conductive coating especially the cleanliness of the surface in order to develop perfect contact.

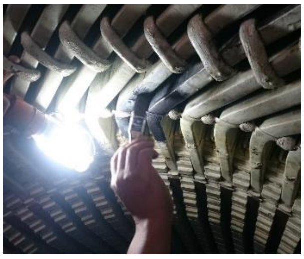


Figure 3.9 Application of varnish in corona protection conductive coating

Figure 3.10 Application of varnish in corona protection semi conductive coating

After repairing anti-corona coating, the next progress was drying. The time of drying progress is based on material provision we used. To determine repair quality, we did offline partial discharge test which is shown in table 3.8, 3.9, and 3.10.

Table 3.8 Comparison of U Phase Offline PD Test

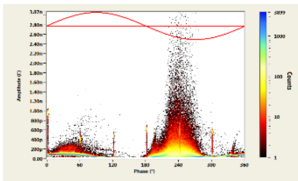
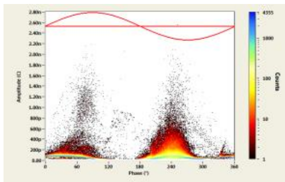
Before Repair	After Repair
	
Qm = 0.88 nC	Qm = 0.38 nC

Table 3.9 Comparison of V Phase Offline PD Test

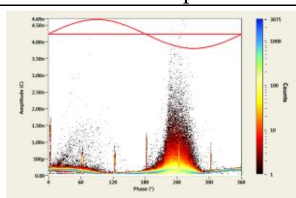
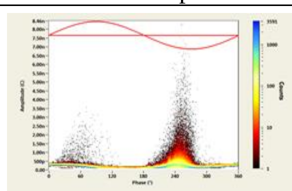
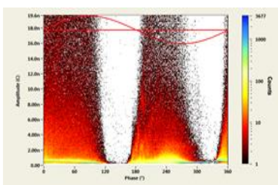
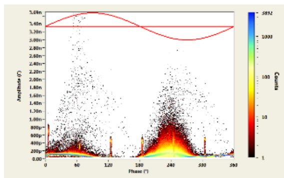
Before Repair	After Repair
	
Qm = 1.18 nC	Qm = 0.90 nC

Table 3.10 Comparison of W Phase Offline PD Test

Before Repair	After Repair
	
Qm = 135.68 nC	Qm = 0.61 nC

Based on test result, we can see there is significant difference between anti-corona coating repairs in end winding. Phase T PD magnitude before repair was on Qm = 135,68 nC and after repair was decreased on Qm = 0.61 nC. Based on best practice, the magnitude result was said to be safe to operate again.

IV. CONCLUSION

1. End winding ties repair method which were consisted of repairing existing ties and adding new ties were very effective to solve looseness problem in end winding area in order to minimalize insulation damage factors.
2. By reducing loose end winding ties amount and by the result of analysis asset, end winding vibration modes below natural frequency was safer to operate.
3. Anti-corona coating repair application in end winding stress grading area was proven to be very effective to solve partial discharge problem in end winding area.
4. Anti-corona repair application was an easy and quick method to lengthen generator lifetime usage.
5. By the affectivity and the applicability of end winding ties repair and anti-corona coating repair in end winding, the method can be applied in other generators dealing with the similar problem with generator in unit 2.3 Priok Power Plant.

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