Heat Transfer Optimization of end Winding Rotor Generator by the Use of Modified Axial Spacer: A Case Study

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Abstract. This paper presents a case study of a rotor fault occurring in the rotor generator of a steam power plant located in Lontar, Banten Province, Indonesia. The steam power plant has 3 x 315 MV capacity and uses hydrogen in the cooling system. The issue arising during the operation was caused by heat transfer exceeding the normal level. The grounding of the rotor occurred through rising vibration and temperature, tripping the generator unit. During repairs, the axial spacer was replaced with a new model, where it is longer than the original, adding a bar spacer at a previously unavailable position and creating a cooling track profile. This is a case study on the replacement of the axial spacer model aimed at preventing the expansion of the winding, so as not to touch with each other, through the installation of a longer axial spacer and the addition of the spacer bar, and lastly adding the track profile to the cooling hydrogen gas flow thereby maximizing the cooling process from the end winding rotor generator. Heat transfer is an analysed parameter related to the model change of the axial spacer. The addition of a track cooling gas flow has been able to maximize the heat transfer process, which is simulated in this paper. The performance of the rotor generator increased through several parameters after the replacement of the axial spacer model.

1. Introduction

An incident of grounding in a rotor generator happened at Lontar steam power plant, which was triggered due to short dashes that occur due to inter-turn migration in end winding coil under generator retaining ring that touches another coil (inter turn) or body of rotor (grounding) [1], this migration being due to the inability of the old spacer to hold the coil on the development process of the coil/copper material being overflowing with DC current when the rotor enabled as a magnet induction. Another effect that occurred due to the migration of the coil is that the coil suffered deformation in the form of extension especially at the slotted coil of most ends 4, 5, 6, 7, and 8 (in the rotor generator there are 8 coil slots on each pole). The inability of the spacer in holding this coil could be interpreted from the inadequate length of the spacer size and the lack of spacers on certain positions. Further inspection carried out by dismantling the generator retaining ring found some damaged end winding coil deformation, burnt and damaged insulation retaining ring, burnt axial spacer and arcing in the
inside of diameter of the generator retaining ring [1]. An example of coil migration due to tripping issue is presented in Figure 1(a).

After dismantling the generator retaining ring (GRR) from steam power plant, the spacer of the end winding rotor generator was found to be unable to protect the winding proper where there is a gap in the coil allowing the coil to migrate or deform. The condition of the spacers that did not separate the coils proper is presented in Figure 1(b).

![Image of GRR](image)

**Fig. 1.** GRR of the steam power plant: (a) Coil migration; (b) Spacer inadequate to protect coil.

Some of the effects that arise due to the weakness of this spacer include:

a. The coils have the potential to cause magnetic flux imbalance in the rotor (asymmetrical flux) resulting in vibration [2].

b. The spacer that separates the rotor coil in one slot from the other, because of the inadequate size of the spacer, causes the coil to migrate until it expanded, causing friction that damages the inter-turn insulation even if the coil can also touch the coil on another slot or the rotor body [3] [4] [5] [6].

c. The coils have potential to occur short inter-turn, resulting in heating at a certain position due to a decrease in the resistance value and a large increase in the current value [7].

d. Cooling access to coil is not optimal, so it has the potential to cause a temperature increase (rotor thermal sensitivity) causing rotor bowing and vibration.
2. Theoretical Background

2.1. The generator rotor’s end winding spacer

The generator rotor’s end winding spacer have a function as a separator between the coil and also as an insulator, but the spacer of the old design did not have optimal capability as a separator when the copper coil expanded due to current flow. The anatomy of Lontar's steam power plant rotor generator spacer is presented in Figure 2. The figure shows the configuration of the spacer end winding rotor generator, divided into four types. This configuration group is attached to four positions:

a. End winding pole A turbine side
b. End winding pole A exciter side
c. End winding pole B turbine side
d. End winding pole B exciter side

The original shape of construction spacers of the rotor generator is presented in Figure 3.
2.2. Heat transfer

The modifications to the axial spacer could make the heat transfer difference occurring on end winding rotor generator after replacing the new spacer, and the following formula is used to calculate heat transfer [8]:

\[ \beta = \left( \frac{1}{\tau_f} \right) \]  
\[ G_rP_r = \frac{g \times \beta x (T_{in} - T_{out}) \times x^3}{v^2} \times (P_r) \]  
\[ \bar{N}_u = C x (G_r x P_r)^m \]  
\[ \bar{h} = \frac{\bar{N}_u}{\frac{L}{d}} \]  
\[ q = \bar{h} x A \times (T_{in} - T_{out}) \]

where,

\( T_{in} \) = Minimum temperature (°C)
\( T_{out} \) = Maximum temperature (°C)
\( T_f \) = Film temperature (°K)
\( \beta \) = Conductivity coefficient of temperature
\( k \) = Thermal conductivity (W/m °C)
\( P_r \) = Prandtl number
\( v \) = Kinematic viscosity (m²/s)
\( c \) = Concentration
\( m \) = Mean flow conditions
\( x \) = Length of object (m)
\( A \) = Area (m²)
\( g \) = Gravity (Kg / m²)
\( R_a = G_r P_r \) = Rayleigh number = Grashof & Prandtl number

3. Methodology

According to the observation and experience faced in the field in repairing the rotor generator, it was decided to optimize the spacer so that after repairing the rotor generator, it performs more reliably. The following are some of the modification steps on the spacer, among others:

a. Opening the retaining ring generator on both the turbine and exciter sides and then replacing the old spacers attached with new spacers with longer dimensions for the turbine and exciter sides. This replacement is particularly directed to the direct axis block spacer type C base on Figure 4(a). Explanation of the replacement of direct axial spacers is shown in Figure 4(b).
Fig. 4. Installation of new direct axial spacer: (a) Dimension comparison of new spacers and old spacers; (b) Position of the old spacers compared to the new spacers

b. Adding insulation blocks at empty gap position on direct axis block spacer that separate coil and centering ring (circle ring insulation) on turbine and exciter sides. The position of the addition of insulation blocks is shown in Figure 5.

Fig. 5. Addition of insulation blocks: (a) Design of addition insulation blocks on circle ring insulation; (b) Circle ring insulation after addition of insulation blocks

c. Create track cooling gas flow on the direct axis block spacer for the turbine and exciter sides. The design of the track cooling gas on axial spacers is shown in Figure 6.
Fig. 6. Track cooling gas flow on axial spacers: (a) Design of track cooling gas flow; (b) Implementation of track cooling on axial spacers

A flowchart of the mitigation process in axial spacer modification installed on the end windings of the rotor generator is described in Figure 7, describing the replacement and modification of the mechanism of the axial spacer, the condition of determination in the installation stage greatly determining the quality of the repaired rotor generator. There are three stages that are the deciding factor in the repair of the generator rotor according to the methodology.

Fig. 7. Chart of replacement the new modification of axial spacer
4. Results and Discussion

4.1. Heat transfer analysis

Analysis of heat transfer is based on the calculations described in chapter II on theory using formulas (1) up to (5) and calculating the area of the end winding rotor generator as well as the area of the modified axial spacers [9] [10]. The value of each heat transfer expansion area between the old spacers and the new spacers relative to heat transfer of the end winding is shown in table 1. Table 1 shows a difference of 351 watts in heat transfer value, which is significant in affecting the performance of the generator [11]. The following parameters in Table 2 show a comparison of the performance of the generator prior to interference and after interference including application of the spacer modification.

| Spacer position | Old Spacer (Watts) | New Spacer (Watts) |
|-----------------|--------------------|--------------------|
| Spacer 1 relative to coil slot 1 and slot 2 | 200182 | 200199 |
| Spacer 2 relative to coil slot 2 and slot 3 | 237408 | 237418 |
| Spacer 3 relative to coil slot 3 and slot 4 | 271881 | 271893 |
| Spacer 4 relative to coil slot 4 and slot 5 | 326299 | 326331 |
| Spacer 5 relative to coil slot 5 and slot 6 | 356618 | 356680 |
| Spacer 6 relative to coil slot 6 and slot 7 | 363237 | 363334 |
| Spacer 7 relative to coil slot 7 and slot 8 | 390911 | 391030 |

4.2. Comparison of generator load

The operating parameter data showing the performance of the generator with the same load on demand from the load control region division at the time before the interference and after repairing the generator rotor using modifications from the axial spacer are shown in Table 2 [12]. The load value compared to the value of 292 MW from the maximum load of 315 MW, while some parameters reviewed for analysis after generator rotor repair are:

a. Active power (MW);
b. Reactive power (MVAR);
c. Excitation current (A);
d. Excitation voltage (V);
e. Current stator phase R, S and T (A);
f. Stator voltage (kV);
g. Vibration bearing journal 5X & 5Y (mm/s);
h. Vibration bearing journal 6X & 6Y (mm/s);
i. Generator rotor temperature (°C);
j. Generator rotor resistance (kΩ);
k. Generator rotor rotation (rpm);
l. Frequency (Hz).

The before interference parameters were taken on December 10th, 2019 at 12:20 PM, while the post-repair parameters were taken on September 17th, 2020 at 14:35 PM. The interference occurred on December 26th, 2019 at 23:00 PM. Table 2 shows that through modifications of axial spacers with the same active power load rated at 292 MW, the excitation current parameters can rise without causing a significant temperature increase of the rotor generator, and also be able to increase reactive power. Vibrations values increased on the side of the bearing 6Y but still below the alarm value rated at 125 mm/s. Modification of the axial spacer on the end winding rotor generator by making cooling gas track is proven to maximize cooling so that the heat transfer process that occurs in coil end winding occurs better and also indicated by the increase in performance of the generator.
Table 2. Comparison of the generator performance before and after repairing the rotor generator

| Operating Parameters of Generator | Before Interference | After Repair and Axial Spacer Modifications |
|-----------------------------------|---------------------|--------------------------------------------|
| Active power                      | 292.72 MW            | 292.34 MW                                  |
| Reactive power                     | 65.07 MVAR           | 115.18 MVAR                                |
| Excitation current                | 1583.90 A            | 1715 A                                     |
| Excitation voltage                | 311.86 V             | 339.94 V                                   |
| Current stator phase R            | 8433.69 A            | 9252.25 A                                  |
| Current stator phase S            | 8475.59 A            | 9213.87 A                                  |
| Current stator phase T            | 8586.04 A            | 9300.59 A                                  |
| Stator voltage                    | 20.54 kV             | 20.22 kV                                   |
| Vibration bearing journal 5X      | 25.61 mm/s           | 34.53 mm/s                                 |
| Vibration bearing journal 5Y      | 29.26 mm/s           | 53.47 mm/s                                 |
| Vibration bearing journal 6X      | 43.40 mm/s           | 50.62 mm/s                                 |
| Vibration bearing journal 6Y      | 37.94 mm/s           | 92.05 mm/s                                 |
| Generator rotor temperature      | 41.75 °C             | 42.82 °C                                   |
| Generator rotor resistance        | 200.32 kΩ            | 200.32 kΩ                                  |
| Generator rotor rotation          | 2995.24 rpm          | 2995.75 rpm                                |
| Frequency                         | 49.99 Hz             | 49.94 Hz                                   |

5. Conclusion

The modification of the axial spacer has been proven to provide performance improvements of the rotor generator, which by extending the dimensions of the axial spacer impacts mechanical ability to withstand expansion of the rotor coil due to heat caused by the flow of high currents. In the same time the creation of a gas track cooling line is able to optimize the cooling process so that the coil end winding becomes cooler even when a bigger current flows on the coil. Finally this repair and modification process is able to improve the performance of the generator, as shown in the operating parameters after repairing of the rotor generator.

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References

[1] Klempner G and Kerszenbaum I 2004 Operation and maintenance of large turbo-generators vol 14 (John Wiley & Sons)
[2] Shuting W, Zhaofeng X, Yonggang L, Zili H and Heming L 2003 Analysis of generator vibration characteristic on rotor winding interturn short circuit fault Sixth International Conference on Electrical Machines and Systems, 2003. ICEMS 2003. vol 2 pp 882–5
[3] Wang X and Song C 2019 Analysis on Nonlinear Dynamic Characteristic of Synchronous Generator Rotor System Complexity 2019
[4] Chen K, Zhou X-C, Fang J-Q and Qin L 2017 Study on frequency characteristics of rotor systems for fault detection using variational mode decomposition International Journal of Rotating Machinery 2017
[5] Meng Q and He Y 2018 Mechanical Response Before and After Rotor Inter-turn Short-circuit Fault on Stator Windings in Synchronous Generator 2018 IEEE Student Conference on Electric Machines and Systems pp 1–7
[6] Li Y, Sun Y, Wang L and Li H 2007 The criterion on inter-turn short circuit fault diagnose of steam turbine generator rotor windings 2007 International Conference on Electrical Machines and Systems (ICEMS) pp 1050–4
[7] He Y-L, Zhang Z-J, Wang X-L, Gao P, Gerada D, Gerada C and Vakil G 2020 Impact of Single and Combined Faults Composed of Rotor Eccentricity and Stator Interturn Short Circuit on Electromagnetic Torque Ripples in Synchronous Generator Complexity 2020
[8] Holman J P 2010 Heat transfer, 10th editi. ed Mc-GrawHill Higher education
[9] Cardone G, Astarita T and Carlomagno G M 1997 Heat transfer measurements on a rotating disk International Journal of Rotating Machinery 3
[10] Yoon M K and Ken Kauh S 2005 Thermal analysis of a small, totally enclosed, fan-cooled induction motor Heat transfer engineering 26 77–86

[11] Guan C, Li W, Huo F and Zheng P 2013 Thermal Analysis of 1000-MW Supercritical Turbo-Generator Under Hollow Strands Blocking Heat transfer engineering 34 642–52

[12] Ghahfarokhi P S, Kallaste A, Vaimann T, Rassolkin A and Belahcen A 2017 Determination of forced convection coefficient over a flat side of coil 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON) pp 1–4