Abstract
Rewinding of generators stator and rotor is a common practice for life extension of the generators being followed by power utilities. This is the stage when the latent defects can be addressed without much of an additional cost. To address these defects strong engineering tools like thermal modeling supported with online site measurements is required to do reverse engineering.
This presents a case study of a unique investigation carried out on a gas turbine driven air-cooled 20 MW generator to find out the cause of overheating at central part of the generator rotor. For investigation a thermal model devised for Air Cooled generators was used. The model was developed for design development and for engineering application tool for generators. It was re-configured for this specific application.
The program of the model calculates temperature of air, stator core, stator windings and rotor body and air pressures, velocities, air flows and ventilation losses in the generator.
The actual operating data such as static and dynamic air pressure, air temperature was collected online by installing additional measurement devices on the generator.
The measurements were carried out at different operating load conditions and transient operating conditions were simulated. The results of the model have added value to the refurbishment plan as has highlighted various efficiency improvement aspects.

Key words
Generator, stator, rotor, radiators, thermal- model, wedges, inter-slot, RTD, winding, harmonic, negative phase sequence current

Introduction
This case study refers to the 5 gas turbine driven generators commissioned in 1981 each of 22.5 MVA capacity. The generators are being used to feed directly to rectifier transformers having diodes for aluminium smelter process. During inspection of rotors in 1998-1999 overheating signs at the central part of the rotors were observed. See picture in Figure 1. The heating marks were surface indicative.
The generators are air-cooled. The ventilation design concept is shown in figure 2. The generators are symmetrically ventilated from both ends except for some airflow to the exciter at the non-driving end. The cooling air circuit to the exciter is shunted across fan inlet.
The stator is ventilated in radial ducts divided in two outflow compartments at each end and one outflow compartment in the centre of the stator. The inflow compartment is situated between the outflow compartments. Two radiators are housed at the top of the generator. The air is cooled by
water in the radiators. The rotor is indirectly cooled and provided with inter-slots between each rotor slot and furthermore two in each pole. The interslot wedges and rotor slot wedges are segmented.

**The need of investigation**

Initial observations preliminarily indicated that this problem is not related to any steady state operation but with no certainties. Generators were marked for life extension hence there was a need to ascertain the cause of overheating so as not to subject the rewound generator to excessive overheating with a view of improving the design.

Possible causes of surface heating at the rotor are-

- Running of generators with partial or without cooling. The cooling water pumps feeding water to generator air radiators are having a routine of weekly changeover with 30 seconds changeover time to prevent surges in the water supply system.
- Negative sequence currents
- Imbalanced load in steady state operation, it was measured and was found to be in the order of 2%. The nature of load is such that it is always balanced being rectifier transformers.
- Out of synchronism breaker closing; no history was traceable.
- Harmonics: The harmonic study indicated THD well below 1%.
- Generic cooling problems with rotor.

**The methodology of investigation**

The design details of generator were not available but the details of a similar though not identical generator from same manufacturer were available. The methodology to evaluate the cause of overheating was to perform calculations as well as measurements of the ventilation and temperatures in one of the five generators. The calculations were done with a thermal modeling program. The program is used for design development of generators at manufacturing works. The model was so far applied where all design details of generators are available beforehand. Adjusting model for generator of different make was a challenge. The model was reconfigured using:

- default values or estimated values based on experience e.g. heat conductivity of core and insulation, filled factor of stator core and efficiency of the fan.
- measured values as input data e.g. pressure rise by axial fan, physically measured dimensions of the stator and rotor.

The above technique was first used on a similar rewound generator to verify the model for the adjustment and application envisaged.

The measurements as well as calculations were performed for four different heat runs:

1. No-load, No voltage running at 3000 rpm.
2. No-load, Rated Voltage 11.5 kV running.
3. Load running with about 60% of the rated output.
4. Load running with 100% of the rated output.

Measurements were performed at steady state operating conditions after stable equilibrium. Additional probes were installed in the generator to measure air pressure at positions 1,2,3,4,5,6 and 7 and temperature of air at positions 2,3,5,7 and 8 during the heat run tests see figure 3. The flow and
The temperature of water at inlet and outlet to radiator were recorded. The ambient temperature and pressure of air around the generator was measured.

The following electrical parameters were recorded during the heat runs.

- Stator terminal voltage
- Stator current
- Current to the brushless exciter.
- Active power
- Reactive power

Concept of the model

The program of the model calculates:
- Temperature of Air, stator iron and winding, rotor body and winding
- Ventilation;
- Air pressures, velocities, air flows etc.
- Losses
- Ventilation, Stator windings and rotor winding

The basic input data for the program are:
- Stator detailed dimensions.
- Stator electrical operating values such as current, air gap flux density, iron losses.
- Stator winding details
- Rotor detailed dimensions.
- Rotor electrical operating values such as current, iron losses.
- Rotor winding details
- End cap dimensional details

The program also needs input data as following:
- Fan curve Pressure rise and efficiency as a function of the air flow
- Iron losses in the stator sheets, stator ends and rotor body
- Air cooler pressure drop at rated air flow.
- Temperature of cold air.

For the purpose of calculations in axial direction the stator is segmented in small steps, in radial direction stator is divided in 4 parts (2 in teeth and 2 in yoke) and the air gap is one part. See figure 4. The rotor is segmented in three parts: Teeth, Pole and Centre.

At each segmental air volume the following properties of air are calculated:
- Air temperature
- Static and dynamic pressure
- Air velocities (Axial, radial and/or rotation)
- Density of air
- Viscosity of air

For the purpose of calculation air is considered as an ideal gas and flow is defined as mass flow. See appendix 1 as a typical test results of the program for 100% load.
**Test Results**

The results from the calculations with the program of the model were found in good accordance. The discrepancy between measured and calculated losses is below 5% in all tests done for total losses see figure 5.

![Fig 5: Total Calculated / measured losses](image1)

The measured and calculated temperature rise of the air is presented in figure 6. A weighted average of readings of the temperatures of warm air gives a better result for the test. The calculated temperature rises in all tests are within maximum and minimum values as measured.

The embedded stator winding temperature probes (RTD) in the stator winding in the centre of the generators measured better temperatures than the temperature measurement of the outflow air. Measured and calculated temperatures of the stator winding above cold air are presented in figure 7.

![Fig 6: Calculated and Measured Temperature rise](image2)

![Fig 7: Stator winding temperature](image3)

The airflows out from some of the stator ducts in the outflow compartments were measured during the tests. The measured and calculated velocities are presented in the figure-8. The duct 0 represents the stator end and duct 24 the centre of the stator. There is good match between measured and calculated velocities except in the central zone. The measured high velocities in the stator ducts in the centre cannot be correct, the probable cause being the high turbulence of air flowing out from the rotor.

The temperature of the air exiting from the stator ducts is close to the calculated see figure 9.

![Fig 8: Air velocity at outlet of stator ducts](image4)
The figure 10 presents the calculated pressure-flow curves for the fan. The measured pressure rise in the fans is less compared to the calculated pressure rises. The main reasons are the asymmetry inflow of air to the fan and the high turbulence level before the fan because of the high radial velocity of air just before the fan. The ‘pressure drop–flow’ curve is also presented. The figure 10 also presents the expected airflow and pressure rise of the fan and these are much higher than measured in the generators.

![Figure 10: Pressure rise and drop at fan](image)

**Other significant finding**

Radiators: The temperature difference between the cold air and the cold water was measured to be 14 °C for generator under evaluation where as it was measured to be 3°C for the rewound generator with the same flow of water. The pressure drops for the air to pass the air coolers was about 370 Pa against 310 Pa respectively. The main reason for higher-pressure drop for rewound generator is a little more airflow than in generator under evaluation.

The performance of radiators found not to be in good condition.

**Evaluation of the results**

The model was used to extrapolate the rotor surface temperature to 300 °C at attain this rotor surface losses shall be increased from normal 19.3 kW to 356 kW i.e. about 18 times. The temperatures thus calculated are as following:

- Rotor winding at centre: 304 °C
- Stator winding at centre: 143 °C
- Stator surface in the air gap at centre: 175 °C
- Air in the air gap at centre: 175 °C
- Warm air before the air coolers (average): 92 °C

These results of the calculation are far above the test observations. Hence measurements and the calculations indicated that temperatures in the generator during normal operation couldn’t cause overheating at the central part of the rotor.

Effect on temperature due to cooling water change over was also simulated during 100% load heat run test. The water flow was about zero for about 40 seconds during the change. No significant

![Figure 11: Effect on air temperature during cooling water pump changeover](image)

![Figure 12: 50 times surface loss with normal temperature of the airflow](image)
change in temperature was observed during these 40 seconds. Hence it was well not considered as the reason of overheating marks on the rotors. See figure 11.

The cause of Harmonic losses was ruled out based on the measurements as THD was measured well below 1% as rectification at each rectifier transformer is 12 pulse hence with 6 rectifier transformers load is with 72 pulse rectification.

Therefore the only incident that can cause such overheating of the rotor is a transient condition. To attain a rotor surface temperature of 300°C the losses at the rotor surface have to be about 50 times the normal losses for a period of 3 to 4 minutes. Negative sequence current other than harmonic currents can only explain such a high losses. ‘Negative sequence current’ of the estimated level of 30-40% can cause this.

The cause of Harmonic losses was ruled out based on the measurements as THD was measured well below 1% as rectification at each rectifier transformer is 12 pulse hence with 6 rectifier transformers load is with 72 pulse rectification.

The calculations of transient temperatures in the centre of the generator as a function of time for a temporary addition of surface losses to 50 times was carried out and is indicated in figure 12. It represents the case with constant temperature of the air in the air gap at centre during the increase of the rotor temperature. The test case of ‘100% load’ from the investigation has been used as reference. The calculations with the transient heating of the rotor are simplified. The following temperatures are presented in figure 12, Stator surface, Air in the air gap, Rotor surface, 50, 100 and 150 mm beneath the rotor surface.

These indicate that the temperature of the rotor surface can increase from 97 °C to 300 °C with in 3 to 4 minutes, and still the temperatures at the rotor windings would not be too bad for short time. The embedded RTDs for stator winding temperature will indicate no changes during this period of 3 to 4 minutes. This incident may go undetected by the RTDs of the stator winding.

According to this analysis, such an incident once in operational life may cause such an overheating. For a generator rotor having electrical insulating parts i.e. balancing screws at the rotor surface in the centre the losses as 50 time’s normal surface losses might arise even for a smaller value than 30-40 % of the Negative sequence current.

**Outcome of Investigation**

The results of the thermal evaluation of the generator to investigate the generator rotor overheating do not recommend any remedial actions as far as operation of the generator is concerned. But this evaluation added value to the refurbishment plan by identifying many generic defects as below-

- The inflow duct of the fan needs modification to reduce the turbulence of air. This will increase the fan efficiency and reduce the noise.
- The efficiency of the air coolers is found low. Replacement of coolers with efficient coolers proposed.
- The balancing screws are modified to make better electrical connections to provide less resistance path to the negative sequence surface currents.
- Change of slot wedge material and length is being reviewed to give a better conductivity.
- Reduction in temperature rise by changing the stator winding resistance will improve the overall efficiency of the generator.

**Conclusion**

The thermal model used to investigate the cause of overheating in the central part of the rotor was reconfigured and verified. With the application of the model it was ascertained that the overheating is of transient nature. Important modifications could be proposed to basic generator parts to improve performance during possible transient conditions. Such a model has a wider prospective to use as an online condition monitoring tool for the generators.

**References**

References are omitted as this is a unique case study and only refers to internal documents.
Appendix - 1

VENTILATION CALCULATION

Air cooled Turbo generator Type: XXXXXX
Reference: Alba PS2 GT 21 100% load

Input data
Frequency
Stator
Dimensional details
Stator ducts:
Stator - electrical values:
Stator winding
Rotor
Dimensional details
Rotor - electrical values
Rotor slots
Rotor winding
Rotor endcap dimensional details
Rotor ends and support ring
References
Rotor shaft dimensions
Axial fan dimensions
Air cooler dimensions and operating parameters
Outside stator core
Generator frame dimensions

Results of calculation
Calculation check
Difference inflow/outflow power 0.02 %

Calculated inflow/outflow power

Stator losses
- Losses top winding 28.1 kW
- Losses bottom winding 16.2 kW
- Losses end winding 35.8 kW
According to input data:
- Added losses end-winding 30.6 kW
- Iron losses (top+bottom) 56.8 kW
- Added losses end parts 31.8 kW
- Total stator losses 199.3 kW
- Total losses 364.3 kW

Calculated total cooling
- Air coolers 347.2 kW
- Ambient air 17.0 kW
- Total cooling 364.3 kW

Calculated iron losses per volume core
- Teeth not stepping part 6.56 kW/m³
- Yoke not stepping part 15.75 kW/m³
- Teeth stepping part 34.09 kW/m³
- Yoke stepping part 27.73 kW/m³

Calculated data in the air gap
Values in the air gap before package number
- P= Static pressure above reference [Pa]
- Q= Air flow [kg/s];
- T= Air temperature [°C]
- Va= Axial air velocity [m/s]
- Vr = Rotational air velocity [m/s]

Package | P | Q | T | Va | Vr
--- | --- | --- | --- | --- | ---
Before 933 | 4.56 | 56.7 | 6.5
1 | 543 | 4.56 | 56.4 | 26.4 | 6.5
10 | 850 | 0.26 | 61.5 | 1.4 | 37.1
17 | 706 | 2.15 | 73.8 | 11.5 | 22.8
Centre 758 | 0.00 | 82.2 | 0.0 | 53.6

Air flows in the air gap package number
- Q1= Air flow before [kg/s]
- Q2= Air flow after [kg/s]
- Qsd= Air inflow(+) outflow(-) stator ducts [kg/s]

Package | Q1 | Q2 | Qsd
--- | --- | --- | ---
1 | 4.56 | 4.20 | 0.36
10 | 0.26 | 0.54 | -0.27
17 | 2.15 | 1.70 | 0.45
Centre | -0.43 | 0.43

Calculated heat transfer coefficient [W/(Kxm²)]

For air and stator at inner diameter

A_{AS} = A_{AS} (\text{between air and stator at inner diameter})

A_{AS} = A_{AS} (\text{between air and stator neck})
$A_{firs} =$ Between air and rotor in air gap
$A_{frs} =$ In interslots (Average in poles and teeth)

<table>
<thead>
<tr>
<th>Package</th>
<th>$A_{firs}$</th>
<th>$A_{frs}$</th>
<th>$A_{firs}$</th>
<th>$A_{frs}$</th>
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<td>87</td>
<td>355</td>
<td>196</td>
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<td>147</td>
<td>24</td>
<td>258</td>
<td>196</td>
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<tr>
<td>17</td>
<td>104</td>
<td>48</td>
<td>294</td>
<td>197</td>
</tr>
<tr>
<td>Centre</td>
<td>177</td>
<td>26</td>
<td>219</td>
<td>81</td>
</tr>
</tbody>
</table>

**Calculated data in the stator duct**

Values before and in the stator duct number

- $P =$ Static pressure at inner diameter of stator before inflow/outflow duct [Pa]
- $Q =$ Air flow in the stator duct, outflow (+) resp. inflow (-) [kg/s]
- $V =$ Air velocity at "inflow from" (+) resp. "outflow to" (-) the air gap [m/s]
- Heat transfer coefficient [W/(Kxcm²)] in Stator $A_{fsd1} =$ ducts, teeth; $A_{fsd2} =$ ducts, yoke

<table>
<thead>
<tr>
<th>Duct</th>
<th>$P$</th>
<th>$Q$</th>
<th>$V$</th>
<th>$A_{fsd1}$</th>
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<td>0.363</td>
<td>16.85</td>
<td>69</td>
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<td>10</td>
<td>938</td>
<td>-0.273</td>
<td>-13.15</td>
<td>55</td>
</tr>
<tr>
<td>17</td>
<td>729</td>
<td>0.453</td>
<td>22.12</td>
<td>83</td>
</tr>
<tr>
<td>Centre</td>
<td>859</td>
<td>0.534</td>
<td>26.86</td>
<td>96</td>
</tr>
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</table>

**Calculated air temperatures in the stator duct**

Values in the stator duct number

- $T1 =$ Top teeth [°C], $T2 =$ Bottom teeth [°C]
- $T3 =$ Top yoke [°C], $T4 =$ Bottom yoke [°C]
- $T5 =$ Outside package number I [°C]

<table>
<thead>
<tr>
<th>Duct</th>
<th>$T1$</th>
<th>$T2$</th>
<th>$T3$</th>
<th>$T4$</th>
<th>$T5$</th>
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<tr>
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<tr>
<td>17</td>
<td>74.8</td>
<td>75.7</td>
<td>76.6</td>
<td>77.5</td>
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<tr>
<td>Centre</td>
<td>85.1</td>
<td>85.8</td>
<td>86.5</td>
<td>87.3</td>
<td>87.9</td>
</tr>
</tbody>
</table>

**Calculated air temperatures outside stator core**

- Before the air coolers 71.7°C
- After the fan 51.6°C
- First compartment 64.1°C
- Centre compartment 81.8°C
- Inflow to inflow compartment 65.7°C

**Calculated temperatures in the stator package**

Values in the stator package number I

- $T1 =$ Top teeth [°C],
- $T2 =$ Bottom teeth [°C],
- $T3 =$ Top yoke [°C],
- $T4 =$ Bottom yoke [°C],
- $T5 =$ Outside package number I

<table>
<thead>
<tr>
<th>Package</th>
<th>$T1$</th>
<th>$T2$</th>
<th>$T3$</th>
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</thead>
<tbody>
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<td>88.6</td>
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<td>10</td>
<td>75.7</td>
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<td>17</td>
<td>83.1</td>
<td>83.6</td>
<td>81.8</td>
<td>80.8</td>
</tr>
</tbody>
</table>

- Centre 92.3 93.2 92.9 93.0

**Calculated temperatures in the stator windings**

Temp. RTD between coil sides 109.0 °C

**Calculated temperatures in the rotor**

Temperature in the rotor body [°C]:
- $Trot=$ Teeth, $Trop =$ Pole, $Troc =$ Centre
- $Trotw =$ Temperature rotor winding [°C]

<table>
<thead>
<tr>
<th>Package</th>
<th>$Trot$</th>
<th>$Trop$</th>
<th>$Troc$</th>
<th>$Trotw$</th>
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</thead>
<tbody>
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<td>10</td>
<td>81.6</td>
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<td>80.1</td>
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<td>17</td>
<td>88.5</td>
<td>77.3</td>
<td>87.3</td>
<td>104.0</td>
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<tr>
<td>24</td>
<td>99.4</td>
<td>85.8</td>
<td>93.1</td>
<td>110.2</td>
</tr>
</tbody>
</table>

Average temp. rotor winding 93.6 °C
Average temp. winding in rotor body 98.5 °C
Resistance rotor winding 0.436 ohm
Resistance rotor winding at 15 °C 0.331 ohm

**Calculated air temperatures in the rotor**

- $Tairga =$ Average air temperature in air gap [°C]
- Air temperatures in interslots [°C]
- $Tairot =$ in teeth, $Tairop =$ in poles

<table>
<thead>
<tr>
<th>Package</th>
<th>$Tairga$</th>
<th>$Tairot$</th>
<th>$Tairop$</th>
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<tbody>
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<td>62.6</td>
</tr>
<tr>
<td>17</td>
<td>74.0</td>
<td>69.6</td>
<td>65.2</td>
</tr>
<tr>
<td>24</td>
<td>82.6</td>
<td>76.8</td>
<td>70.6</td>
</tr>
</tbody>
</table>

**Calculated air velocities in the rotor**

<table>
<thead>
<tr>
<th>Duct</th>
<th>$V$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Into</td>
<td>59.4</td>
</tr>
<tr>
<td>Out</td>
<td>19.1</td>
</tr>
<tr>
<td>Out</td>
<td>32.7</td>
</tr>
<tr>
<td>Out</td>
<td>35.9</td>
</tr>
</tbody>
</table>

**Calculated air pressures above reference pressure**

- Pressure before the fan -241 Pa
- Pressure before the air cooler 289 Pa
- Pressure at outflow compartment 1299 Pa
- Pressure at centre outflow compartment 302 Pa
- Pressure at inflow compartment 877 Pa
- Pressure at outside stator coil ends 933 Pa

**Calculated dimensions**

- Length normal stator package 40.9 mm
- Depth of rotor slot 1 132.2 mm
- Depth of rotor slot 2 132.2 mm
- Depth of turns in remaining slots 132.2 mm
- Average length of rotor winding 6876 mm