Quantification and Management of Grid Interaction Effects on Turbo-Generator Sets

Mark NEWBY 1, Ronnie SCHEEPERS 1

1 ESKOM Technology Division, South Africa; Phone +27 11 629 5798; mark.newby@eskom.co.za, ronnie.scheepers@eskom.co.za

Abstract

Power stations located at the extremities of transmission networks are susceptible to grid interaction effects if a fault occurs on the transmission network. This interaction results in a sub-synchronous torsional excitation to the generator rotor, which in turn leads to a torsional pulse being applied by the generator rotor onto the turbine train. The torsional excitation can exceed 30% of the rated output torque for the turbine and can result in excitation of the blade natural frequencies with consequent damage in the blade root areas. This presents a difficult condition monitoring problem in managing random damaging events where the effect on fatigue life can vary with each event. This paper presents a case study where the grid interaction effects were quantified by means of strain gauge based telemetry measurements and proposes a condition monitoring methodology for managing the long term effects of grid interaction on the turbine blades.

Keywords: transmission grid, telemetry, strain gauge, turbine blade modelling, grid interaction

1. Introduction

Power generation low-pressure (LP) steam turbine blades have always shown a degree of vulnerability to degradation mechanisms that could lead to failure. Eskom has had a number of blade failures through the years of which the Duvha power station failure in 2003 is the most prominent because of the high secondary damage incurred. Degradation is often associated with stress corrosion cracking, corrosion fatigue or high cycle fatigue.

While blade cracks often have a high-cycle fatigue appearance, it is argued that the mechanism that causes crack propagation must be intermittent. A continuous mechanism would result in rapid blade failures because of the rapid accumulation of cycles. It is often apparent that the crack behaviour is unpredictable. Relatively short periods of operation can result in extensive cracking while, on the same turbines, no cracking is found after long periods of operation. The LP turbine blades at Koeberg power station recently received specific focus because of this behaviour where inspection intervals would be intolerably short if worst case statistics were used as a measure.

Koeberg is located at the furthest point on the national grid in South Africa and is susceptible to grid interaction effects if a fault occurs on the transmission network. This interaction results in a sub-synchronous torsional excitation to the generator rotor, which in turn leads to a torsional pulse being applied by the generator rotor onto the turbine train.

Modal analysis of the LP rotors revealed that the turbine blade packets had torsional natural frequencies close to 100Hz. It was realised that crack propagation could be caused by interaction between electrical torque and natural frequencies of the turbine generator shaft and bladed disc system. This phenomenon has been positively identified as the cause of last-stage blade failures in the large (1500 MW) nuclear machines elsewhere.
The generator at Koeberg is driven by a high-pressure (HP) turbine connected to three LP turbines. A project was initiated to consider the effect of grid interaction on LP rotor blade cracking. In order to achieve this it was necessary to measure the torque on the shaft between the generator and LP3, which is the rotor connected to the generator. The measurement needed to monitored online and have the ability to trigger when a grid event occurred.

It was decided that strain gauges connected to a telemetry system would be used to measure when these events took place and what the actual torsional excitation levels were. The measurement of this type of dynamic torque required a system that has high resolution (16 bit), very good reliability, remote power and ruggedness. The environment would also have an oil mist present due to the chosen measurement point being inside the bearing cover. The Accumetrics AT4400 system was chosen due to a proven track record within the Eskom research program.

The disadvantage of the telemetry system is vulnerability of failure due to damage of the rotating part of the installation. During the course of the research a torsional laser system was also investigated to determine if a suitable signal could be obtained from it. The advantage of this system is that the laser is stationary and focuses on the periphery of the shaft.

In parallel with this project Eskom contracted an American company to analyse the grid interaction pulses from an electrical viewpoint and design a protection system that would control the effect of the events. As part of their scope of work they have installed a system that monitors two toothed wheels, one at each end of the turbine generator train. This is known as the GPB system, the data from the GPB system is fed into a lumped mass torsional model of the turbine generator train and predicts the torque at each coupling point.

### 2. Measurement of Shaft Torsional Events

#### 2.1 Telemetry Measurements

Strain gauges were applied on the turbine shaft between the generator and LP3 rotor. The strain gauges were applied using an epoxy glue type HBM X280 in a full bridge configuration, with the half bridges on opposite sides of the shaft. The strain gauges were type HBM XY41 6/700, which are designed to measure torque. The connecting cables were fine single core wires with varnish insulation, these were held in place with a thin layer of epoxy adhesive type HBM EP310. The connecting cables were led to a solder tab that had been glued to the shaft in the same way as the strain gauges.

The telemetry system selected for monitoring the strain gauges was an Accumetrics AT4400 unit. The amplifier and transmitter were mounted in a split collar that was clamped to the shaft next to the gauge point. The amplifier circuit digitizes the input signal with 16 bit resolution which is then transmitted in digital format to the receiver, after which it is converted back to an analogue voltage. The system has a frequency response of 2000Hz. Power is supplied inductively to the amplifier and transmitter via the receiving aerial. Photographs showing the installation are presented in Figure 1.

The input sensitivity of the amplifier was preset to 1,529mV/V at the factory. This was verified using a strain gauge simulator box, type HBM K3607, and the data is shown in Figure 2. The signal from the receiver was connected to a data logger located in an equipment room at Koeberg. The logger used was a SOMAT eDAQlite with four analogue...
The eDAQlite was connected to the Eskom intranet to enable remote control of programming and data downloads.

The logger was set to record with a sample rate of 2500Hz. This would result in very large data files if run continuously, so a triggering system was used. A threshold trigger was set to catch the transient events, this captured 5 seconds of data prior to the event and 25 seconds after the event. A second trigger was set to record 20 seconds of data every hour to check the system integrity.

The data captured by the telemetry system was converted to torque using the sensitivity from the calibration graph shown in Figure 2, together with the shaft diameter and shear modulus of the material. The time series and frequency analysis of the data was done using Glyphworks signal processing software.

\[ \text{Torque} = \frac{\pi d^3 \varepsilon_i G}{32} \]

where:
- \( d = \text{Shaft Diameter} \)
- \( \varepsilon_i = \text{Indicated Strain} \)
- \( G = \text{Shear Modulus} \)

**2.2 GPB Toothed Wheel System**

The GPB system was designed and installed by Instrumentation Technology Inc, USA and consists of two toothed wheels mounted at either end of the turbine–generator shaft. A number of proximity probes are mounted around the wheels, and the pulses are passed through a processing unit that allows the torsional oscillation of the shaft to be calculated very
accurately and with a rapid response. The signals from the front and rear wheels are compared and correlated with a lumped mass model of the turbine–generator system to determine the torque at the rotor coupling points down the turbine train.

The primary function of the GPB system is protection of the generator from electrical faults, but in the case of this project the intention was to investigate whether the data could be used for condition monitoring of the turbine system.

2.3 Measurement Results

A number of events were recorded, but in this paper the detail is shown for an event that occurred on the 13th of November 2009. On this day five events came through in quick succession and Event 3 has been selected as the most representative. Data was also available from the GPB system and this has been combined into the data file so that a direct comparison of the frequencies can be made between the signals. The amplitude from the GPB system is shown as a unity value as the system had not yet been calibrated.

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 : Torque</td>
<td>Torque from telemetry system</td>
<td>kN.m</td>
</tr>
<tr>
<td>8 : W front</td>
<td>Rotational speed at HP wheel</td>
<td>Unity</td>
</tr>
<tr>
<td>9 : W rear</td>
<td>Rotational speed at Exciter wheel</td>
<td>Unity</td>
</tr>
<tr>
<td>17: T45</td>
<td>Modelled Torque at telemetry location</td>
<td>Unity</td>
</tr>
</tbody>
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Figure 3: Time Series of Telemetry and GPB Data Showing Full Event
Figure 4: Frequency Analysis of Telemetry and GPB Data

Figure 5: Zoom of Time Series in Telemetry and GPB Data
2.4 Discussion

A number of grid interaction events were captured by the telemetry system. These events were more frequent in bad weather, when line faults were more likely to occur. Results from one of the events are shown in Figures 3 to 6.
In Event 3 in the GPB system was working and so a comparison between the two systems was possible. The following comments can be made about the two systems:

- In Figure 5 the time series correlation between the telemetry signal and the modelled torque T45 is very good for the first second after the trigger. After the first second some of the higher frequencies seem to be amplified.
- The timing difference of the rear and front toothed wheel channels illustrates the lag down the turbo generator train as the event occurs (Figure 5).
- The sub-synchronous response of the turbo-generator is at 6.4, 12.2 and 16.3Hz. This is as predicted by the GPB modelling and measurement.
- The results confirmed that excitation of torsional modes on blades was occurring during the event, this is illustrated in Figure 6. There is however some variation between the channels at the 88 and 93.1Hz frequencies. This still needs to be investigated further.

The amplitude of the torsional excitation varied considerably for different recorded events, but the highest dynamic amplitude of 1500 kN.m was recorded during an event on the 13th of October 2008. This represents approximately 26% of the normal operating torque.

### 3. Blade Stress Calculation and Modelling

It is well known that torsional natural frequencies of turbo-generators are sensitive to excitation from grid events and, due to low torsional damping, can result in resonance and fatigue damage. Estimation of the cyclic stresses in the rotor shafts during such events is generally done by 1 dimensional (1D) finite element analysis based on the lumped mass approach. The complexity of these models varies depending on a number of parameters including the frequency range of interest, the type of analysis and the complexity of the components (e.g. generator rotor). It has been shown that the accuracy of these models in the sub-synchronous frequency range is acceptable whilst predictions in the super-synchronous range are not so good. In turbines with long flexible blades, such as in most nuclear units, a further complication arises in that these blades can participate in some of the torsional modes. This effect is accounted for by the use of branched 1D FEA models.

Rotor stresses for grid events can be estimated from transient response analysis using these models. However, for the prediction of turbine blade cyclic stress and resultant fatigue life accumulation it is proposed that a detail 3D cyclic symmetric model of a sector of the rotor including a blade/s be used. The transient rotational displacement response for the carrier disc calculated from the 1D model can then be applied as an input load to the detail 3D model to obtain the stress/strain response in the blade root.

### 4. Condition Monitoring Philosophy

The proposed condition monitoring philosophy for the LP turbine blades suspected of participation in torsional vibration response during grid events is summarised in the flow chart presented in Figure 7 below. As discussed above trigger levels are set to pre-determined levels to record data for significant events. Shaft strain gauge data as well as generator electrical parameters are recorded. A generator forcing function is calculated and applied to the lumped mass torsional model. Calculated response at the strain gauge position/s is compared with measured data and the model calibrated if required. In the case of Koeberg further calibration and verification is also possible with GPB data.
Figure 7: Proposed condition monitoring philosophy.
After calculation of the blade root cyclic stress from the detail 3D FEA model, the incremental fatigue damage fraction for the event is calculated using the prior developed fatigue model. The accumulated fatigue damage fraction is the summation of all recorded events.

The calculated fatigue life fraction can then be used to inform the planning of NDT intervention intervals.

5. Conclusions

A blade conditioning monitoring philosophy is proposed that uses the measured strain gauge data to calibrate 1D FEA models that are in turn used to predict the transient torsional response of the rotor. A detail 3D FEA model is then used to calculate the blade root stress response which is used to calculate a fatigue life fraction for the event. Decisions on planned NDT interventions can be informed by the accumulated fatigue life fraction.

Acknowledgements

The authors gratefully acknowledge the support of the Eskom research program as well as invaluable assistance from Johan Huggett of Koeberg power station.

References

References should be written in the order in which they appear in the text in the following format:
2. EPRI (2005), Steam Turbine-Generator Torsional Vibration Interaction with the Electrical Network, EPRI, Palo Alto, CA.