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TURNING GEAR MOTOR FAILURES, CONFIRMED BY MODEL BASED VOLTAGE & CURRENT METHOD
(Technical Brief)

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ABSTRACT

This technical brief aims to showcase relevant information related to Model-Based Voltage and Current (MBVI) method. The paper discusses several fatal failures on the Turning Gear Motor (TGM) over the short time period of one-month, resulting in two motor replacements. The Turning Gear Motor was monitored by an online monitoring system using improved Motor Current Signature Analysis (MCSA), aka. Model-Based Voltage and Current (MBVI). TGM mechanical and electrical malfunctions are reflected in the dynamic current spectrum using improved MCSA. Utilizing this methodology, prompt and precise diagnostics was carried out and subsequent decision could take place regarding the electrical and mechanical integrity of this motor installed on this critical Centreline Machine Train. The paper further shows the real case data analysis and findings on this Electric Motor.

The paper outlines the Expert Diagnostics System's (based on MBVI) ability to distinguish automatically among different malfunctions. The Expert System uses the power spectral density (PSD) of the difference between the expected current obtained from the model and the actual current. These differences include only abnormalities generated by the motor anomaly. Therefore, they are immune to the noise or harmonics present in the supply voltages.

MBVI is a suitable alternative or complimentary monitoring method, which does not require any sensor installation on the monitored equipment. All the measurements are carried out remotely in the motor control cabinet. The MBVI uses dynamic motor currents and spectrums to identify electrical, mechanical or process problems. MBVI is especially attractive for inaccessible motor driven equipment, particularly in this case, where the electric motor is located in the closed compartment of the Gas Turbine in the vicinity of the high temperature gases.

INTRODUCTION

Improved Motor Current Signature Analysis (MCSA) aka. Model-Based Voltage and Current Analysis (MBVI) can be an alternative or complementary method to the Vibration Analysis.

There are many similarities between the Vibration Analysis and improved MCSA - MBVI. Both are sensing the magnitude and frequency of signals being generated by the equipment to identify malfunctions and their severity. MBVI is using the motor as the sensor, where Vibration Analysis can use eddy current proximity probes, electromagnetic velocity sensors or piezo-electric accelerometers. The difference between these two techniques is that vibration sensors detect mainly radial (or axial) forces, whereas using the motor as a sensor is more sensitive to torsional forces. This means they can be complementary and the use of MBVI systems can give new insights to situations that have previously been assessed only by conventional Vibration Monitoring. A significant advantage of the Model-Based Voltage and Current System is the built in Expert System, which automatically detects the faults, assign the severity and send the notification to the user.

The MBVI method is demonstrated on the 11kW Turning Gear Motor installed on the Centreline Train, consisting of Steam Turbine-Generator-Gas Turbine, which represents the critical asset protecting the entire train from rotor bow. The TGM is located inside the machine casing and is not directly accessible. Moreover, the replacement of the faulty motor is a costly exercise in terms of labour, parts, and lost production. If a replacement motor is available, down time can be expected to exceed two weeks. Lead time for manufacture and delivery of a replacement motor can be up to 6 months.

HISTORICAL BACKGROUND

Following successful work carried out on the Centreline Train during a short-term outage, the Turning Gear Motor had been running continuously awaiting synchronization instruction from the grid when the motor suddenly stopped. Several attempts were made to re-start the motor but these failed.
The historical data and the improved MCSA, aka. Model-Based Voltage and Current (MBVI) method was used for root-cause analysis. One year prior to the event, the Online Monitoring and Expert system registered an increase at the inner-race ball-pass fault frequency (BPFI) of the non-drive end (NDE) motor bearing, suggesting the onset of bearing deterioration. Three months before the event, the system indicated a significant increase (10 times) of Standard Deviation (SD) amplitude levels in the Rotor Band (frequency band around rotor running speed), exceeding the Alarm threshold and indicating a severe rotor problem.

MOTOR CURRENT SIGNATURE ANALYSIS

Motor Current Signature Analysis (MCSA) is based on capturing the current demanded by the machine at steady-state and applying the Fast Fourier Transform (FFT). The current spectrum, obtained with the FFT, provides the harmonic content of the captured current signal and indicates the frequencies [Hz] and amplitudes [dB] of the different harmonics. When a certain fault is present, several components are amplified in the current spectrum, similarly as in vibration spectrum.

Based on Walker (2017), conventional MCSA is limited in its analysis capability because the motor current is not only affected by phenomena within the motor and driven equipment system, it is also affected by the voltage applied. This is not only a question of the scalar magnitude of the voltage (as measured by an RMS Figure), it is also a question of the shape of the dynamic waveform. A voltage waveform that is not a pure sinusoid, but may be distorted, will result in a current waveform that will likely be distorted in some way from being a pure sinusoid. Such distortions are very common, particularly when dealing with equipment driven by an inverter. These distortions may not indicate any problem with the electric motor or the equipment, they are purely caused by the distorted voltage input. Conventional MCSA is unable to distinguish between these distortions caused by the voltage waveform and faults that are a genuine indication of developing equipment problems.

The new solution is Model Based MCSA, known in the literature as Model-Based Voltage and Current Analysis (MBVI), which effectively uses the electric motor driving the equipment as a sensor, and makes use of the fact that the current drawn by an electric motor depends on two main factors:

- the voltage applied to the motor, and
- the behavior of the motor and driven equipment system.

MBVI Systems are able to separate out the impact of distortions coming from the voltage supply, by making a mathematical model of the relationship between current and voltage and using this to identify those components that are coming from the internal behavior of the system. The approach used is represented in Figure 1.

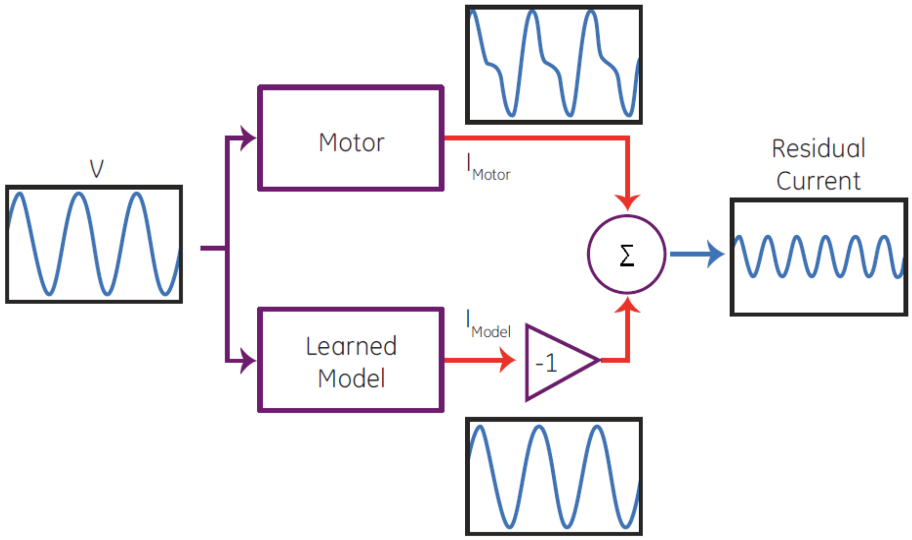

Figure 1: Model Based Motor Anomaly Detection (Courtesy of Bently Nevada)

Bently Nevada (2012), Model Based Motor Anomaly Detection Monitor uses MBVI, a combination of voltage and current dynamic waveforms, together with learned models for motor anomaly detection. Motor fault detection is based on a learned, physics-based motor model, where constants in the model are calculated from real-time data. Automated diagnostics (Expert System) is based on the Power Spectral Density (PSD) amplitudes in particular frequency bands, in relation to learned values and alarm thresholds. The spectrum-based fault detection in MBVI Monitor is similar to MCSA, but with several important differences. The MBVI Monitor takes the input voltage waveform and passes it through the model transfer function to obtain a theoretical current waveform. The theoretical current waveform is subtracted from the measured current waveform to produce a residual current waveform (Figure 1). The residual waveform contains the “errors” between theory and reality. The Fast Fourier Transform (FFT) is applied on residual waveform to obtain residual PSD Spectrum.

Power Spectral Density (PSD) shows the strength of the variation (energy) as a function of frequency. PSD is Auto Spectrum divided by its frequency resolution (the increment between frequency lines). If the units of an Auto spectrum are (g^2), the units of its corresponding PSD are (g^2 / Hz). The Auto Spectrum is calculated by multiplying the Fourier spectrum of a signal by its complex conjugate. The Auto Spectrum has magnitude only and its phase is zero.

The significant advantage of MBVI systems over conventional MCSA is that by being based on measurements of all three phases, phase unbalance can be identified, and this itself can be of significance, both as an indicator of problems with the motor windings, and as a cause of torque oscillation that can put additional stresses on components such as couplings.

Based on Walker (2017), the practical deployment of MBVI systems involves measuring current and voltage on the lines supplying the motor. Generally, the best place to measure this is in the motor starter cabinet, which is typically in a switch room, which is generally a dry location with no flammable atmosphere hazards. The MBVI units are typically installed in the motor cabinet itself, or in a separate cabinet mounted nearby. The current signal can either be provided by installing a fixed Current Transformer (CT), or in some cases by making use of existing CTs that are often already installed for metering or motor protection purposes. Since these are all inside the motor starter cabinet, they are not vulnerable to accidental damage during normal operation or maintenance work.

Model-Based Voltage and Current Systems offer the ability to identify and give advance warning of a wide range of commonly occurring failure modes, across a wide range of mechanical, electrical and operational areas. This is the essential information required to support the adoption of a Condition Based Maintenance (CBM) regime. They are simple to install, robust against accidental damage, and inexpensive.

The main advantages of the MCSA/MBVI are:
- Non-invasive method as no mounted sensor is required on the pump casing.
- The current transducer/transformer is easy to install, usually clamp on.
- The current transducer/transformer is usually installed in airconditioned motor control cabinet and there are no problems with the outside temperature or in case of cryogenic pumps with cryogenic temperatures.
- No environmental problems with the transducer installation as it's installed inside, in dry location with no flammable atmosphere hazards.
- The built-in Expert System, with automated advisory, reporting and notification.
- The condition monitoring mainly depends on Power Spectral Density analysis, similar to the vibration spectrum analysis.
- Individual spectrum bands for typical machine malfunctions can be trended.

The main disadvantages of the MCSA/MBVI are:
- Conventional MCSA is limited and affected by network loads and power supply harmonics. Model-Based Voltage and Current Analysis (MBVI) needs to be used to compensate for distortions coming from the voltage supply.
- It's not that widely used and understood method in the industry.
- There are limited international standards with the recommended alarm values to compare across the fleet.
- There is not one overall current value, which can be trended and compared against the alarm values or standards.
- There are only individual spectrum band values, which can be trended and compared against the alarms, usually defined and limited to experience with given machine types and fleet.

MODEL-BASED VOLTAGE AND CURRENT (MBVI) EXPERT SYSTEM

Based on Bently Nevada (2012), the Model-Based Voltage and Current Analysis (MBVI) Expert System uses 12 mechanical parameters, obtained from the Power Spectral Density (PSD) plot, sensitive to mechanical faults like unbalance, misalignment, looseness, transmission or bearing problems. The Expert System also uses 8 electrical parameters to feed the model, further classified in two groups: Internal and External. Based on created electrical model internal and external electrical faults are diagnosed, while other mechanical faults are diagnosed based on PSD plot. Internal electrical parameters indicate problems associated with rotor, stator, winding etc. External electrical parameters indicate electrical supply problems such as voltage unbalance, isolation problem of cabling, capacitor, motor connector, terminal slackness, defective contacts etc.

An example of Expert System results and automated advisory is shown in bar graph (Figure 9). Bar graph compares the signal of an equipment, collected during the analyzed period, with the closest fitting healthy baseline database. The bar graph represents the fault severities under different categories. Green dotted line represents the healthy average level of the closest fitting healthy baseline. There is "Caution" yellow region, which suggests attention and closer monitoring the fault parameters. The "High" red region suggests that values within this zone are normally considered to be of sufficient severity to cause damage to the machine. The example of Expert System automated report further contains Power Spectral Density (PSD) (Figure 2), used for detailed explanations of the findings. Recall that the PSD is calculated from the model residuals. The Expert System on bar graph may further suggests increased severity of the Internal and External Electrical faults, based on electrical parameters and the physics-based motor model.

Table of average electrical parameters (Figure 10) shows measured and calculated electrical values compared with reference thresholds, used for additional advisory of Expert System. The example of Expert System results further suggests if all the electrical values are within their expected range.

The motor waveform and the learned model of MBVI output waveform are subtracted, producing a residual current waveform. The residual waveform represents the error between theory and reality. There is two step model building process: model learning and model improving. During the learn period, the reference model is established. This reference model basically consists of model parameters, their mean values, and their standard deviations. During the improve period, while monitoring varying load conditions, the model is being improved, and model parameters updated. When learn and improve modes are completed, the model is compared with the fleet data (healthy baseline) from similar motors and similar driven equipment. If the learned model values exceed the threshold values, then an alarm is given. The final residual current curve is obtained (represented as blue line in the Figure 2 below), known as "Learned PSD" or "Equipment PSD". The residual current displayed in the frequency domain as shown below where x-axis is frequency (Hz) and y-axis is the standard deviation amplitude.

The monitor classifies PSD energy into 12 typical spectral frequency bands associated with particular fault classes: Loose foundation, Transmission elements, Rotor problems, Bearing parameters 1, Unbalance, Misalignment, Loose windings, Stator problems, Bearing parameters 2, Bearing parameters 3, Bearing parameters 4, Other problems.

The Energies (higher amplitudes, peaks) in the bands are automatically reflected to the associated faults and represented in the bar graph. "Normal" and "High" regions represent the deviation limits/thresholds from the healthy baseline (fleet data). If the equipment signal exceeds the “High” threshold for a particular frequency range, the monitor will trigger the associated alarm.

There are 18 mechanical and electrical parameters, which can be trended individually: Loose foundations, Unbalance/Misalignment, Transmission/Driven Equipment, Bearing, Rotor, Loose windings/Stator, Internal Electrical fault, External electrical fault, Other, Voltage, Current, Voltage unbalance, Current unbalance, Power factor, Active power, Signal Frequency, Motor status, Total Harmonic Distortion and all the harmonics. Trending these individual parameters displays the faults progressing over the time and interpolates when equipment will likely require action.

ROOT-CAUSE ANALYSIS

The MBVI method is demonstrated on the 11kW Turning Gear Motor installed on the Centreline Train. Turning Gear Motor (TGM) is 11 kW, 50Hz, three phase, four pole, asynchronous electric motor, with nominal speed of 1460rpm and 2.67% slip. TGM Drive End (DE) bearing is deep groove ball bearing, 6310-RS1-C3 type, with 9 rolling elements, grease lubricated. TGM Non-Drive End (NDE) bearing is deep groove ball bearing, 6308-RS1-C3 type, with 8 rolling elements, grease lubricated. TGM is transmitting the power through Worm Gear (60:1 ratio) to the main rotor of the Centreline Train, consisting of Steam Turbine-Generator-Gas Turbine rotor, turning it at 24rpm protecting the entire train from rotor bow.

To evaluate the sequence of the malfunctions, historical data was reviewed. The Power Spectral Density (PSD) plot from January 1, 2019 indicated a normal PSD curve, with no significant problems visible in the data (Figure 2). The measured instant PSD curve (red curve) is close to the baseline (blue curve). Later, on March 10, 2019 the PSD curve showed increase at BPFI frequency of NDE motor bearing, suggesting beginning of bearing deterioration. Amplitude levels in Misalignment band 2 and Rotor band 4 was yet normal. Then, the PSD plot (Figure 3) from December 12, 2019 confirms bearing problems (Band 12) and additional misalignment (Band 2) present, but still no rotor related issues (Band 4).

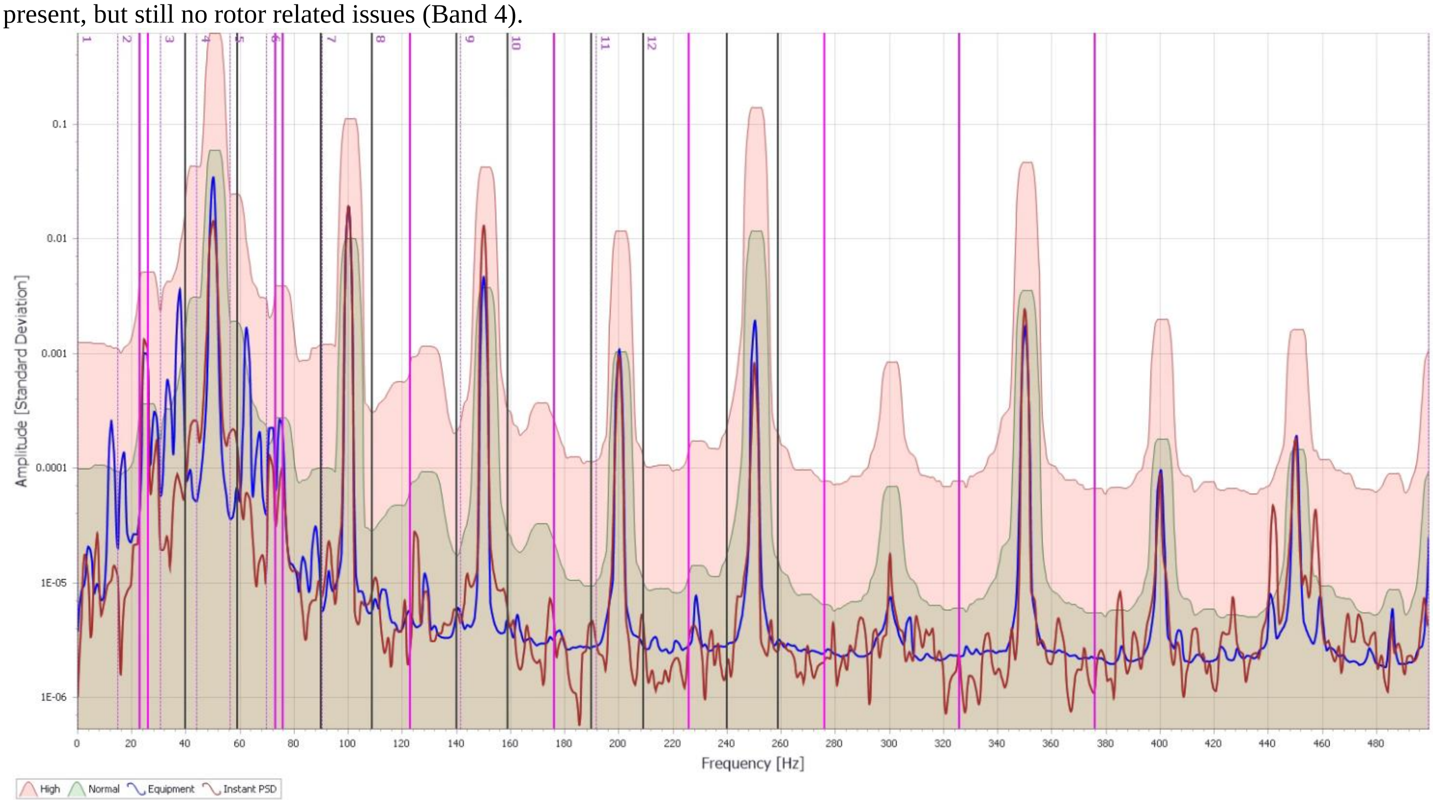

Figure 2: Power Spectral Density Plot, January 1, 2019; (pink colour – BPFI)

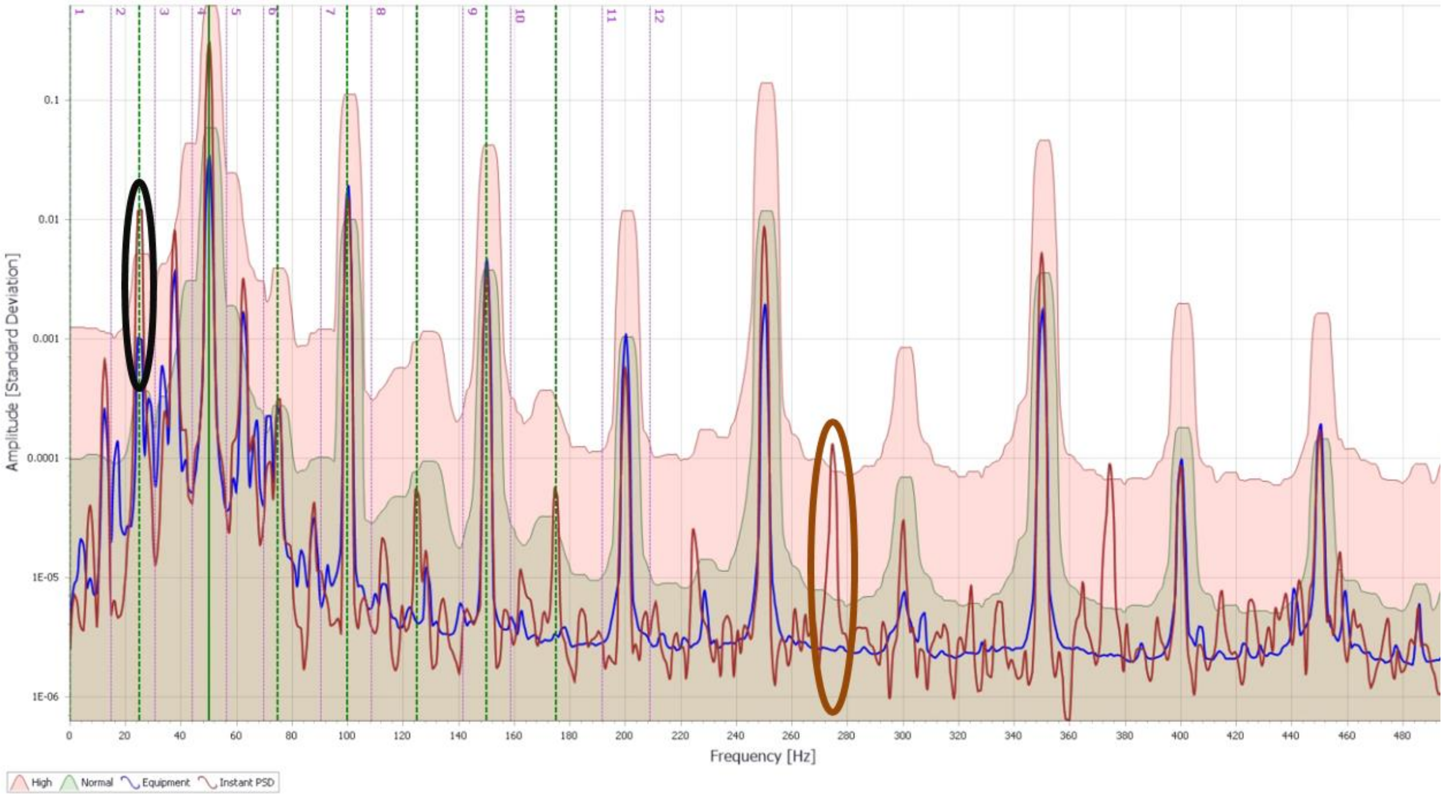

Figure 3: Power Spectral Density Plot, December 12, 2019; (green color – 1X harmonics)
Black oval – Misalignment band; Brown oval – BPFI of NDE bearing, 6308-RS1-C3 (8 Elements)

The PSD plot (Figure 4) from March 09, 2020 shows, in addition, significant increase of amplitude levels in the Rotor band (from 0.1 to 1), exceeding the Alarm threshold and indicating severe rotor problems. The amplitude levels in the Misalignment band and bearing BPFI band have stayed elevated as before.

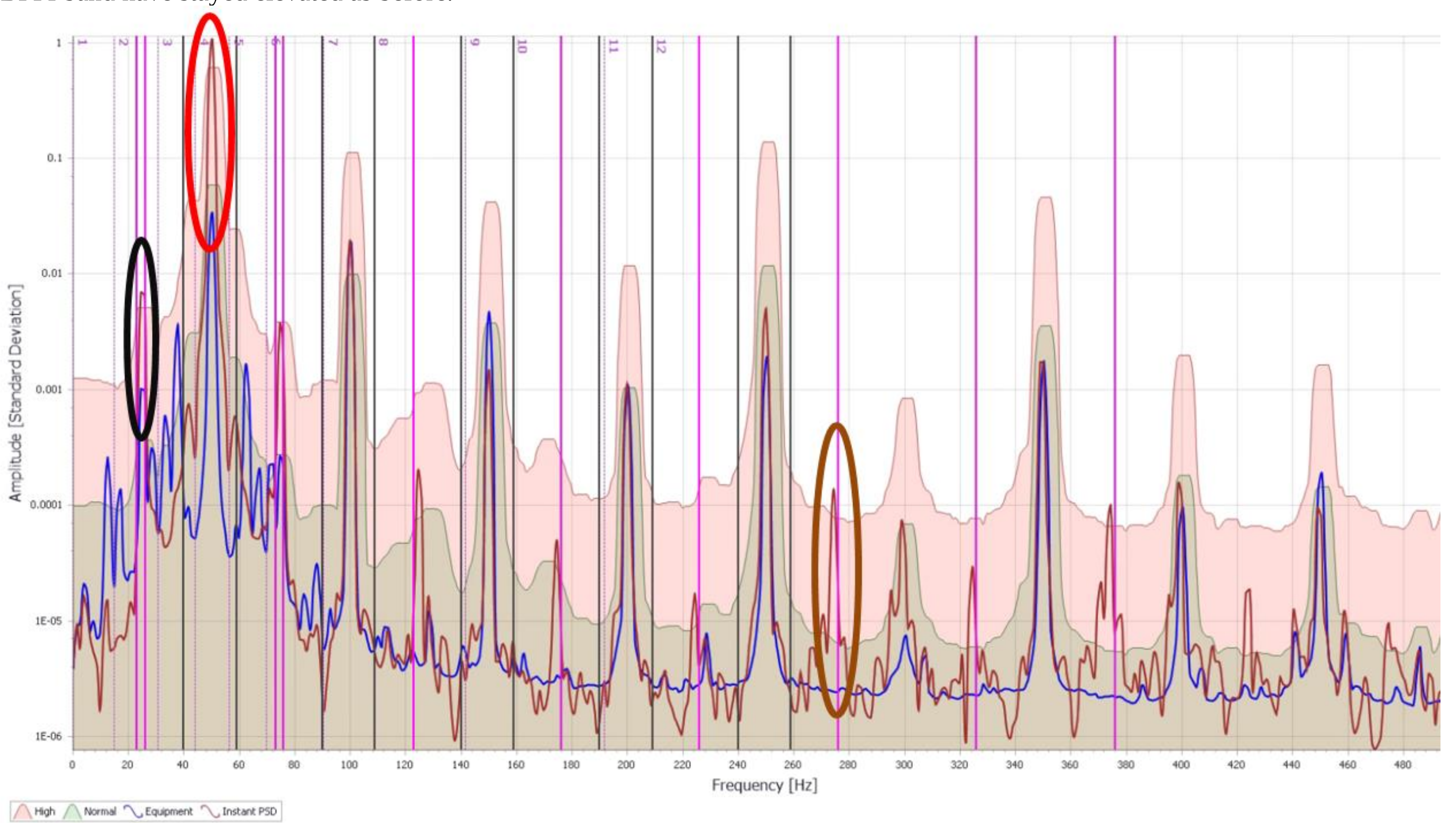

Figure 4: Power Spectral Density Plot, March 09, 2020; (pink color – BPFI)
Black oval – Misalignment band; Red oval – Rotor band; Brown oval – BPFI of NDE bearing, 6308-RS1-C3 (8 Elements)

The TGM stopped operating on May 24, 2020. The independent contractors were brought to site to investigate the issue and it was determined that there was a direct short to ground on the TGM preventing it from starting. The TGM had to be replaced.

After the motor dismantling and inspection, the motor NDE bearing was found collapsed, caused a mechanical rotor rub (Figure 5). The bearing rubber seal was discovered to be damaged when changing over units. There were the signs of oil in the motor stator windings and endshields found (Figure 6).

Possible reasons why the NDE bearing was damaged:

- TGM NDE bearing got dry, possibly due to being contaminated by the oil from turning gear assembly, after bearing seal damage.
- The bearing rubber seal was discovered damaged. The seal on the NDE side was found hardened, possibly due to high temperature and this allowed oil into the motor stator windings.
- The bearing rubber seal when replaced must be the correct type, capable of withstanding the oil category.

Figure 5: Turning Gear Motor as found damaged on May 24, 2020; NDE bearing was found collapsed

Figure 6: Turning Gear Motor as found damaged on May 24, 2020; The signs of oil in the stator windings and endshields.

The TGM was replaced in May 2020 with a refurbished motor from the warehouse, that had been stored on site for four years. The replacement TGM was in operation for approximately one month before another failure occurred. A root cause analysis became critical in order to decide if the recently installed TGM needed to be replaced again or if it could continue to operate somehow (e.g. in single-phase conection as an electrical test had showed an issue with the L2 phase coil).

Based on the historical data and the Model-Based Voltage and Current (MBVI) method used for root-cause analysis carried out the following conclusions were derived:

- The online MBVI Monitoring and Expert system indicated a significant rotor problem, and no stator related problems. As no stator issues were indicated, three phase operation was preferable as opposed to the suggested single-phase operation.
- Immediately, following the motor replacement (end of May 2020) on June 02, 2020, the Rotor Band Trend (Figure 7) showed significantly increased values (42 times above the alarm threshold). The highest values (61 times above the alarm threshold) are visible on June 6, 2020. Subsequently, the values decreased but remained at 36 times above the alarm threshold.
- The Power Spectral Density Plot (Figure 8) display the PSD from June 6, 2020, shows a significant increase of amplitude levels in the Rotor band 4 (42 times above the alarm threshold), suggesting possible rotor problem.
- The Stator Band Trend was well below the alarm threshold, which suggested a rotor related problem rather than stator.
- The Internal Electrical Fault Band and the External Electrical Fault Band Trends, corresponded with the Rotor Band Trend, and were significantly above the alarm threshold (36-50 times above).
- The Stator Voltage and Stator Voltage Balance Trends showed normal values.
- The Stator Current Trend showed higher values for current Is vs. Ir, It.
- The Stator Current Balance Trend showed current unbalance exceeding 5% threshold, close to 9% value.
- It was recommended to replace the TGM when a suitable opportunity allowed.

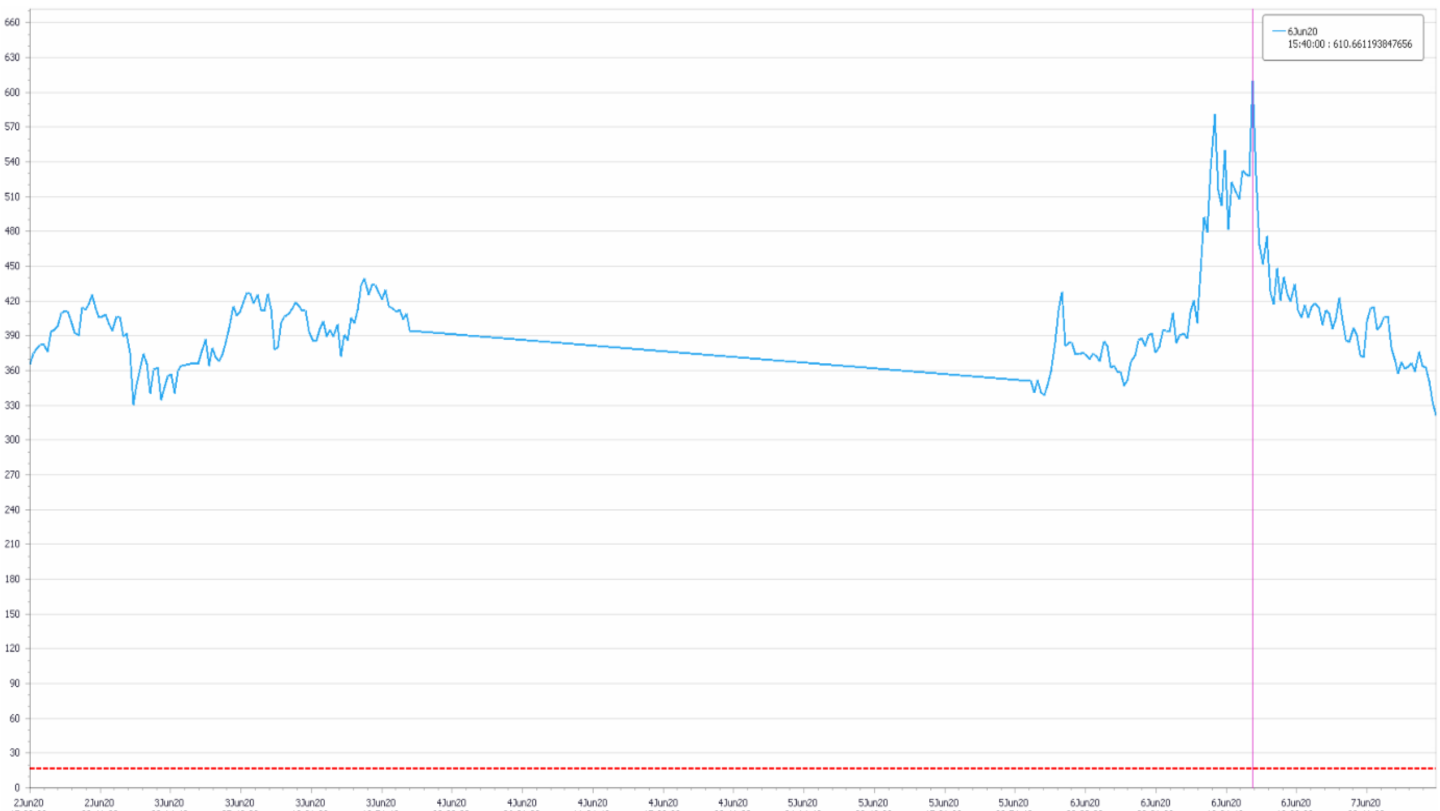

Figure 7: PSD Rotor Band Trend ; Red line – Rotor band alarm threshold

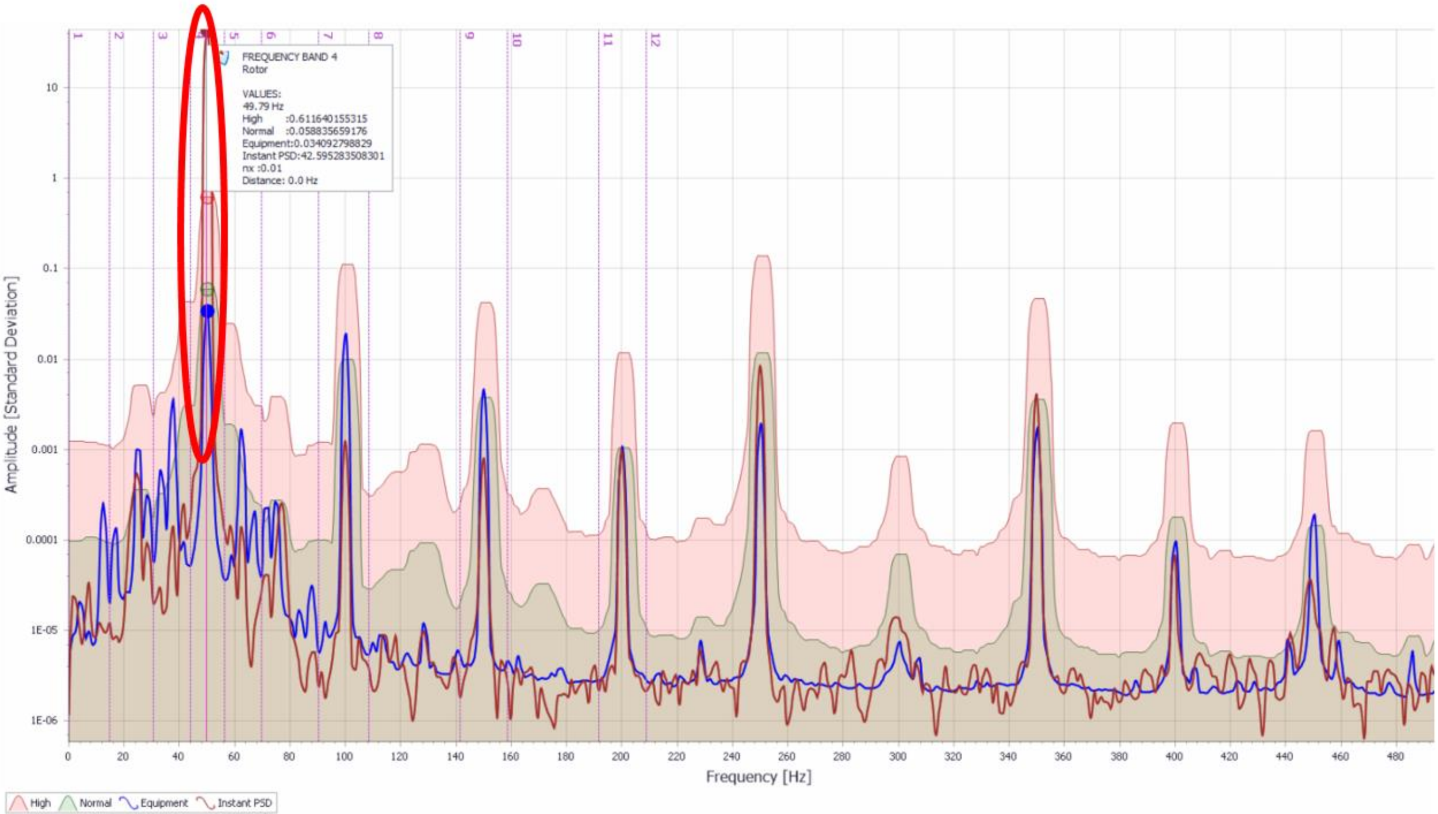

Figure 8: Power Spectral Density Plot; June 6, 2020; Red oval – Rotor band

The Model-Based Voltage and Current (MBVI) expert system Bar Chart (Figure 9) indicated enlarged Electrical Fault Indicators (internal and external). Electrical Internal parameters bargraph indicates problems associated with rotor, stator, winding etc. Electrical External parameters bargraph indicates electrical supply problems such as voltage/current imbalance, isolation problem of cabling, capacitor, motor connector, terminal slackness, defective contactors, etc.

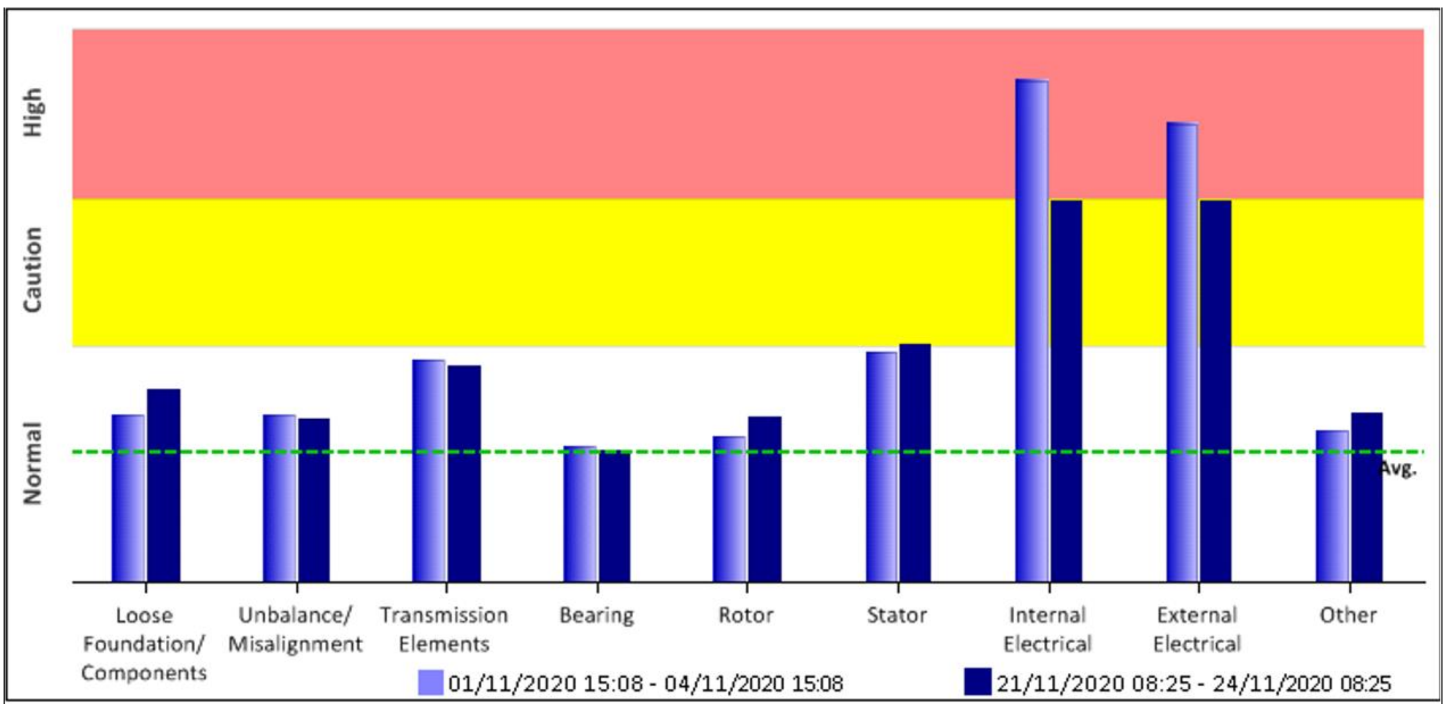

Figure 9: The Expert system Bar Chart

The Electrical Parameters table (Figure 10) showed increased Avg. Current Unbalance, above 5% (close to 9-12% value), in the yellow zone. This is supporting evidence for the elevated Electrical External parameters bargraph. Current unbalance causes motors to overheat and lose torque. Developing short circuit faults due to the degradation of isolation materials may also cause increasing or decreasing current unbalance over the time. Electric motors should not be operated with high current unbalance and must be checked for stator faults, short circuits, isolation faults, partial discharge. These checks were suggested and it was recommended to replace the TGM when a suitable opportunity arises.

Average Values of Electrical Parameters ☐ Instant ☑ 1D ☐ 1W ☐ 1M

Status	Name	Value	Reference
OK	Power Factor	0.96	
OK	Active Power [kW]	4.2	
OK	Reactive Power [kVAr]	1.1	
OK	Vrms(L-N) [V]	237	≤ Vn + 10%
OK	Irms [A]	5.8	≤ In + 10%
OK	V Unbalance [%]	0.69	≤ 2.0
Watch	I Unbalance [%]	9.7	≤ 5.0
OK	Frequency [Hz]	50	
OK	THD [%]	1.1	≤ 5.0
OK	3th Harmonic [%]	0.16	≤ 5.0
OK	5th Harmonic [%]	0.87	≤ 5.0
OK	7th Harmonic [%]	0.41	≤ 5.0
OK	9th Harmonic [%]	0.02	≤ 5.0
OK	11th Harmonic [%]	0.11	≤ 5.0
OK	13th Harmonic [%]	0.15	≤ 5.0
ELECTRICAL VALUES	Electrical values are outside of their expected range. They should be noted and watched to identify the cause.		

Current and Voltage Unbalances

☑ Current unbalance exceeds 5%. Check for stator faults, short circuits, isolation faults, partial discharge, etc. ***EEE:*** *Voltage and current unbalances cause heat and up to 3% loss in energy efficiency.*

Figure 10: The Electrical Parameters table

Based on Machindery diagnostics analyses, conclusions and recommendations, the Turning Gear Motor was overhauled and inspected on August 26, 2020. The inspection confirmed problems with both the stator and the rotor (Figure 11). The stator had significant amounts of oil contamination as a result of the bearing rubber seal hardening and thereby compromising the seal integrity. The NDE bearing housing and bearing showed signs of wear and need for refurbishment. The DE bearing appeared in good condition however, the bearing grease was in poor condition and was close to being ineffective. The seal on the DE bearing was hardened as well, possibly due to temperature and allowed oil into the windings.

The new motor was installed around the August 26, 2020 and replaced the refurbished motor installed previously in May (Figure 12).

If this refurbish TGM replaced only in May 2020 was not removed for the overhaul, the bearing had potential to collapse and cause a severe rotor rub which would result in the requirement for a complete electrical rewind. The 11kW Turning Gear Motor installed on the Centreline Train, consisting of Steam Turbine-Generator-Gas Turbine, represents the critical asset protecting the entire train from rotor bow.

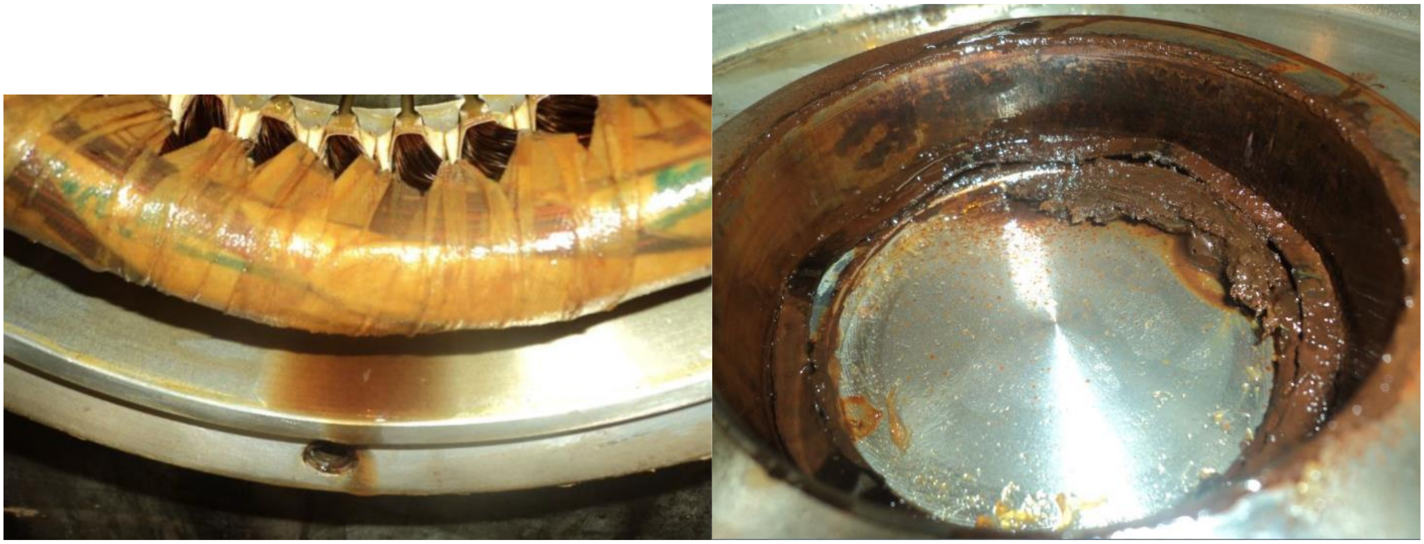

Figure 11: Turning Gear Motor as found damaged on June 6, 2020

Figure 12: New Turning Gear Motor installed on August 26, 2020

CONCLUSIONS

The paper discusses several fatal failures on the Turning Gear Motor (TGM) over the short period, resulting in two motor replacements. The 11kW Turning Gear Motor installed on the Centreline Train, consisting of Steam Turbine-Generator-Gas Turbine, represents the critical asset protecting the entire train from rotor bow.

The Turning Gear Motor was monitored by an online monitoring system using improved Motor Current Signature Analysis (MCSA), aka. Model-Based Voltage and Current (MBVI).

The paper outlines the Expert Diagnostics System's (based on MBVI) ability to distinguish automatically among different malfunctions. The Expert System uses the power spectral density (PSD) of the difference between the expected current obtained from the model and the actual current. These differences include only abnormalities generated by the motor anomaly. Therefore, they are immune to the noise or harmonics present in the supply voltages.

MBVI is a suitable alternative or complimentary monitoring method, which does not require any sensor installation on the monitored equipment. All the measurements are carried out remotely in the motor control cabinet. The MBVI uses dynamic motor currents and spectrums to identify electrical, mechanical or process problems. MBVI is especially attractive for inaccessible motor driven equipment, particularly in this case, where the electric motor is located in the closed turning gear assembly compartment of the Gas Turbine in the vicinity of the high temperature gases.

Use of the Model-Based Voltage and Current Monitoring and Expert system enabled an in-depth analysis and understanding of the motor condition without the need for intrusive actions, resulting in planned maintenance activities and associated reduced costs and downtime.

MBVI data analysis and inspection of the failed motors indicated that the root cause of the failures was related to the bearing rubber seal, it's hardening and thereby compromising the seal integrity. This resulted in significant amounts of oil contamination to the stator, and damage of the bearings due to misplaced grease lubrication, mixing with gear oil. Following the bearing damage, internal misalignment caused rotor - stator rub, resulting in rotor damage. Consequently, the TGM stopped due to direct short to ground on the TGM preventing it from starting.

Determination of the root cause facilitated the opportunity to review the seals and oil characteristics, with the possibility of design changes being implemented to reduce/eliminate similar future failures. It was recommended to upgrade and integrate the standalone MBVI monitoring and expert system into one system management platform, integrating all, motor current, vibration, and process data. It was also recommended to include MBVI monitoring system into the automatic protection system. It was suggested to reevaluate the TGM criticality, as the critical asset protecting the entire train from rotor bow, improve the overall condition monitoring strategy, ensuring regular TGM intensive care.

NOMENCLATURE

Acronyms

AC = Alternating Current
ASME = American Society of Mechanical Engineers
BPFI = Ball Pass Frequency of Inner Race
BPFO = Ball Pass Frequency of Outer Race
BSF = Ball Spin Frequency
CBM = Condition Based Maintenance
CT = Current Transformer
FC = Fundamental Component
FFT = Fast Fourier Transform
FTF = Fundamental Train Frequency
FIG = Figure
H = Horizontal direction
HPSO = High Pressure Send-Out pump
IEPE = Integrated Electronic Piezoelectric
LF = Line Frequency
LNG = Liquefied Natural Gas
LSL = Lower Specification Limit
USL = Upper Specification Limit
MBVI = Model-Based Voltage and Current Analysis
MCSA = Motor Current Signature Analysis
NPSH = Net Positive Suction Head
NPSHa = Net Positive Suction Head available
NPSHr = Net Positive Suction Head required
PPF = Pole Pass Frequency
PSD = Power Spectral Density
PSH = Principal Slot Harmonics
REB = Rolling Element Bearing
RMC = Remote Monitoring Center
RMS = Root Mean Square
RPM = Revolutions Per Minute
SD = Standard Deviation
SSA = Supporting Services Agreement
SWLP = Sea Water Lift Pump
SWVP = Sea Water Vaporizer Pump
TEM = Thrust Equalizing Mechanism
V = Vertical direction
VA = Vibration Analysis
WH = Winding Harmonics

Variables

f = supply frequency
f_r = rotor rotating frequency
f_s = slip frequency
f_O = REB Outer Race Frequency
f_I = REB Inner Race Frequency
f_B = REB Ball Frequency
f_C = REB Cage Frequency
n = number of poles
N_b = number of rolling elements
N_r = rotor rotating speed
N_s = field synchronous speed
p = number of pole pairs
R = number of rotor slots
s = slip

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