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IMPROVING TURBOMACHINERY HEALTH MONITORING USING ADVANCED SHAFT TELEMETRY SYSTEM

S.H. Hesler
Electric Power Research Institute
Charlotte, NC 28262

C. A. Suprock PhD
Suprock Technologies LLC
Exeter, NH 03833

ABSTRACT

Turbine-generator shaft systems used in power generation applications are exposed to degradation mechanisms that could result in high consequence failures if not discovered prior to damage accumulation. Grid-induced torsional vibration, growth of cracks in the shaft forging, and large blade vibration are some examples of degradation that remains unmonitored in most commercial plants today. In many cases, the sensing and subsequent trending of high-quality vibration data obtained directly from the shaft surface can be the basis for a decision to continue to operate versus inspect or repair. Detection of small changes in torsional and lateral vibration mode properties can be sensed at a single shaft location and trended using techniques such as Advanced Pattern Recognition to reveal the very early signs of rotor distress.

Contemporary barriers to widespread application of wireless shaft vibration measurements for health monitoring were studied and addressed in the development of the Turbine Dynamics Monitoring System (TDMS). The resulting design evolved around the industry need for low sensor maintenance, high reliability, ease of installation, and high data quality to enable early detection of critical component changes. These improvements capitalized on advances in strain gage and accelerometer technology, micro-telemetry, radio-frequency power systems, and advanced adhesives for installation. The new system has been successfully applied in the field on large steam turbine-generators to detect grid-induced torsional vibration.

The paper will describe background of turbine-generator torsional vibration as well as the technical features of this advanced telemetry application with examples of field data.

INTRODUCTION

Industry Need

Turbine-generator shaft systems used in power generation applications are exposed to degradation mechanisms that could result in high consequence failures if not discovered prior to damage accumulation. Grid-induced torsional vibration, growth of fatigue cracks in the shaft forging, and blade vibration are some examples of degradation that remains unmonitored in most commercial plants today. In many cases, the sensing and subsequent trending of high-quality vibration data obtained directly from the shaft surface can be a viable basis for early detection of shaft component health degradation. Small changes in torsional and lateral shaft mode frequency values can be sensed at a limited number of shaft locations and trended using techniques such as Advanced Pattern Recognition to reveal early signs of rotor distress. This paper describes the development and early field application of a new wireless sensor package that will benefit turbomachinery condition monitoring efforts in power generation. Initial field applications have been applied to measurement of torsional natural frequencies of large steam turbine generator sets to ensure compliance with ISO Standard 22266-1:2009. Future applications are envisioned to include tracking of fatigue damage accumulation due to grid transients and monitoring for evidence of cracked shaft elements.

Previous Work

Much of the available literature on the subject of turbomachinery shaft torsional vibration relates to assessing the impact of the electrical grid on the turbine-generator. Walker [1] provides the fundamentals of turbomachinery shaft torsional vibration, covering both the analytical modeling and field measurements. Giesecke [2] describes a case study involving large steam turbine torsional modeling and testing. The nature of electrical grid interaction with large generators is covered by EPRI in a 2006 report [3]. The use of measured shaft torsional vibration data obtained from a nuclear steam turbine to quantify fatigue life consumption of attached blades is described in a 2012 publication [4]. A 2013 thesis document submitted by Bhana [5] describes an experiment to detect shaft damage using a range of monitoring technologies, including strain gage telemetry. This work revealed the need for high sensitivity strain measurements, with low measurement noise floor, to enable clear detection of the shaft natural frequencies without need for external excitation.

More recently, alternatives to direct shaft sensing of torsional vibration are described by Luo et.al. [6]. This non-contacting technique uses phase demodulation of a high time resolution data stream obtained from a fixed sensor placed in the proximity of a toothed wheel or optical barcode on the shaft surface.

Based on an assessment of the previous research, EPRI initiated the sensor and telemetry development effort in 2013 that is described in this paper. The objective was to develop and commercialize a system with attributes needed for broad application to turbine-generator shaft health monitoring. This system is referred to herein as the Turbine Dynamics Monitoring System (TDMS) and is currently addressing the growing requirement for verification testing of shaft natural frequencies.

NOMENCLATURE

TDMS	Turbine Dynamics Monitoring System
ISO	International Standards Organization
LP	Low pressure
m/s^2	meters per $second^2$ acceleration
HDI	high density interconnect
LED	Light emitting diode
kPa	Kilopascal pressure
°C	Degrees Centigrade temperature
RPM	Shaft speed in revolutions per minute
Hz	Frequency in cycles per second

TURBINE-GENERATOR TORSIONAL VIBRATION

A brief introduction to the subject of turbine-generator shaft torsional vibration is provided in this section. This background will provide the basis for understanding the TDMS attributes.

Mechanism

Large turbine-generator sets are characterized by a series of relatively stiff rotor body elements, connected by shafting and bolted flanges. The resulting mass and stiffness distribution produces a multitude of system natural frequencies both above and below the electrical grid frequency. As the unit size increases, the larger blades in the low-pressure (LP) turbine contribute additional flexibility which alters the system torsional modes slightly. Many large turbine-generator sets have torsional vibration modes in proximity of twice electrical grid frequency. These modes often include LP blade motion, which results in the potential to contribute to blade fatigue life consumption if excited over sustained time periods [1, 2]. Twice grid frequency torsional excitation of the generator field is produced by the small electrical phase imbalance that is present in all operating units due to the unequal single-phase loads [3]. Electrical arc furnaces in steel mills, if located nearby the power plant, have the potential to produce relatively strong torsional excitation at twice grid frequency as well as transient torques. In addition to sustained torsional excitation at twice grid frequency, grid transients also have the potential to produce high transient response levels in the turbine-generator. The light mechanical damping inherent to turbine-generators results in a long transient response time and accumulated fatigue damage. In addition to excitation near twice grid frequency, subsychronous excitation (below grid frequency) can occur as a result of the electrical transmission system and operation. Transmission system electrical resonances, if not adequately damped, can excite the turbine-generator mechanical system [4]. Finally, large steam turbine-generators are being subjected to load sequestering and cyclic power contribution from intermittent renewable generation sources. This leads to operation of the steam path in states outside of the original design basis which may exacerbate flow dynamics issues such as blade flutter in the last stage blades at high backpressure operation.

History

A 2005 EPRI report describes several forms of grid-induced torsional excitation and lists twelve cases in which damage to turbine-generator components at a commercial power plant were attributed to torsional excitation [7]. In this sample of twelve industry events over a 33 year time period, there were five reported events at coal-fired units, and seven events at nuclear units. Of the twelve reported events, five involved damage to LP turbine blading including some cases of blade liberation. Four cases involved fatigue damage to the shaft elements in the coupling keyways. Finally, two cases involved fretting damage to the shrunk-on generator retaining rings. It is important to note that in all cases, there is potential for significant damage and injury resulting from failure of a high-speed turbine-generator shaft component. An example is the 1985 failure of Taiwan Power Maanshan Unit 1, a 1057 MVA unit that experienced eight LP turbine final stage blade failures due to the cumulative effects of off-frequency operation on a torsional mode near 120 Hz. The subsequent repair of the shaft train required eleven months.

During the time period that damage was accumulating in these units, there were no on-line monitors installed that could have detected the vibration. Instrumentation was applied in most cases following the discovery of damage to these units.

Methods of Shaft Torsional Vibration Detection

Traditional shaft bearing vibration instrumentation monitors the relative radial movement between the shaft and bearing housing. Any torsional vibration of the shaft would not be detected with these probes. To detect shaft torsional vibration requires a sensor that can measure either shaft twist (strain) or tangential oscillation of the shaft surface. Using shaft surface strain to detect twist provides good vibration sensitivity in situations where the amplitude is low. A full-bridge configuration utilizing semiconductor strain gages is recommended for maximum sensor performance.

A second option for torsional vibration measurement is to detect shaft surface motion (velocity or acceleration) in the tangential direction. Compact accelerometers such as semiconductor strain based devices can be attached directly to the shaft to measure tangential motion. Alternatively, a non-contacting method using high time resolution keyphasor can be used to measure shaft surface velocity [6]. For this approach, either a multi-toothed wheel or a bar-code strip is attached to the shaft surface. A proximity probe, or alternatively an optical probe, is positioned near the shaft surface to detect the passing of gear teeth edges or the light-dark transitions of the bar-code tape, providing multiple pulses per revolution. A phase demodulation process then is applied to produce shaft angular position as a function of time, from which the time series derivatives yield shaft surface velocity and acceleration.

Considerations in Selection of Vibration Detection Scheme

The choice of a strain-based or motion-based sensing system should be made based on knowledge of the mode shape of the torsional mode(s) of interest. In general, for a desired sensor location along the turbine-generator assembly, the shaft surface might exhibit primarily *strain* (twist) or angular *motion*. The extent of shaft twist and surface motion at each potential sensor location will depend on the deflection shape for each mode.

Turbine-generators offer very limited options for physical access the shaft surface. Inside the turbine casings, and inside the generator are not yet considered feasible locations for torsional sensing. Each of the 10-20 torsional vibration modes of a large turbine-generator that typically occur in the frequency range of interest (between 2X and 3X shaft speed) have a unique mode shape. The result is that if only a single sensor type (either strain-based *or* motion-based) is used, it is very likely that not all vibration modes will be clearly observable at a single sensor location. The use of multiple sensor locations along the shaft has been a commonly-used option to avoid missing the effect of some vibration modes in this situation. This option, however, increases the cost and complexity of the sensor installation and upkeep.

A second option that avoids missing modes is to integrate a strain-based sensor *and* a motion-based sensor (accelerometer) into a single module that is attached to the shaft in one operation. This integrated option has the advantage that only a single shaft location needs to be instrumented without concern over missing any vibration modes. The combination of strain and acceleration measurements in a single module is a key feature of the EPRI Turbine Dynamics Monitoring System (TDMS).

Attributes of a Continuous Shaft Vibration Monitor

The following are considered key attributes to meet the needs of a turbine-generator shaft health monitoring system.

- High sensitivity and low noise floor to enable clear identification and monitoring of all vibration modes.
- If shaft-mounted sensors are employed using telemetry, the powering of these sensors should be uninterrupted and not require batteries that need periodic replacement.
- The capability to acquire high time-resolution data as well as high-resolution spectral data so that small mode frequency shifts can be observed.
- An integrated sensor suite consisting of a shaft strain measurement, and shaft surface motion measurement, to cover all possible mode shape characteristics.
- A reliable method for attaching the sensors to the shaft surface that preserves the measurement quality and can withstand the high centrifugal loading due to shaft rotation. The attachment method must be optimized to allow rapid installation during short time periods of availability within maintenance outages. The environment in the shaft sensor location could be as hot as 100°C and include oil mist from nearby bearings.
- Analysis and trending of the continuously acquired vibration data should be automated. Software should identify and track each mode to flag any small changes that could be the result of structural degradation. Integration of this data with power plant process data would allow application of advanced pattern recognition tools. Transient vibration events can be logged and archived to assess impact on shaft components.

DESCRIPTION OF TURBINE DYNAMICS MONITORING SYSTEM

Sensors

The TDMS contains a suite of sensors in a single module that measure the turbine shaft dynamic signals of interest, internal operating conditions of the telemetry hardware, and timing/phasor signals [8]. The ability to measure turbine dynamic signals is supported by the *internal* sensors that assure that hardware operation is within nominal parameters and that the dynamics sensors are passing unit tests. The phasor sensors allow for time synchronization of multiple separate modules using an externally applied optical strobe.

The dynamic sensors consist of strain gage bridges and two accelerometers. The strain gage bridges are configured to separately detect rotor torsional (twisting) and lateral (bending) strain. The accelerometers are configured to measure tangential and radial surface acceleration. The internal sensors consist of current sensors, voltage sensing, resistance sensing, and temperature sensing.

By sensing four signals of motion and torsion at the shaft surface, the TDMS is designed to capture a comprehensive display of the rotor dynamics. This is an advantage for the TDMS to be located in a single axial location without regard to location in the mode shapes. Because energy is conserved, vibrational modes are active in elastic, kinematic, or combined behavior.

Internal sensors allow for unit tests upon the strain gages and accelerometers to ensure that the elements are not damaged and that the four vibration signals are in a reliable state. This feature is important for long term critical measurements since the TDMS is continually subjected to centrifugal acceleration between 22,000m/s^2 and 50,000m/s^2. These internal measurements are designed to capture granular information on sensor health such as the resistance of individual strain gage elements.

Sensor technology

The dynamic sensors are constructed from semiconductor strain gages. This permits high signal to noise ratios, and a gage factor approaching 150 for elastic strain measurements. Likewise, the accelerometers are built from semiconductor strain gages on silicon beams. The resolution of signals from these sensors corresponds to 0.001 microstrain.

The sensor modules are built as complete units in a proprietary surface mount process. The semiconductor strain sensors are mounted into packages that can be attached to a printed circuit board. The outcome of this is precision integration to the package without complex manual wiring of gage lead wires or compensation completion packages.

Telemetry

The telemetry is constructed from HDI (high density interconnect) PCB that integrates the sensors, analog circuits, and digital circuits into a single package. The shaft dynamics sensors are integrated as surface mount components into the design.

The sampling process of each sensor occurs time synchronously at a local rate of either one million samples/second or 128,000 samples/second, depending on the telemetry module hardware configuration. This signal is subsequently decimated to a bandwidth to match analog antialiasing filters and, ultimately, matching the mechanical bandwidth of the system.

A sampling rate of up to 7800 samples/second is available from the telemetry on-air. This is sufficient for systems having mechanical vibration that is under 400Hz, with information of interest typically being under 200Hz. The frequency resolution of the system is typically 0.0017Hz when data is captured in 10-minute time windows, however the frequency resolution is dependent only on the time window of the data sample.

Excitation

Power excitation is provided through radio. Unlike traditional methods of battery or inductive excitation, this provides several advantages in a steam turbine-generator environment. The use of radio in the TDMS is a response to contemporary issues with battery life and the concern of electrolyte contamination in the turbine oil or steam path. Radio does not require tight clearances and precise axial antenna location that traditional inductive excitation requires. Furthermore, the rotor-mounted antennas such as that shown in Figure 1 are compact and can be installed without 360 degree access to the rotor. This is a response to issues with contemporary telemetry approaches relying on inductive ring antennas in a circumferential configuration. The TDMS hardware broadcasts digital information, including the measured shaft vibration data, over a radio signal using the same multi-band antenna.

Figure 1 – On-rotor antenna configuration

Packaging

The packaging of the TDMS eliminates the need to apply strain gages the rotor surface in the field, saving time and improving reliability. The package contains all sensors in a solid unit, shown in Figure 2, with only the interconnections to antennas exposed for field assembly. The package mechanically amplifies the surface strain through the application of a stress concentration near the strain sensor location in the module package.

Light pipes are exposed in the face of this package for visual LED indicators of status.

Figure 2 – Telemetry modules, waveguides, and antenna components.

Rotor attachment

The shaft attachment of the TDMS is achieved through a proprietary bonding process. This process leverages significant advancements in bonding methodology to produce a fully degassed and decontaminated bond line, as shown in Figure 3. The surface attachment produces a bond that has been tensile tested to 50,000 kPa at 80°C. Applications testing of this attachment methodology has been conducted in spin pit survival testing to 6000RPM at 540 millimeter diameter in atmospheric pressure. Typical applications of the TDMS are 450-900 millimeter diameter at shaft speeds of 1800 RPM for 4 pole generators and 3600 RPM for two-pole generators. Plant overspeed test conditions may reach 3960RPM in a two-pole system. The spin pit testing has confirmed a design factor of at least two for the highest loaded field application in a full-speed rotor in overspeed. The testing verified not only the bond strength, but all the module and antenna mechanical connections as well.

The most important aspect of the rotor attachment is the elimination of surface welding which has been documented to produce changes in microstructure and local hardness, potentially leading to micro cracking of the shaft surface. Stress cracking and fatigue crack propagation is a serious consideration in steam turbine-generators. Traditional methods employ welding to attach strain sensors.

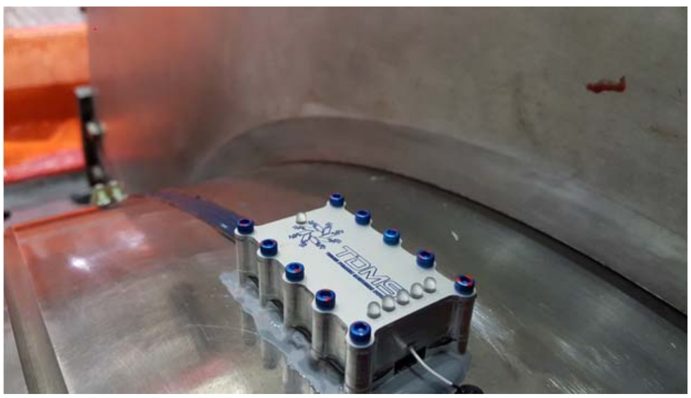

Figure 3 – Telemetry module attached to rotor surface.

Typical installation process

The installation process of the TDMS begins with surface preparation by light abrasion of surface contamination, oil varnish, and oxide layer. Once the surface is prepared mechanically, a solvent cleaning is applied to the rotor area where the bond will be applied. The telemetry package is applied with a degassed proprietary adhesive process. Once the adhesive is cured (typical cycle time is 2-3 hours) the telemetry is connected to antenna components and the system can be run immediately. Figure 4 shows the bonding setup with mechanical setup jigs built to apply the telemetry components. Using a digital controller, the set up jigs are monitored for temperature, adhesive hardness, and bonding cure time.

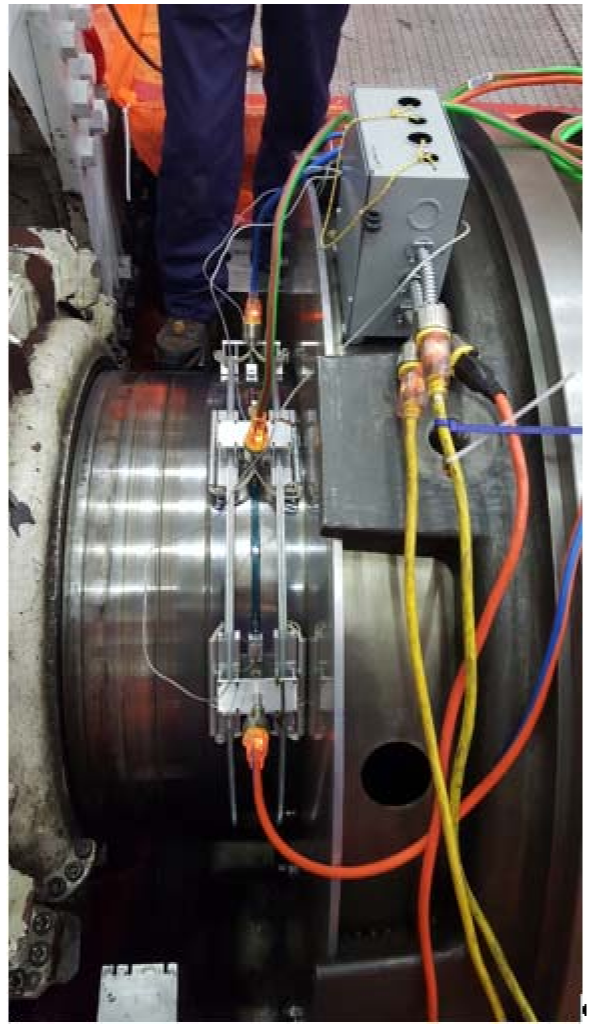

Figure 4 – Installation of two antennas and telemetry module on a 900mm diameter generator input shaft

SUMMARY OF ADVANCES EMBODIED IN TDMS

The TDMS system was designed to solve challenges experienced during the installation, data collection, and longevity of traditional steam turbine-generator torsional measurement systems. The TDMS leverages modern telemetry technology to survive the conditions of steam turbine-generator systems without relying on limiting features such as batteries or close inductive coupling. The advancements may be presented by the contemporary problems that they are intended to address:

- Elimination of on-rotor welding. This addresses significant concerns with crack growth related to the welds applied with traditional telemetry attachments.
- Longevity of the system, without relying on batteries in the telemetry.
- Elimination of an inductive data or power ring. This addresses axial thermal growth and position concerns in tight shaft access conditions.

- Elimination of a tension-based strap. This addresses concerns with diametric limits as well as mechanical failure modes and personnel safety related to strap tension.
- Elimination of a split ring collar design. This addresses limits in the centripetal loading limits of this approach, and eliminates need for a long lead-time collar component.

EXAMPLE DATA FROM PROTOTYPE INSTALLATIONS

Data acquisition attributes and options

The data acquisition interface for the TDMS is focused on initial display of the time data and accompanying plot of frequency information. The signals for all telemetry sensors are being captured digitally and stored to a computer hard drive. The data acquisition interface also allows for the telemetry to execute self-test functionality. The approach to having data displayed in real time serves the purpose of 'reality checking' the incoming data to ensure sensors are operating properly. It is also advantageous to display information if monitoring decisions are expected near real time.

The approach to saving data is to save all raw packet data from the telemetry so that it may be accessed at a later time. This choice was made to better serve analysis approaches without making assumptions about how the data should be reduced during the data acquisition process. Subsequent analysis can be made on the data, retrieved for historical reasons, or archived. This was found to be useful for report generation as well as looking at the data comparatively to observe changes over time.

Example plots

The shaft vibration data retrieved from the TDMS system shows the dynamic behavior of the steam turbine-generator with a high dynamic range. Mechanical vibration features such as that shown in Figure 5 are useful for understanding the behavior of the entire rotor train. Particular attention is paid to the vibration modes near excitation sources such as 60Hz and 120Hz, as frequencies near these points may be indicative of high vibrational energy that can cause fatigue damage to turbine blades in a 60Hz electrical grid.

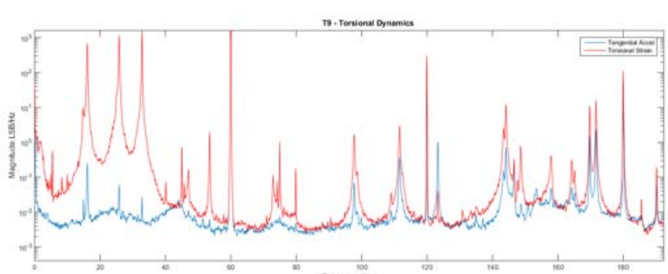

Figure 5 – Spectral plot of large steam turbine shaft torsional vibration, including both torsional strain and shaft surface tangential acceleration

The sub synchronous modes (those below grid frequency) are excited by sources such as transmission line resonance and grid behavior. These modes will exhibit high energy in torsional vibration. In some cases, the sub-synchronous modes can have magnitudes high enough to produce damage to sensitive components such as generator retaining rings and couplings.

The modes most important to observe are those involving blade root strain and cyclic fatigue that can lead to blade liberation events. In the figure above, there is a mode that is being exited at approximately 123Hz, close to the 120Hz grid excitation. Because the frequency is close to excitation, this is a mode that is important to understand through OEM or third party analytical work. In this case the mode was a generator dominated torsional mode that may cause significant damage if it approaches the excitation frequency and gains energy.

The ability to measure both kinematic and elastic dynamics is paramount in a steam turbine-generator telemetry. As shown in Figure 5, The TDMS had captured both torsional strain and tangential acceleration. At the axial location in this test, the tangential acceleration signal was substantially higher than the torsional strain signal. This is important since a traditional single-type strain measurement would have required two separate installation axial locations to capture this mode with confidence.

These measurements can be illustrated by a spectrogram of the dynamic data from any channel of the TDMS telemetry. A spectrogram is able to show features of time variant frequency behavior. This can be a valuable way to illustrate subtle changes in frequency such as effects of turbine-generator warming. The spectrogram is also effective at identifying significant torsional behavior during ramp-up and run-down. Similar to a turbine blade Campbell diagram, this data can be used to better understand the rotor dynamics and to confirm torsional behavior of the observed modes.

The example spectrogram in Figure 6 below is obtained from an 800MW turbine generator during a unit trip event at 400MW. The effects of stress stiffening in the blades can be observed during the ramp-down, as several modes between 120 and 200Hz are changing frequency. Viewing the data in this way can be essential for determining which spectral indications correspond to shaft torsional modes, shaft lateral modes, and modes involving the large blades. This supports accurate modeling efforts of the turbine-generator if design revisions are required.

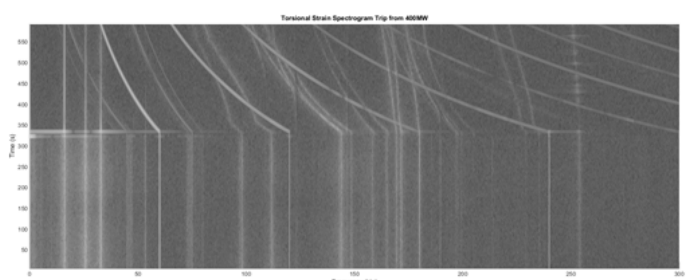

Figure 6 – Spectrogram of shaft torsional strain showing changes in frequency as a function of shaft speed following a unit trip

FUTURE DEVELOPMENT AND APPLICATIONS

The initial TDMS applications have been on steam turbine generator sets requiring verification that torsional natural frequencies are outside the twice grid frequency exclusion zone in accordance with ISO Standard 22266-1:2009. These first applications will be the basis for assessing long-term durability of the sensor hardware and attachment methodology. Future opportunities for long-term monitoring of turbine-generator shaft system health by tracking changes in natural frequencies will be pursued in parallel with development of automated data analysis software. This software should include a data feature extraction capability to identify and trend torsional mode frequency values from averaged spectral plots. The ability to pinpoint location of shaft damage will depend on the pattern of mode frequency changes and could theoretically be aided by results of torsional computer model parametric studies. In other related EPRI research, the TDMS will be used in field research to verify the potential to detect large LP turbine blade flutter events using only shaft measurements.

Other potential power generation applications include monitoring of combustion turbine generator sets to detect early signs of compressor blade clashing, compressor surge, or rotating stall events. Any condition occurring inside the combustion turbine that results in either transient torque or changes in harmonic torque on the generator connecting shaft will be possible to detect outside the turbine casing using the TDMS. A hydroelectric turbine generator trial monitoring application is also being planned currently. In this application, the TDMS attached to the shaft connecting the turbine runner and generator rotor is expected to reveal torque fluctuation changes caused by cavitation and anomalies in wicket gate condition or controls.

CONCLUSIONS

Several technical barriers to the increased use of direct shaft vibration sensing have been addressed in the recent development of the TDMS. Initial field applications demonstrate that the instrumentation is robust and sensor installation does not significantly impact the power generating unit availability. TDMS is a good foundation for future work on characterizing turbine-generator rotor degradation through the automated trending of high-resolution shaft vibration data.

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