Monitoring of Generator Stator End – Winding Vibration
How Reliable Are Existing Monitoring Systems?

EPRI
Generator Predictive Maintenance and Refurbishment
January 15 – 18, 2000 New Orleans, LA

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ABSTRACT

The economic performance of turbo generators and hydro generators can be enhanced considerably using on-line monitoring techniques. Parameters routinely monitored on-line include vibration signals, temperature, hydrogen pressure, hydrogen purity, flow rate, partial discharge, shaft voltage and field winding shorted-turns. These data are used for condition assessment of the entire generator.

Vibration, especially stator end-winding vibration, is an extremely important index of the overall soundness of rotating electrical machines and can be used for the early detection of abnormalities and trouble. High vibration can lead to loosening of the entire end-winding support system, deterioration of supports, insulation wear, rupture of coil conductors or fatigue cracking of conductors. All of these conditions require extensive out-of-service repairs.

In recent years Fiber Optic Vibration Systems have been developed to measure the stator end-winding vibrations in high voltage generators where conventional hardwired transducers cannot be safely mounted. Because of their importance, vibration process data are frequently integrated into the on-line monitoring system of many generators. A modern Fiber Optic Vibration System provides a data base which is helpful in anticipating generator end-winding vibration problems and predicting future maintenance needs, extending inspection and minimizing down time for maintenance.

The generator end-windings of the stator experience forced mechanical vibrations during operation. The frequency of vibrations excited by the stator current is twice the electrical synchronous frequency of the generator (120 Hz in the United States). In addition, single frequency vibrations (60 Hz) can be transmitted from the rotor to the stator end-winding support system. These two vibration sources are superimposed on one another and in some cases, displacements produced by the single frequency approach, or even exceed displacements produced by the double frequency vibrations

Most installed fiber optic sensors pick up only the double frequency vibration (120 Hz) and thereby ignore rotor-induced phenomenon. These sensors do not give a full or accurate picture of the total vibrations exciting stator end-windings. Because end-winding mechanical stresses are defined by the total vibration amplitude, accurate stator end-winding lifetime assessment requires monitoring of the entire spectrum of frequencies exciting the end-winding.

In many cases the composite peak-to-peak end-winding deflections exceed manufacturer's established limits and concern must be expressed. Measuring results confirm that 60 Hz vibrations affect stator end-winding lifetime and that modern reliable instrumentation should be available to monitor this condition.

This paper describes a Fiber Optic Vibration Sensor System that is capable of measuring vibrations at all frequencies. The paper provides an example of an operating generator where a newly installed system revealed significant 60 Hz vibration which had been undetected using the previous sensors. Displacements resulting from 60 Hz vibration – previously assumed to be negligible - are shown to be comparable in magnitude to those of the 120 Hz vibration and must be taken into consideration. Measuring results confirm that 60 Hz vibrations affect stator end-winding lifetime and that modern reliable instrumentation should be available to monitor this condition.

FIBER OPTIC VIBRATION SYSTEM

On-line monitoring system can considerably enhance the economical operation of turbo and hydro generators. Vibration and process data (e.g. temperature, partial discharge, hydrogen pressure, hydrogen purity, flow rate, shaft voltage and field winding shorted-turns etc.) can be monitored and used for evaluation of complete generator condition. This is very significant when users tend to stretch the overhaul intervals more and more: ten (10) to twelve (12) year intervals are not rare.

Since vibrations - particularly in stator end-windings - are very important for the detection of premature anomalies and problems, vibration measurements are vital in evaluating the generator condition. Stator end-windings are excited by both electromagnetic and mechanical forces during operation. Electromagnetic vibration amplitudes are proportional to the square of the generated current and the frequency is twice the electrical line frequency. On end-windings with loose supports, larger vibration amplitudes can be measured at partial load than at full load. High end- winding vibration quickly leads to loosening of the end-winding basket, insulation abrasion or cracks, as well as fatigue rupture of bars and solder links. Any of these failures entail long shutdowns and considerable repair costs. Consequently, a vibration monitoring system not only provides valuable data to plan revision and maintenance measures, but also helps reduce downtime in case of failure shutdowns.

Because end-winding vibration depends on generator operating conditions, a reliable monitoring system was designed to integrate additional process parameters (Fig. 1). It allows trending and statistic reports regarding the end-winding vibration behavior. This provides comprehensive data presentation correlated with machine operating conditions without the long and difficult interpretation of printed data.

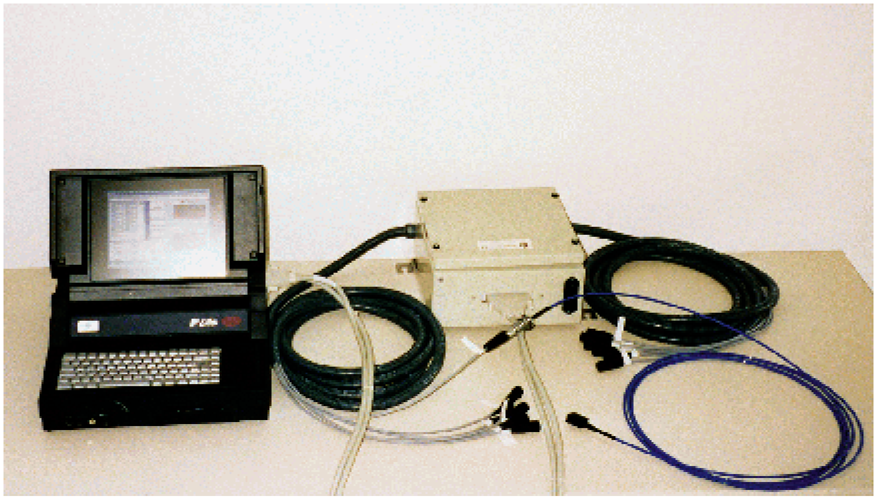

Fig. 1: Fiber Optic Measuring System

A typical fiber optic accelerometer is shown in Fig. 2. Its uni-body design consists of a small size sensor head of non-conducting material, a fiber optic cable, and a feed-through connector with built-in opto-electronic circuitry. It is sensitive to vibration in a single axis. The sensor head is located at the end of a three single strand, multimode, optical fiberglass cable. One fiber carries the light generated by the conditioning electronics for illumination. The sensor head returns two optical signals of variable intensity through the remaining fibers. When the fiber-optics accelerometer is subjected to vibrations, the force proportional to the absolute acceleration encountered caused angular deflection of an elastic cantilever. This angular variation changes the angular position of a mirror mounted on the cantilever. The incoming beam is reflected at an angle proportional to the magnitude of acceleration. The electrical isolation of the optical circuit allows the sensor to be mounted directly to the stator coil ends.

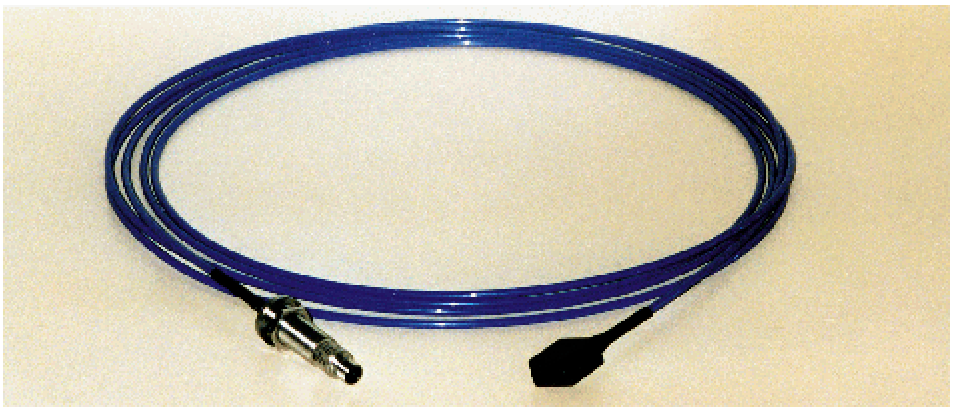

Fig. 2: Fiber Optic Accelerometer with Feed-through Conditioner

In the conditioning electronics, the optical signal is converted to an electrical signal by optoelectronic circuitry, processed and amplified to an acceptable level. The resultant measured signal is proportional to vibration acceleration that can be further processed by a computer. The analog output is a signal that is factory-calibrated to produce 100 mV when the detector senses an acceleration of 1g. An appropriate bandpass filter attenuates the noise and resonance frequency of the cantilever. Specially designed software provides signal processing, display and data storage. In addition, vibration velocity and displacement are processed. After Fast Fourier Transform (FFT), the measured signals are displayed as amplitude-frequency spectrum (Fig. 3). The system can be used in stand-alone operation or linked to plant control system.

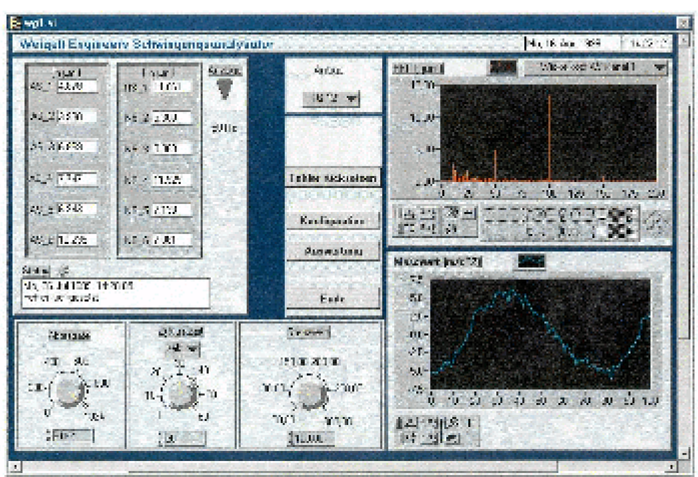

Fig. 3: Overview of software user interface

INSTALLATION OF FIBER OPTIC ACCELEROMETERS

The fiber optic system as shown in Fig. 1 consists of fiber optic accelerometers and cables, power supply and a computer. Such a system can be installed on generators in about seven days during an overhaul. Usually, twelve (12) accelerometers are installed per turbo-generator, six (6) sensors on each side. Sensors are required for each group of phases in radial and/or tangential directions. On pump generating sets, large generators, and depending on winding design six (6) to twelve (12) or more accelerometers may be necessary.

Fiber optic accelerometers are used for vibration measurements where conventional accelerometers are precluded. Because the accelerometer is sensitive in only one direction, it is possible to monitor vibration of an installation in radial, axial and tangential directions. Fig. 4 shows how accelerometers and cables are installed on the end-windings. It is important to respect the minimum bending radius of the optical cable to avoid breaking. It is also important to mention that the feed-through units must be equipped with O-rings capable of withstanding the hydrogen environment of the generator and must be mounted on a flange as shown in Fig. 5. The output electrical signals are available at the feed-through conditioning unit.

Fig. 4: Installed Fibre Optic Accelerometer for Radial Measurement

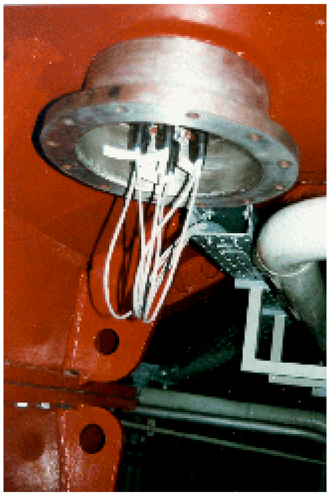

Fig. 5: Sealed Flange with Six Feed-through Conditioners and Cable

IMPLEMENTATION AT MISSISSIPPI POWER'S PLANT DANIEL

This section of paper presents results of vibration testing performed on Mississippi Power's Plant Daniel Unit #1 generator. The purpose of the test was to further investigate high end turn vibration readings recorded using conventional Westinghouse accelerometers which respond only to 120 Hz vibrations thereby ignoring rotor-induced phenomena . General information on the site and specific generator under test is given in Table 1

Table 1: Site Information

Station Name	Daniel Generating Station (Mississippi Power Company)
Unit Number	1
Power Rating	548 MW
Voltage Rating	18 kV
Test Date	June 5, 2000
Performed by	Generator & Motor Services
Equipment Used	GMS Fiber-Optic Accelerometer Test System

The fiber-optic accelerometer used for this test consisted of three parts:

- optical sensor head,
- fiber-optic integral cable, and
- a sealed feed-through connector/conditioner.

This portion of the system was installed in the Daniels #1 unit on May 12, 2000 during a scheduled outage. The sensor head was installed on the Group 8 end-winding at the turbine end of the Unit #1 generator. The feed-though was positioned to be accessible from the left side of the generator as viewed from the exciter end. Vibration data from the fiber-optics accelerometer was recorded on June 5, 2000 during a visit to the plant by GMS engineering personnel.

TEST RESULTS AND ANALYSIS

Figure 6 shows the resultant scope display of the GMS fiber-optic accelerometer as recorded during the test. The rms voltage reading corresponding to the signal shown in Figure 6 was .708 volts as displayed by the GMS equipment display software.

An initial evaluation of the data confirms that the primary signal is 120 Hz as expected. However, the shape of the Figure 6 trace (alternating high and low peaks in the 120 Hz waveform) indicates an appreciable 60 Hz content in the signal. From the trace it is clear that the 60 Hz amplitude is significantly smaller than the primary 120 Hz signal, but it must be remembered that displacements are inversely proportional to the square of the frequency. Accordingly, there will be four times as much displacement at 60 Hz than at 120 Hz for a given measured acceleration.

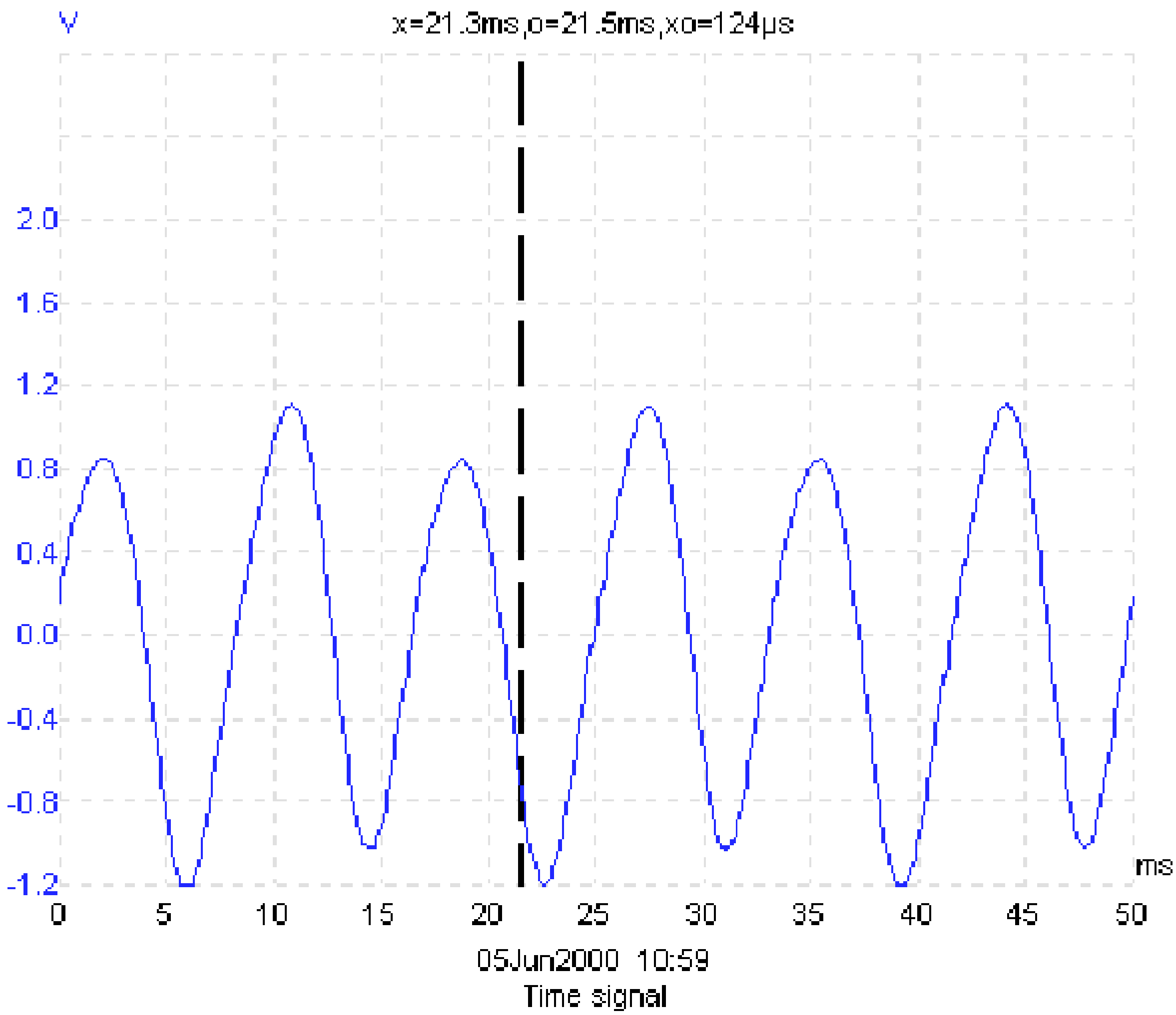

Figure 6: Scope Display of the GMS Fiber-Optic Accelerometer Data

A spectral analysis of the accelerometer readings is required accurately evaluate deflections. This analysis can be completed automatically using the Fast Fourier Transform (FFT) algorithm that is built into the software, but to better understand the interactions of vibrations a regression analysis has been performed.

The spectral analysis involves separating the composite signal show in Figure 6 into its primary components. Since the two major components are at 60 Hz and 120 Hz, the signal can be represented by an equation of the form:

$$V = A \sin(\omega t + \phi) + B \sin(2\omega t)$$

where $\omega = 2 \pi 60$ and ϕ is the phase angle between the 60 Hz and 120 Hz vibrations.

A regression technique was used to determine the "best" values for A, B and ϕ to fit the waveform produced by the experimental accelerometer data. This evaluation yielded the following results:

A = 165 mV (i.e., the amplitude of the 60 cycle vibration was 165 mV),

B = 1005 mV (i.e., the amplitude of the 120 cycle vibration was 1005 mV), and

$\phi = -\pi$ radians (i.e., the two signals were 180 degrees out of phase).

There is no particular significance to the phase angle between the two signals because the 120 Hz signal changes phase twice during each cycle of the 60 Hz signal. Thus if the data acquisition had begun one cycle later in the 120 Hz signal, the phase angle would have been zero.

Figure 7 displays the "goodness-of-fit" between the measured voltage and the synthesized voltage trace calculated using the Equation (1) expression with the regression analysis constants. The calculated expression consisting of 60 and 120 Hz components can be seen to agree very closely with the measured values.

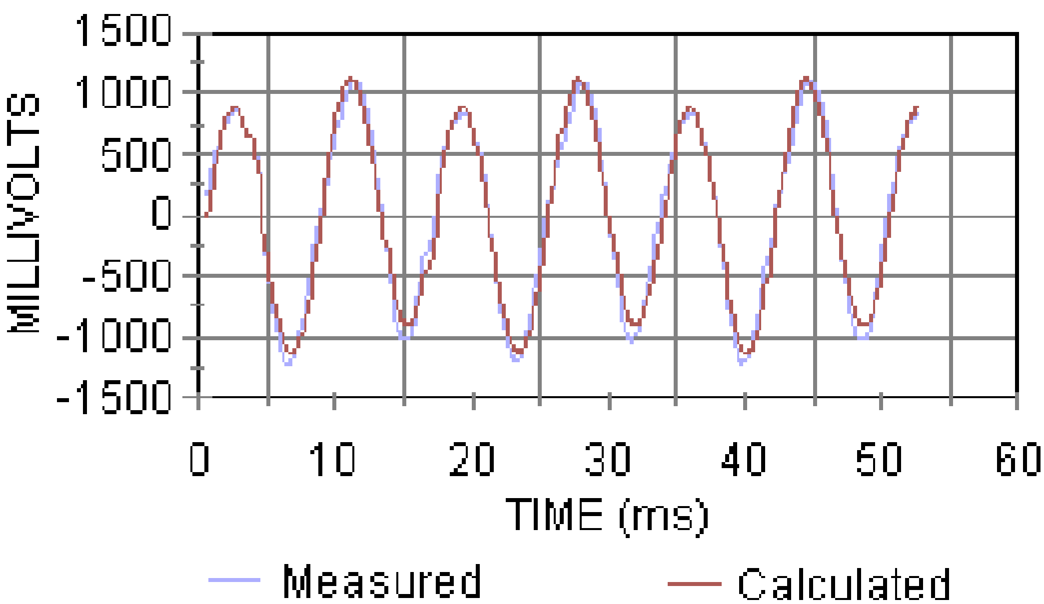

Figure 7:   Comparison of Calculated and Measured Voltage Traces

The rms voltages related to the calculated amplitudes are as follows:

V_{rms} at 60 Hz = 117 mV, and

V_{rms} at 120 Hz = 711 mV.

Given the calibrated value of 100 mV per g of acceleration, displacements associated with these vibrational modes can be calculated as follows:

Displacement at 60 Hz = 9.0 mils (peak-to-peak), and

Displacement at 120 Hz = 13.7 mils (peak-to-peak).

The calculated 120 Hz displacement agrees well with data from the previously installed accelerometer. On the day GMS fiber-optics accelerometer measurements described in this paper were taken, the conventional accelerometer located on the same end-winding (Group 8 on the turbine end of the Unit #1 generator) recorded a 12.8 mil displacement. A displacement of 13.8 mils was recorded by the conventional accelerometer positioned on the adjacent Group 7 end-winding. This correlation is expected since the conventional accelerometer is designed to respond to 120 Hz vibrations only. However, displacements resulting from the 60 Hz vibration are found to be nearly comparable in magnitude to those of the 120 Hz vibrations and cannot be ignored.

Since the 60 Hz and 120 Hz signals do not peak simultaneously, the resultant maximum displacement cannot be determined by simple addition. Rather, it is necessary to superimpose the displacements on one another as a vector sum. This is shown graphically in Figure 8. In this plot, the 60 Hz and 120 Hz displacements are plotted along with the resultant. The composite displacement, which is the sum of the instantaneous component displacements, actually peaks at ± 10 mils (20 mils peak-to-peak).

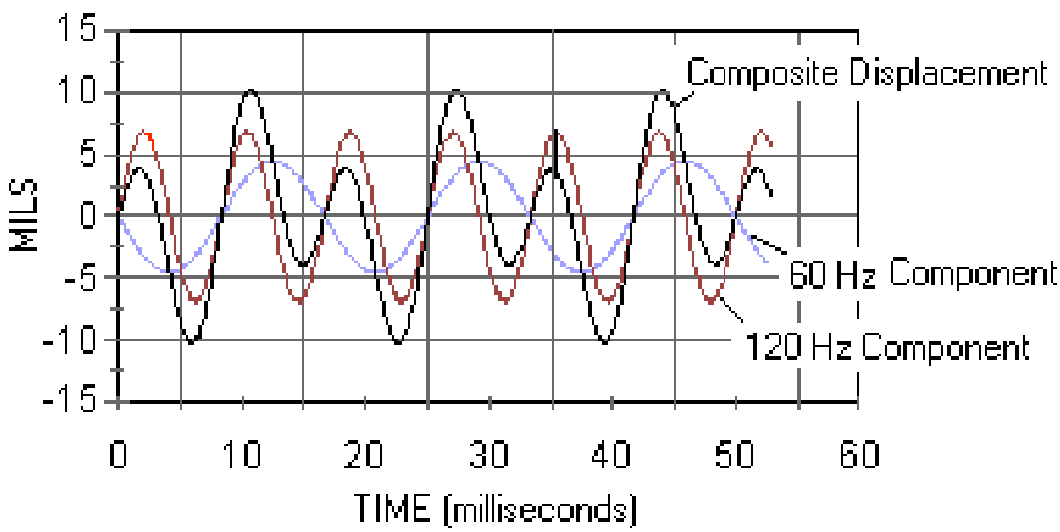

Figure 8: Calculated Displacements

Because the measured vibration amplitude of 20 mils exceeds guidelines set by generator manufacturers, concern must be expressed. The 60 Hz component is most likely present as a result of rotor bearing wear or rotor imbalance being transmitted to the stator end-windings.

Since no previous 60 Hz vibration readings are available, it is not possible to determine whether this phenomenon has developed recently, or if it is a long-term situation. In light of this, has been recommended that the GMS fiber-optics accelerometer be monitored at least monthly.

CONCLUSIONS

These results confirm clearly that significant 60 Hz vibrations produced by rotor bearing wear or rotor imbalance can be transmitted to generator stator end-windings. In some cases, these rotor-induced vibrations can produce end-winding displacements that approach, or perhaps exceed generator manufacturer guidelines. This condition can be assessed only if on-line monitoring techniques capable of responding at 60 Hz are incorporated. The GMS fiber-optic accelerometer system described in this paper is sensitive to vibrations at all frequencies and is clearly superior to conventional vibration monitoring systems which measure vibrations at 120 Hz only.

Results of the GMS fiber-optics accelerometer tests confirmed the high end-winding displacement measurements associated with 120 Hz vibrations observed by Mississippi Power for the Unit #1 Generator. The 120 Hz displacement measured using the GMS equipment was 13.7 mils compared with 12.8 mils recorded on the same generator end-winding at roughly the same time using the previously installed accelerometer which senses only 120 Hz vibrations.

The GMS fiber-optic accelerometer tests also revealed a significant amount of 60 Hz vibration which had been previously undetected. These 60 Hz end-winding vibrations are most likely transmitted mechanically from the rotor and produce independent deflections of 9.0 mils. A composite peak-to-peak end-winding deflection of 20 mils is calculated when considering vibrations at both frequencies. This 20 mil vibration amplitude of 20 mils exceeds guidelines set by generator manufacturers, and indicates that the situation must be monitored closely to ensure that the situation does not worsen.

It is important to distinguish between 60 Hz and 120 Hz vibrations because the conventional blocking techniques used to control stator current induced vibrations will not be effective in reducing the lower frequency vibrations that are mechanically induced from the generator rotor. Elimination of the 60 Hz vibrations requires that rotor repairs be completed.

On the basis of this work it is concluded that use of the GMS fiber-optics accelerometer system can significantly improve the reliability of generator stator end-winding vibration monitoring systems.