END-WINDING VIBRATION IN LARGE ROTATING MACHINES

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ABSTRACT

In the past 10 years, risk of failure due to end-winding vibration has been clearly acknowledged by both end-users and OEMs (original equipment manufacturers). As one industry expert puts it, "You have to monitor the level of end-winding vibration if you want to have any real idea on the health of your machine". Though it may be a relatively simple concept, measuring end-winding vibration is by no means a simple strategy. Innumerable factors are in play. Among the many decisions to be made; How many sensors? Where should they be placed? Is the data reliable? How much is noise? What levels are important? Whether a plant should even invest in the technology is really what is at stake. This paper has been written to help plant managers assess whether or not an investment in an End-winding Vibration Monitoring Program should be made. It will review some history on the subject, decision making considerations, cost (time and money) considerations, practical data interpretation and recourse. This paper is a practical guide for those who will be taking a closer look at the health of their machine – Monitoring End-winding Vibration.

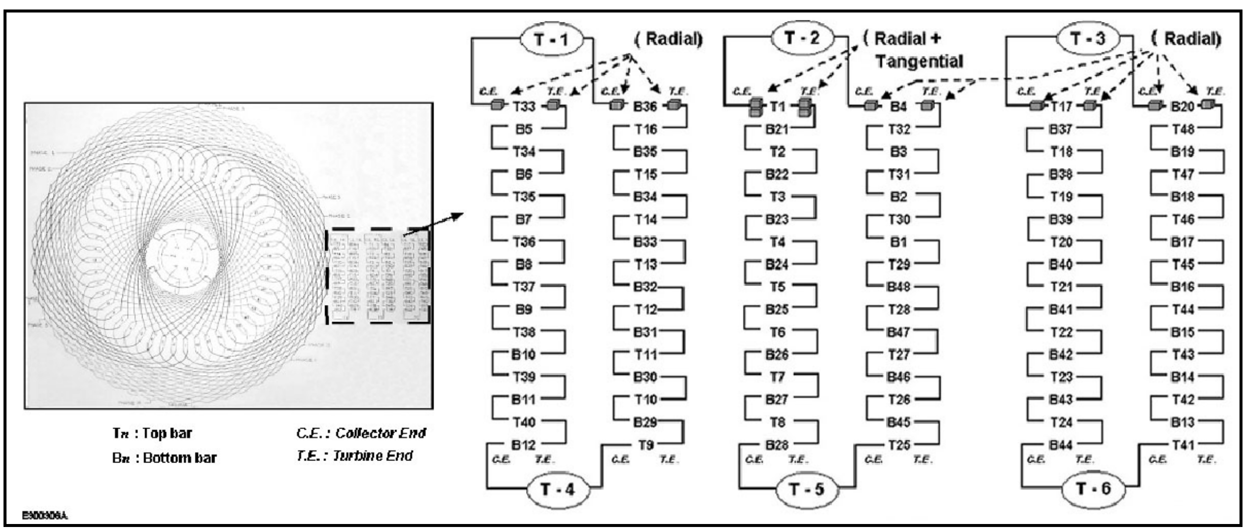
INTRODUCTION

Vibration monitoring has long been the primary strategy implemented on turbo-driven generators in order to ensure some predictive maintenance capability and thus prevent major failures. Shaft displacement probes are commonly used to monitor the radial vibration of the shaft, in X and Y axis, and hence attempt to keep the vibration levels below existing or manufacturer specified standards. Different technologies exist in the field (capacitive, inductive, piezo-electric etc) and have shown to be usually reliable. However, these probes are mainly installed either in air or in oil, away from electrical and environmental hazards. End-winding vibration monitoring presents a particular series of challenges. The least of which, maintaining reliability while being exposed to high voltages, temperatures ranging from 60ºC to 125ºC and most importantly, making sure the measuring chains does not affect the end-winding in any way and is safe for personnel. In recent years, fiber optic technology has produced a new series of sensors, which allow for installation directly on the end-winding. Because of their electrical insulation, they are not affected by the high magnetic fields and do not cause any harm to the Unit itself. The FOA-100 (one axis) and FOA-200 (Dual-axis) Fiber Optic Accelerometers were designed by VibroSystM specifically for this purpose. They have proven to be an invaluable part of end-winding vibration monitoring strategy for an increasing number of utilities and OEMs in the last few years. Their reliability and accuracy have provided critical data to users and have, in many cases, allowed utilities to invoke warranty claims as end-winding vibration was found to be beyond acceptable levels.

INSTALLATION CONSIDERATIONS

Many different issues are involved in planning the installation of fiber optic accelerometers. Although these sensors are designed for the harsh environment present in large turbo-driven generators, specifications must be taken into account before installation can begin. Parameters such as maximum temperature, maximum hydrogen pressure, distance between sensor head and penetration flange etc. In addition, position of sensor is limited to the minimum bending radius of the fiber optic cable. FOA-100 & FOA-200 sensors can be installed on any bar of the stator winding. However, it is well known that some stator bars are more vibration prone than others. The bars most likely to show vibrations are those connected to the terminal of each phase. Unlike other bars, these high-voltage bars are not mechanically interlocked on the lower plane. It is also recommended to select and monitor the vibrations on these bars, as these are also likely the first to fail from degraded insulation. In addition, usually the largest amplitude of vibrations is found on the bars located closest to the air gap, called top bars. These vibrations result from a combination of the alternating magnetic field in the machine and the natural resonance frequency of stator windings. It is highly recommended to use the manufacturer supplied drawings to identify the individual coils. In some cases, there known problem areas and specific bars can be targeted for monitoring.

To correctly monitor the occurrence of vibrations, the installation of accelerometers at both ends of stator and monitoring of at least one bar per phase in the radial axis of vibration is recommended. To monitor the second most common axis of vibration, the tangential, a single accelerometer on each end of any high-voltage bar is sufficient. On a typical turbo-generator with two-coil windings, a total number of 14 FOA-100 accelerometers: 6 on each end of the high-voltage bars for radial displacement monitoring, plus one on each end for tangential displacement monitoring. In the case of FOA-200, 12 sensors are sufficient. Figure 1 represents a typical layout of FOA accelerometers.



Stator windings diagram and location of accelerometers
FIGURE 1

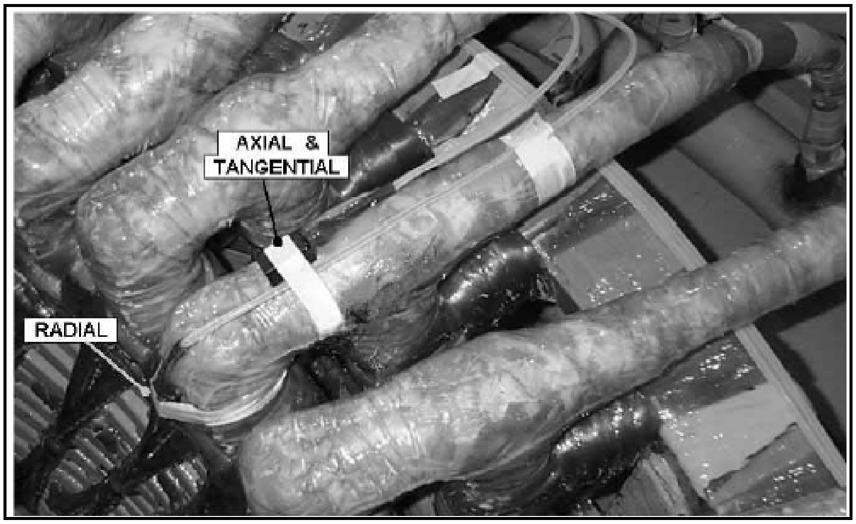
Once the location of the sensors is determined, the installation can begin. To properly fasten these sensors, two different types of epoxies are used; one for instant fastening to the end-winding surface and a second one which is used with fiberglass tape for final fastening of the sensor. Figure 2 is an example of the FOA accelerometer.

Fiber Optic Accelerometer: FOA-100
FIGURE 2

We can see in Figure 3 the actual installation of FOA accelerometers on the end-windings.
As can be clearly seen, care must be taken when routing the fiber optic cable to prevent damage.

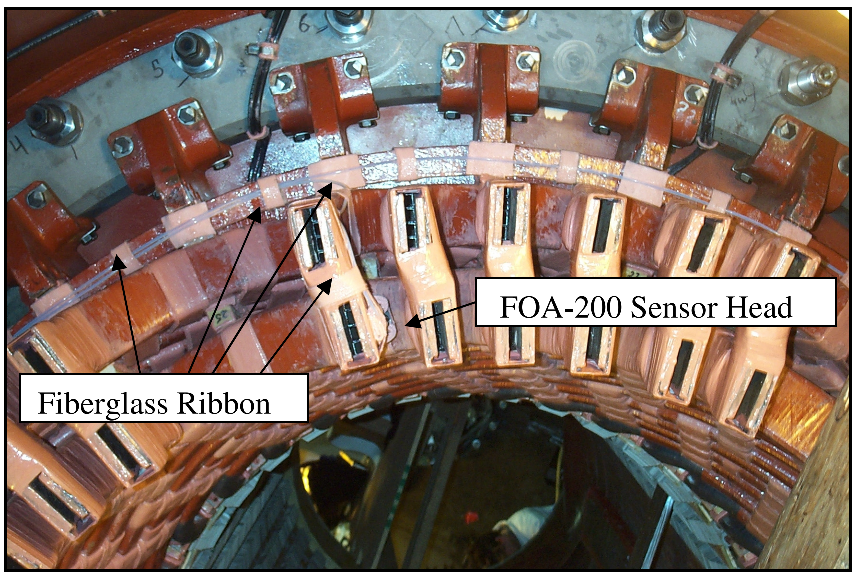
Use of adhesive tape to hold FOA accelerometers sensors
FIGURE 3

We can see in Figure 4 location of FOA-100 & FOA-200 accelerometers on the end-windings. FOA-100 for radial vibration and the FOA-200 for axial and tangential vibration,



Positioning One-Axis and Dual-Axis sensor heads on axes of displacement (radial, tangential and axial)
FIGURE 4

We can see in Figures 5 & 6 the routing and fastening of the fiber optic cables. These cables are usually fastened together and then exit the housing through penetration flanges.



Tying the fiber optic cable
FIGURE 5

Other example of fiberglass ties and bundling of fiber optic cables
FIGURE 6

Figures 7& 8 shows the exit hole and penetration flange used in many cases to fasten the FOA conditioners. Extension cables are then connected to the conditioners for signal output.

Managing excess cable in hydrogen-cooled turbo-generators
FIGURE 7

Sealed flange with six conditioners installed
FIGURE 8

CASE STUDIES

CASE STUDY 1 - REDHAWK POWER STATION

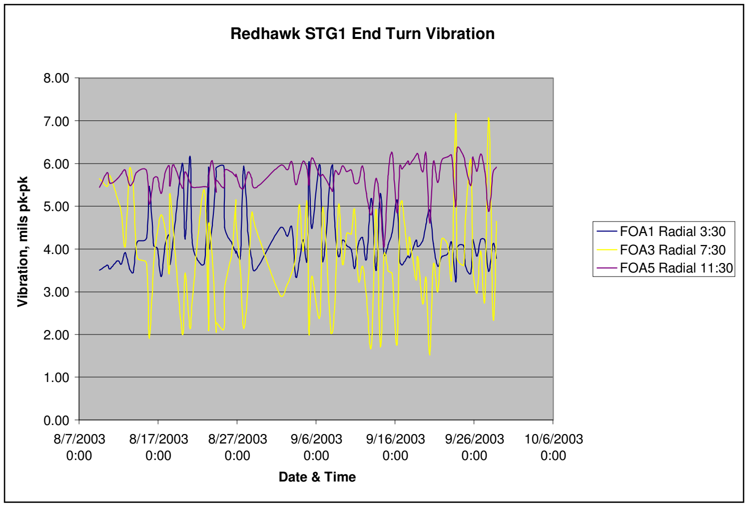
Arizona Public Service Company (APS) is the largest investor owned electric utility in the state of Arizona. The Redhawk Power station began commercial operation in the spring of 2003 just in time to help supply the summer's high peak air-conditioning load. In early June 2003, the plant received notification from the STG manufacturer of the potential for serious problem with the phase lug connectors on the collector ring end of the generator. High end turn vibration had been linked to a catastrophic phase lug failure at another installation. The manufacturer's recommendation was to immediately shut down both Redhawk steam turbine generators until the resources required to make a phase lug and end turn modifications could be mobilized in the fall of 2003. The prospect of a four-month forced outage and the loss of over 400 MW of generation during the summer peak was unacceptable to PWEC (Pinnacle West Energy Corporation) and APS. Alternatives that would allow continued operation throughout the summer were sought.

Redhawk plant management made a decision to proceed with obtaining a temporary monitoring scheme for the 2003 peak generating season. The particular points of concern were on the generator's collector ring side end turn structure. Three pairs of fiber optic accelerometers (FOAs) were mounted on the end turn structure at the 3:30, 7:30 and 11:30 positions as per the generator manufacturer's instructions. The FOA voltage output was sent back to the instrumentation rack located in the exciter building approximately 75 feet away.

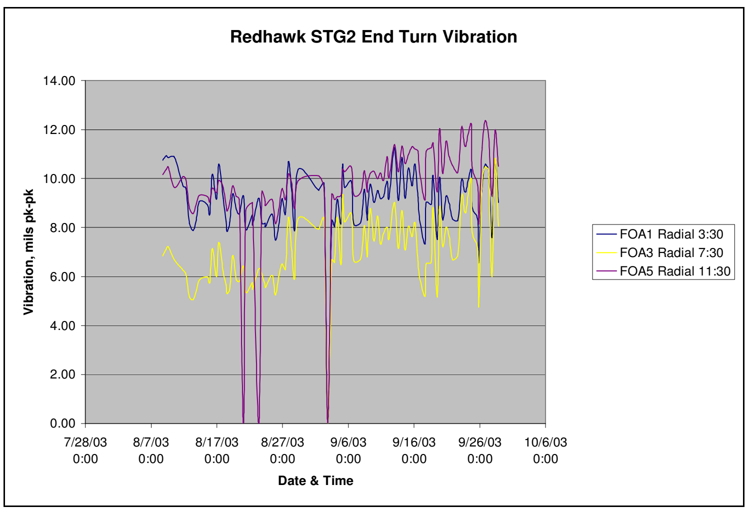
RESULTS – 2003

The FOAs were installed in early August on both units. The FOAs were able to detect exactly what had been suspected – a pattern of increasing end turn vibration over the summer of 2003. Figure 9 is a plot of end turn vibration for the Redhawk #1 STG through the summer of 2003. Depending on the radial FOA location, sensor outputs held in the 2 to 6 mils peak-to-peak range. End turn vibration primarily varied with real power load and somewhat with reactive power load. The good news was that these levels were well below the 10.83 mils alarm level specified by the generator manufacturer. Figure 10 is an end turn vibration plot for the Redhawk STG #2 over the same time frame. Initial data from early August showed radial vibration in excess of 10 mils. Vibration reached a minimum of approximately 8 to 9 mils in late August and then began to trend upward. By late September, radial vibration at the 11:30 position had exceeded 12 mils. By October 2003, end turn vibration had increased to the level at which a curtailment was imperative. Fortunately, system load had diminished to the point that both units could be removed from service.

The FOAs served their intended purpose. They confirmed a trend of increasing end turn vibration on STG 2 and had allowed the Redhawk Power Plant units to operate through the summer to meet customer energy needs. Plant management took the conservative approach and committed the resources necessary to permanently reinstall the 6 FOAs on each unit. Reinstalled FOAs would provide an expedient check of the effectiveness of the modification.



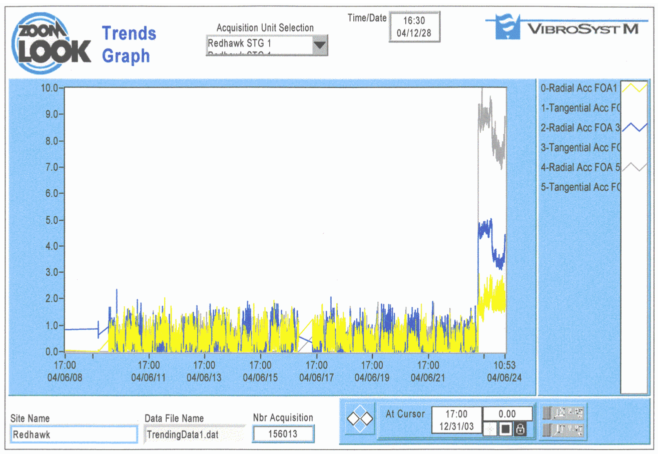
End Turn Vibration – STG #1 (2003)
FIGURE 9



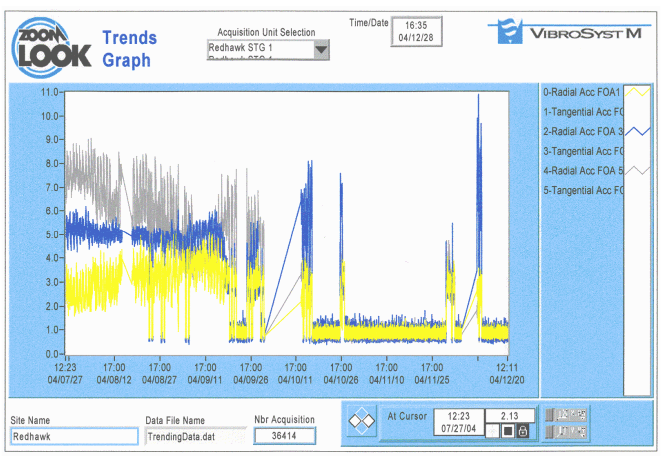
End Turn Vibration – STG #2 (2003)
FIGURE 10

RESULTS – 2004

Figure 11 is a plot on vendor supplied software that documents end turn vibration for STG1 during June 2004. When STG1 began to operate routinely near the end of the month, the 11:30 position radial FOA showed vibration approaching 10 mils (grey trace on trend graph on Figure 11). This was close to the 10.83 mils limit imposed by the generator manufacturer prior to the end turn structure modifications. Vibration levels at the remaining two radial sensors were acceptable – typically in the level below 5 mils. Figure 12 documents STG1 end turn vibration from late July through December 2004. Note that radial vibration at the 11:30 position (grey trace on trend graph on Figure 12) trends downward but vibration at the 7:30 position (blue trace on trend graph on Figure 12) trends upward to the point that the 10.83 mil limit was exceeded in early December 2004. End turn vibration data was periodically transmitted to the



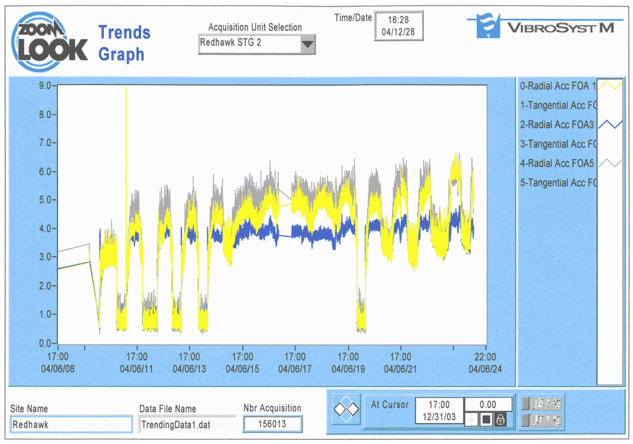
End Turn Vibration – STG #1 June 2004
FIGURE 11



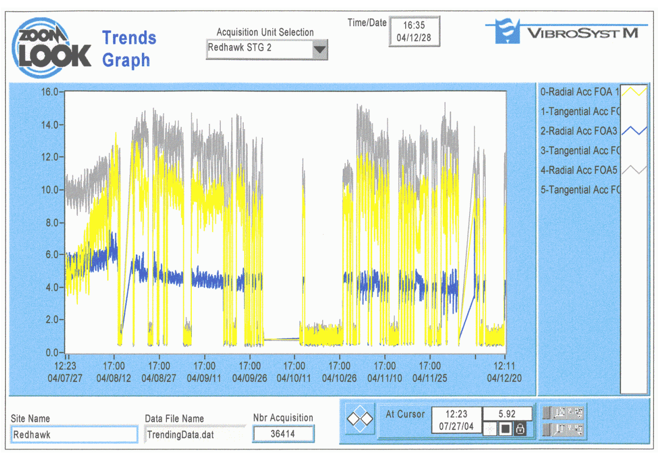
End Turn Vibration – STG #1 July to December 2004
FIGURE 12

generator manufacturer for analysis and concurrence that continued operation was prudent. Figure 13 presents the results for STG2 during June 2004. Redhawk combined cycle unit 2 was load cycled daily for much of the month and the vibration levels clearly depict that cycling. What is of most concern, however, is the steady climb in radial end turn vibration. When the unit first comes on in early June, all three radial end turn vibration reads were under 4 mils. By the end of the month, all were exceeding 6 mils.

Figure 14 picks up the vibration increase in late July 2004 and shows that two of the three radial FOAs at the 3:30 and 11:30 positions (yellow & grey traces on trend graph respectively on Figure 14) now read well over 10 mils. The 7:30 radial position FOA (blue trace on trend graph on Figure 14) reads peak at over 7 mils in early August and then begin a gradual ramp downward towards year's end. The result of most concern was an increase in vibration at the 11:30 radial position (grey trace on trend graph on Figure 14) to as much as 15 mils by mid-August 2004. The manufacturer's recommendations were immediately sought. The data gathered assisted the manufacturer in development of an end turn stiffening system to be installed in 2005. In recognition that another round of end turn modifications would be required, the manufacturer allowed temporary operation at these elevated vibration levels through the remainder of peak season by careful monitoring of vibration levels and trends. Figure 14 documents that vibration levels remained elevated through the end of 2004.



End Turn Vibration – STG #2 June 2004
FIGURE 13



End Turn Vibration – STG #2 July to December 2004
FIGURE 14

Conclusions & Future Work of Case Study 1

End turn vibration monitoring on the Redhawk STGs has proven to be a necessary and effective tool in allowing continued operation of the units with higher than expected end turn vibration. The turnkey monitoring package described has allowed the excessive vibration to be detected early and treated as a warranty item. An important feature to PWEC was the ability to transmit data back to engineering staff offices in Phoenix so that plant operations and engineering personnel would not be burdened with data analysis and interpretation.

Close monitoring with the temporary FOA system through the summer of 2003 allowed operation of both STGs without a forced outage curtailment due to end turn vibration. Consequently, the enormous costs associated with purchase of over 400 MW of replacement energy were avoided. Management plans continued close monitoring through 2005 after warranty repairs are made to the end turn support structure and phase lugs.

CASE STUDY 2 - GENERIC POWER STATION

The following case study is a good example of end winding vibration being analyzed in order to establish the source of the vibration. FOA accelerometers were installed at both ends of the unit, installed for radial measurement. Figure 15 shows a typical raw measurement of accelerometers on the end windings. This measurement was recorded at a rate of 5000 samples per second.

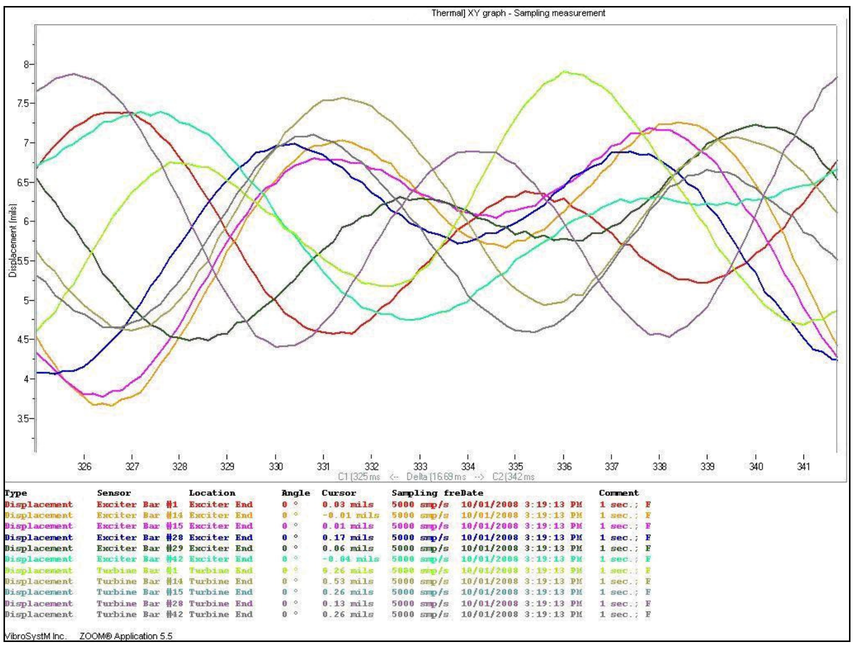


FIGURE 15

Figure 16 shows a Fast Fourier Transform (FFT) of the same data. We can clearly see both the 60 and 120 Hz components of the end winding vibration. We can also see that although the 60 Hz component is fairly high in regards to the 120 Hz, both signals are quite low (± 1 mil, peak).

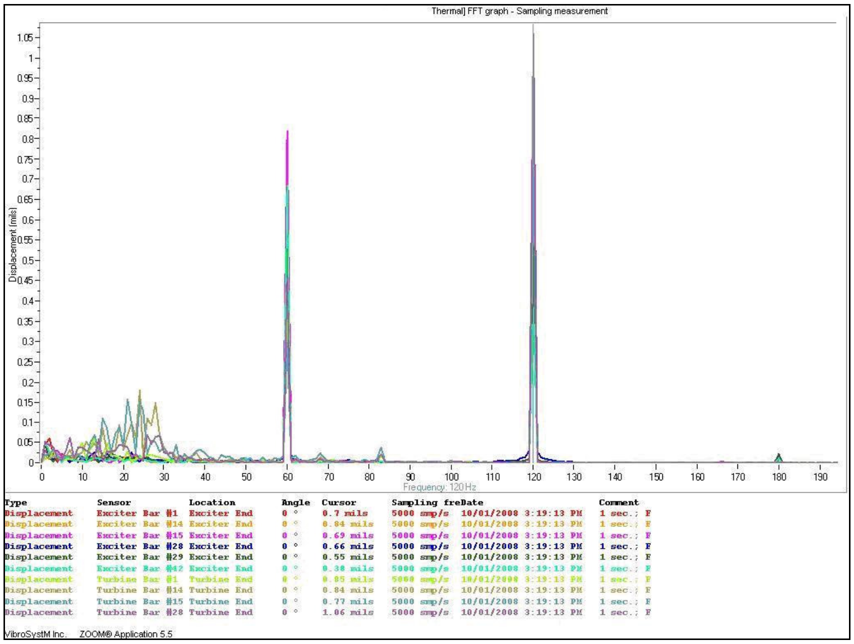


FIGURE 16

In order to properly analyze the vibratory behavior of the generator, the Unit was put through various operating conditions and various parameters were recorded. The following tests were performed:

TESTS PERFORMED ON GENERATOR 1

Test(s)	**Parameters**				
	Active Power (MW)	**Reactive power (MVars)**	**Field Current (A)**	**Stator Voltage (KV)**	**Stator Current (KA)**
A	**502**	**-1**	**3191**	**23.8**	**12.0**
B	**502**	**-43**	**2977**	**23.6**	**12.4**
C	**501**	**100**	**3671**	**24.6**	**12.1**
D	**490**	**202**	**4201**	**24.9**	**12.4**
E	**611**	**182**	**4308**	**24.6**	**14.7**
F	**741**	**0**	**3959**	**23.9**	**17.8**
G	**681**	**14**	**4415**	**23.9**	**16.6**
H	**611**	**-6**	**4415**	**23.9**	**14.7**
I	**512**	**77**	**3618**	**24.1**	**12.4**

The results of the tests are presented in the following pages in the form of XY graphs (Figures 17,18 & 19). Figures 17 & 18 represent the peak-peak readings of 6 individual accelerometers but categorized by frequencies. We can see that in most cases, the 60 Hz component is higher than the 120 Hz component, which is uncommon if a Unit is operating properly. The explanation for this phenomenon is seen in Figure 19 where the shaft displacement is displayed. We can see that these values are quite higher than the recommended maximum peak-peak vibration of 1 mil, and are the main cause for the high 60 Hz component in the end winding vibration.

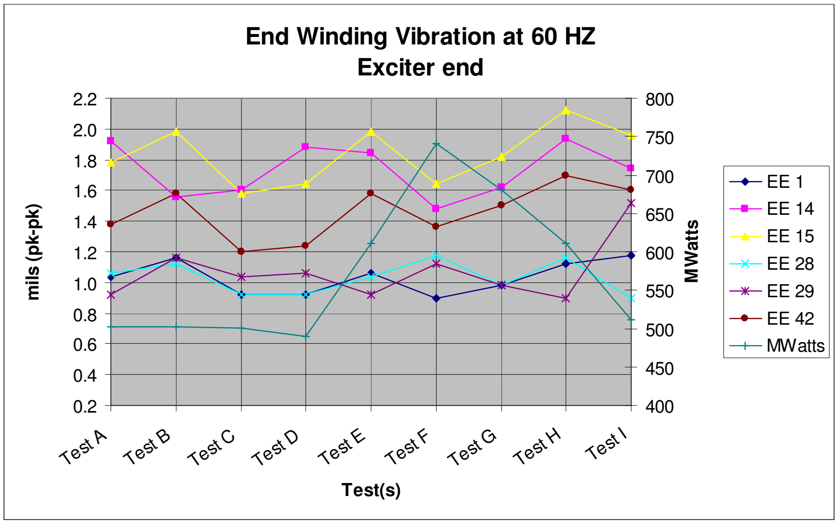


FIGURE 17

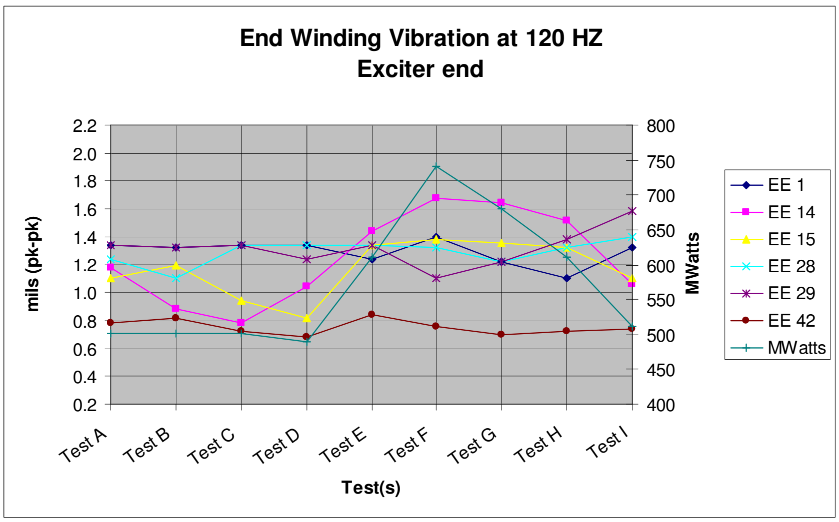


FIGURE 18

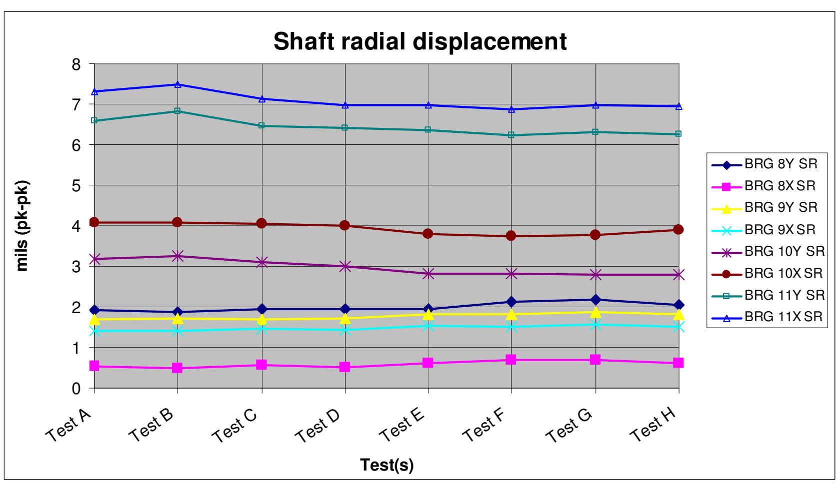


FIGURE 19

CONCLUSION

For diagnostics, it is very important to have a device that provides the highest bandwidth possible to analyze all possible causes of abnormal vibration in the generator. In this case, mechanical forces (shaft vibration) were inducing more vibration on the end-winding than the electromagnetic forces. This needed to be corrected in order to avoid abnormal wear on the machine and also on the end-winding insulation and/or support structure. FOA vendors' supply of 10 to 1000 Hz ranges and temperature up to 180°C will contribute in providing better analysis of end-winding phenomena, without compromising the safety of the Unit and personnel manipulating the data.

ACKNOWLEDGEMENTS

The author of the paper would like to express gratitude to Mr. Andrew Tesla & Mr. Marc Bissonnette of VibroSystM for their contributions and review of the paper.

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BIOGRAPHY

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