# Stator Bar Vibration Sensors and Fiber-Optic Accelerometers

## *New Tools Used to Measure Stator Winding Vibration in Large Turbine Generators*

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## Abstract

Vibration analysis has been conducted on large rotating machines for many decades. Proximity probes and accelerometers are traditionally used to measure bearing and shaft vibration in an effort to keep mechanical condition in check. Simple measurement of amplitude, to the more complex analysis such as Fast Fourier Transforms, are made by maintenance personnel in an effort to identify the source, severity and trend of vibration threatening proper operation of their generator fleet.

Up until the last few years, vibration analysis technology has generally focused on external components, resulting in an incomplete method of identifying problems caused from internal movement. New technology is now emerging to help maintenance management take the next step – internal vibration analysis focusing on stator windings in the slots and end-winding region.

The ability to conduct accurate and direct vibration analysis of stator winding systems can help operators implement a more effective condition-based and predictive maintenance approach.

This paper will review field experience with two products that conduct on-line monitoring inside the generator:

1. Stator Bar Vibration (SBV™) sensors used to measure in-slot displacement of stator bars.

2. Fiber-Optic Accelerometers (FOA™) used to measure vibration of end-windings.

## Introduction

Vibration analysis is the cornerstone of mechanical diagnostic monitoring on rotating machines. Well-placed proximity sensors can provide accurate and reliable vibration data on generator rotor shafts and bearings. This type of analysis is important for basic machine operation. It has been said that (for power producers), vibration sensitive generator rotors may cost hundreds of thousands of dollars in downtime [1]. Moreover, a major US generator manufacturer reports its installed fleet as "*rapidly approaching the limit of the original intended life*" [2]. This suggests that a large number of units are reaching an age where advanced on-line diagnostics is equal to, if not more important than traditional methods. Traditional vibration analysis does not provide a complete picture of system health. A cost-effective on-line system providing accurate and timely in-depth data on machine condition is worth further investigation.

Reasons to improve on-line machine condition assessment technologies are also a function of the recent deregulated electricity markets. Price guarantees and stability are vanishing. Supply and demand are now subject to the ebb and flow of an open market mechanism and has increased the importance of having shorter and well planned maintenance outages. As a result, new diagnostic and risk management systems are more readily accepted as the competition among power producers becomes more apparent.

To meet the new demands on predictive maintenance management, two types of sensor technologies have emerged. A Stator Bar Vibration (SBV) sensor based on a capacitive measurement technique, and a Fiber-Optic Accelerometer (FOA) based on a bi-refringent or wave interference measurement technique. The strength of these sensors lay both in their construction and application within the generator.

It is worth noting that, applying these sensors inside the generator (especially two and four pole) offers significant challenges. Areas available for application are few and space is limited. Generally speaking, the SBV sensor has to be of slim design to fit in the air gap between the stator and rotor. The FOA accelerometer must be made from materials with high voltage insulating properties to be safely applied to the end-winding region. For both sensors, safe *pressure-vessel* penetration must accompany installation on hydrogen-cooled units.

## Relative Motion Affecting Stator Winding Deterioration

Stator windings are a complex design with numerous electrical, mechanical and thermal constraints. They must operate under high voltage, high temperature and mechanical stress.

This paper deals with monitoring two regions of the stator winding:

1. Inside the stator core where the winding is made up of insulated copper bars that are designed to be held firmly in the stator slots by a nonmetallic wedging and packing system.

2. Outside the stator core in the end-winding area where the individual bars exit and are braced and blocked firmly forming a basket at both ends of the generator.

### *Stator Core Region*

One of the most important components to monitor in a high-voltage rotating machine is winding insulation [5]. Consider the basic operation of large gas or steam turbine generator. The rotor field produces a strong alternating magnetic field inducing large currents in the stator winding. These alternating (100Hz or 120Hz) forces are imposed on each stator bar. Over a period of up to 25 years (or more), the stator bars are subject to the high possibility of movement in the slot. Even small radial or tangential displacement (see EPRI 3-9-1) [9] occurring over the life of the generator may result in abrasion of the exterior insulating surfaces. Semi-conductive coatings may erode through to the ground wall giving rise to partial discharge. The presence of PD would then contribute to further deterioration. In the case of severe bar motion, mechanical damage can occur to both the ground wall insulation and the core.

During the expected period of operation, the stator bar is also subject to thermal expansion and contraction from stops and starts. For peaking units, this can amount to thousands of thermal cycles over a ten year period. A typical example is that of a European utility operating a 750 MW peaking unit. After ten years of operation, the plant manager reported approximately 3800 stop/starts.

Thermal cycling may introduce a number of deteriorating mechanisms because of different thermal coefficients of the materials used. The most obvious comes from expansion and contraction of stator bar copper relative to the stator core and other restraining components. The possible resulting change in size plays a leading role in loosening of the bar in the slot. Another contributing factor to deterioration is thermal aging. Stator insulation may experience a small amount of shrinkage during high temperature operation over long periods of time. This change in size will also result in looseness.

Wedging and packing systems designed to keep the bars in place have undergone a number of design improvements over the years. Among others, the introduction of ripple spring fillers have helped to maintain firm positioning in the slot. Not all installations have both top and side filler springs and for those that do - the ripple springs have a finite life. The life of any filler system is dependent on; material used, quality of installation and operating environment. Large quantities of lubricating oil inadvertently introduced from the bearing system can greatly influence the effectiveness of any filler system.

Regardless of the wedging system used, alternating magnetic forces over the life span of the generator has a direct impact on bar looseness over time. Stator bar tightness must be tested as part of any comprehensive condition based maintenance approach.

### *End-Winding Region*

The end-winding region is also subject to strong magnetic forces at double the line frequency. Some researches have observed that end-winding vibration is proportional to lagging power-factor (MVAR production) [3]. As a result of possible deterioration sustained from end-winding vibration, tremendous efforts have been made in designing baskets and bracing systems to keep the entire end-winding in place. The issue of end-winding vibration is so problematic that some manufacturers advertise *"retightenable stator end-winding support system"* as part of their large 2-pole generator design.

A large global power producer has reported end-winding vibration that has lead to failures on the end-winding hydraulic links possibly causing water leaks [3]. There has also been concerns regarding insulation deterioration, rupture of the coil and fatigue cracking of the conductors. These scenarios are made possible because the end-winding protrudes a considerable length beyond the stator core and is very difficult to support. Because of the cantilever effect, any end-winding displacement produces high stress at the point where the bars leave the stator core slots.

Even though risk from stator bar and end-winding vibration may be easy to appreciate, management of these problems is more difficult. For example, what levels of displacement are acceptable and at what point does corrective action become necessary? Does the deterioration follow a linear trend or does failure arrive as some catastrophic event along the relationship of an exponential curve?

The prospects of clear and concise answers to these questions lie in the ability to accurately monitor parameters such as magnitude, magnitude over time, magnitude versus operation, spectral components and many other relationships between observed vibration an prevailing conditions. Appropriate application must therefore be considered.

## Sensor Design and Application Overview

The SBV sensor is based on a capacitive measurement model [6] as follows;

$$C = \varepsilon \frac{A}{L}$$

Where: $\boldsymbol{C}$ = Capacitance, F
$\boldsymbol{\varepsilon}$ = Dielectric permittivity, F/m
$\boldsymbol{A}$ = Area of the capacitive plates, $\boldsymbol{A}$ ($m^2$)
$\boldsymbol{L}$ = Distance between capacitive plates, m

It is possible to determine a variable distance $\boldsymbol{L}$ between two capacitive plates as long as the dielectric $\boldsymbol{\varepsilon}$ and area $\boldsymbol{A}$ remain constant and the variable capacitance $\boldsymbol{C}$ can be accurately measured.

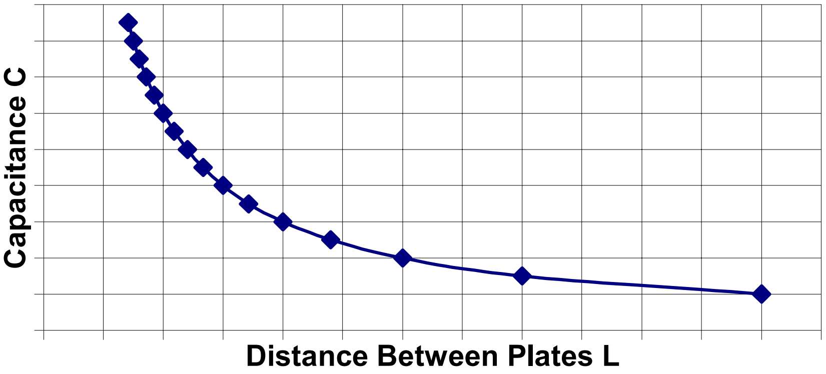


**Figure 1: Capacitances as a Function of Plate Distance**

On close inspection of the equation, it can be seen that the capacitance $\boldsymbol{C}$ has a *curvilinear* relationship with the distance $\boldsymbol{L}$. Substitution of values in the equation yields the relationship as in the graph above.

Now consider a sensor mounted in front of the stator bar (with a fixed area) acting as one plate of the capacitive model, the stator bar acting as the opposite plate, and the wedging components upon which the sensor is installed acting as the dielectric. If the stator bar becomes loose and the radial distance between the stator bar and the installed sensor changes over time, the measured capacitance should also change. Further to the same model, if the stator bar is held firmly in place with no radial movement, the measured capacitance should remain unchanged.

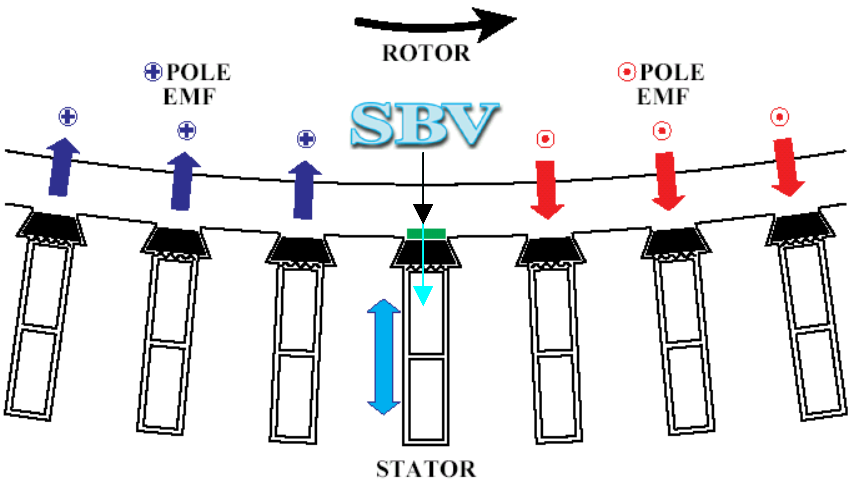


**Figure 2: SBV Sensor Model**

The numbers of sensors chosen for installation depends on a rational economic approach. Important assumptions about the loosening process must be first made. For example, looseness might be more likely to occur on certain wedges over others. Alternatively, looseness of specific wedges represents a higher risk to machine operation. Having arrived at an appropriate balance between the two constraints, quantity and placement can proceed using a small sample of the stator wedges installed. For a two circuit/phase winding design, sensors are installed on the line-end coil of each circuit of each phase at both ends of the stator. This approach brings us to a total of 12 sensors.

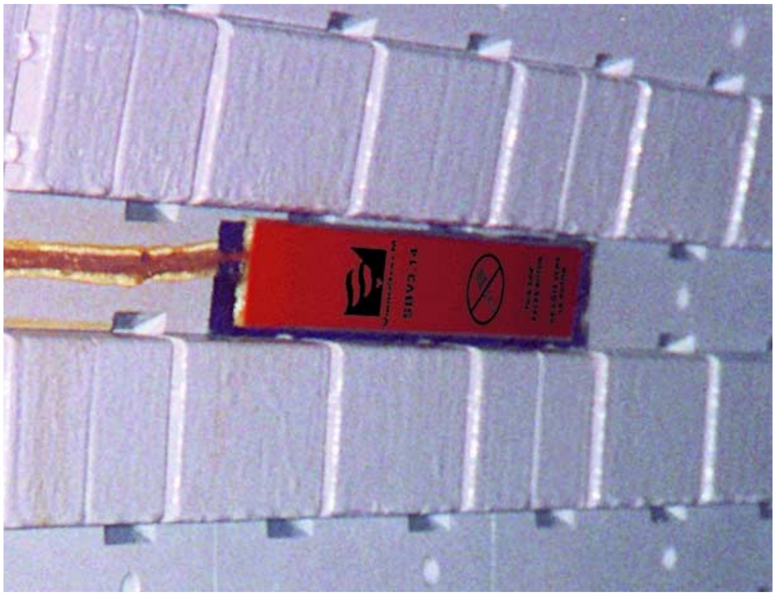


**Figure 3: Installed SBV Sensor**

One of the concerns raised with a wedge-mount design is the possibility of wedge looseness giving rise to false readings. Even though this may introduce an accuracy issue for actual bar vibration, wedge looseness detection would still be possible and identifiable as an abnormal condition. Never the less, the possibility of the wedge following the bar with an identical radial distance and frequency seems unlikely given the complexity of the design components such as ripple springs and side packing. However, arrangement of a bridge-mount sensor can be made to accommodate this type of concern. The sensor would have a non-conductive backing allowing installation on the immediate stator wall of each side making a bridge configuration.

The SBV sensor is manufactured using a patented capacitive design requiring a linearizing signal conditioning module (LIN). The LIN provides the necessary power signal and returns a choice of two linearized analog outputs. They include a 0 to $10V_{DC}$ unbiased signal or 4 to 20mA current loop. These signals are directly proportional to the distance measured from the face of the sensor to the top semi-conductive coating of the stator bar. The LIN provides a signal with a frequency response of DC to 1 KHz (-3 dB). This allows measurement of both vibration or displacement of the bar in the slot.

Once installation of both sensor and LIN is made, measurements can be taken using any type of data acquisition device. Multi-meters, oscilloscopes or A-D data acquisition units can be used to make measurements using numerous strategies. Data taken under changing load conditions as well as constant load conditions over time can provide real-time direct measurement of stator bar movement. An extremely effective application includes warrantee issues. After a new stator winding has been manufactured and installed, some settling and filling of insulation voids are expected. Following a burn-in period, SBV sensors can keep track of any further developing movement or shift of the stator bar.

In contrast to the SBV, the FOA is based on patented optical technology. It is comprised of an optical head and conditioning electronics connected by 10 meters of fiber-optic cable. Measurement is accomplished by sensing changes to specific wavelength properties as the optical head accelerates up to 40*g*.

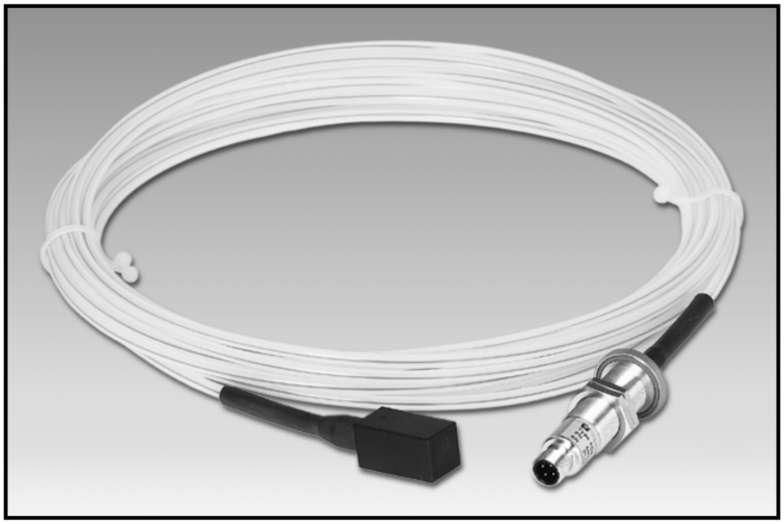


**Figure 4: Fiber-Optic Accelerometer**

Recent advances in optoelectronics and fiber-optic engineering have allowed this type of device to be successfully manufactured and housed in high-voltage insulating material, ideal for harsh environments. The insulating material is rated up to 27 $kV_{RMS}$ (or greater) and is designed for direct installation on the end-winding surface. Optical coupling of the sensor is accomplished via 10 meters of fiber-optic cable providing excellent immunity and safety from the extreme environments within the generator end-winding region.

The optical cantilever head with orientation clearly marked is located at one end of the fiber-optic cable. The light source and signal conditioning electronics is located inside a metal cylindrical housing at the other end producing a precise 100mV/*g* signal. The metal housing is tapped and ready for installation on an access panel or flange for hydrogen-cooled units.

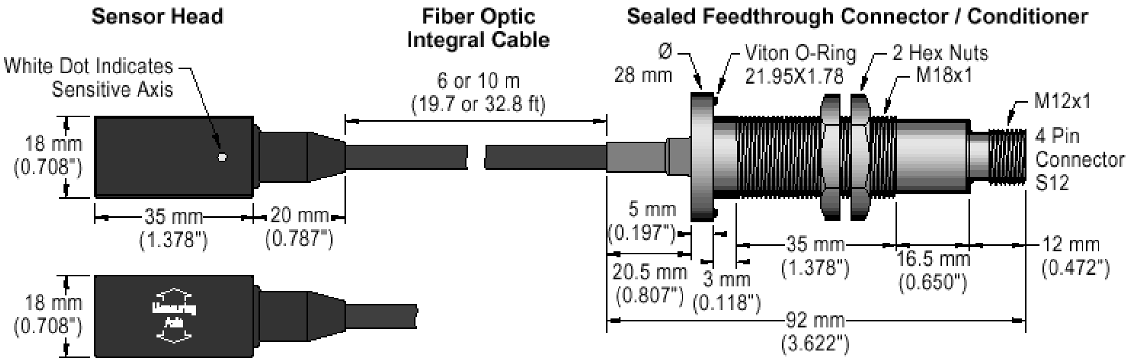


**Figure 5: FOA Dimensions**

As with the SBV, the number and orientation for installation of the FOA is dependant on the suspected area of concern. A number of arrangements have proven successful. In one application, the utility installed a total of 20 sensors on a 600-MW machine. Five sensors were installed on the turbine side and 15 installed on the exciter side. Alternatively, the user can install the FOAs using a more conventional approach. A total of fourteen sensors could cover a two circuit/phase winding equally at both ends of the generator. In this arrangement, 12 sensors are oriented for radial displacement and two are oriented for tangential displacement.

**Figure 6: FOA Installation on End-winding**

Once installed, the sensors are ready for data acquisition. A $24V_{DC}$ power supply is the only additional hardware required to energizer the unit. Output is provided in the form of a single-ended DC coupled signal with a bias voltage of $6\ V_{DC}$ +/- 100mV/*g*. The operating bandwidth is 30 to 350 Hz however, an extended upper limit of 950 Hz is available. Given the measured frequency, displacement can then be calculated using the following formula:

$$D = 495050 \frac{A}{f^2}$$

Where: ***D*** = *Distance in μm pk-pk*
***A*** = *Acceleration in peak*
***f*** = *Frequency in Hz*

These calculations are based on the assumption that end-windings fundamentally vibrate at twice the line frequency. Results obtained using spectral analysis have shown this to be true. Similar research has also shown complex relationships between the generator's operating conditions and vibration modalities. However, one need not delve too deep into scientific analysis to benefit from data obtained. Given multiple machine monitoring, plant managers can compare measured results and apply comparative condition-based maintenance approach [4]. Monitoring one machine over a period of time would allow the operator to trend the information and conduct a predictive maintenance approach.

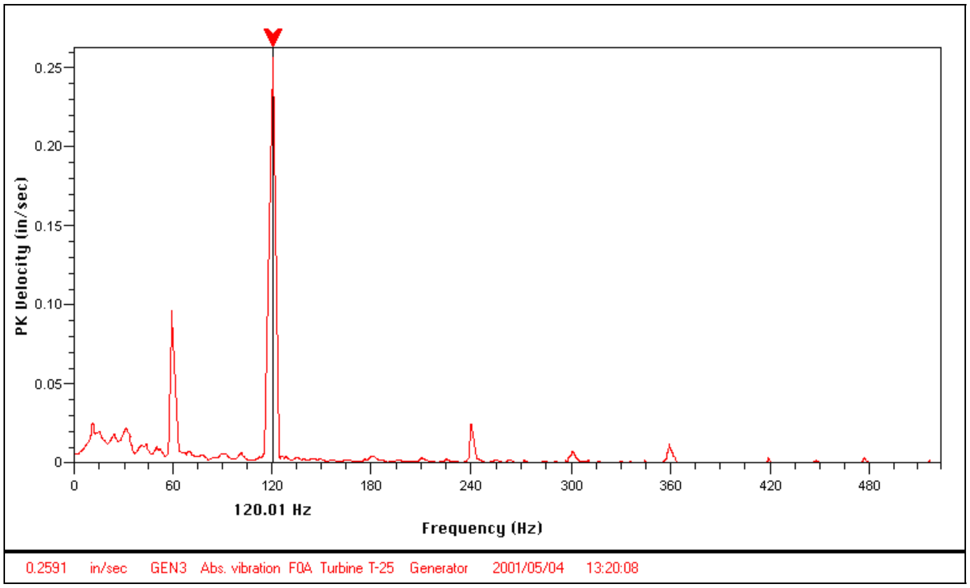


**Figure 7: FOA Spectral Response on an 870-MW Unit End-winding**

As described earlier, FOA outputs can be fed directly into condition monitoring systems able to accept the $6\ V_{DC}$ ±100 mV/g signal. However, retrieving and displaying these signals need not be complicated. Supporting hardware that can be directly connected to the output of the FOAs are available. The PCU-100 is a programmable analog to digital rack mount signal processor. It can be setup to display various calculated parameters including RMS, Peak, Average, AC/DC, Maximum or Raw data.

Five direct benefits from use of the PCU-100 in conjunction with the FOA are:

1. Local Display of real and unaltered values by third party monitoring systems
2. Conversion of FOA signals to a 4-20 mA signal for simple transmission of acceleration data
3. Local processing of raw signal into user definable data
4. Access to raw signal for operation verification
5. Local alarm threshold programming and detection
6. Protection relays locally activated

**Figure 8: PCU-100 Programmable Monitor**
**Used with FOA Accelerometers**

For requirements where more sophisticated condition monitoring equipment is used, the PCU-100 can also act as a conduit providing front end verification of signals before they are sent into a complex data acquisition and storage system.

## FOA Case Study

J.H. Campbell is Consumers Energy's largest coal fired generating complex. It is located in the United States on the shores of lake Michigan. The site contains three generating units with a total installed capacity of about 1400 MW. Unit 1 has the following ratings;

**Original Equipment Manufacturer: Allis-Chalmers**
**Year of Manufacturing: 1962**
**Stators Rewound and Restacked: 2000**
**Cross-compound Rating: 2 x 156 MVA, (Units A and B)**

A total of twelve FOA sensors were installed in unit **B** in 2000. The turbine end (TE) and collector end (CE) each had six FOA installed for radial displacement measurement. In the spring of 2001, measurements were taken from each of the twelve sensors at 10-minute intervals over a period of six hours. The displacement measurements were made in mils pk-pk.

Other parameters including MW, MVAR and slot temperature were recorded. The data was tabulated as follows:

| Time | Avg. Slot Temp | MW | Turbine End Vibration (mils) | | | | | | Collector End Vibration (mils) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | TE Slot 29 | TE Slot 35 | TE Slot 5 | TE Slot 11 | TE Slot 17 | TE Slot 23 | CE Slot 29 | CE Slot 35 | CE Slot 5 | CE Slot 11 | CE Slot 17 | CE Slot 23 |
| 0:10 | $T_{0}$ | $MW_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ | $D_{0}$ |
| . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . | . | . | . | . | . | . | . |
| 6:00 | $T_{35}$ | $MW_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ | $D_{35}$ |

**Table 1: Matrix of Tabulated Data**

Using data from this table and appropriate statistical functions such as *covariance* or *correlation,* some general observations can be made. Covariance is a statistical measure of the relationship between two variables. More accurately, it is a measure of the difference of the variation between two series of variables. For example, if variable ***A*** increases with a similar proportional increase to that of ***B***, ***A*** and ***B*** are said to have positive covariance. Should ***A*** decrease while ***B*** increases, they are considered to have negative covariance. Should one remain perfectly constant while the other changes, they are said to have no covariance. The covariance formula uses the product of ***A*** and ***B***, however easier interpretation can be used from the correlation coefficient calculation. The correlation coefficient ***(r)*** translates covariance into a linear scale providing a relative value between -1 and 1. The values can be used for general observation of the relationship between two variables as follows:

| ***Relationship or Dependence*** | ***Correlation Coefficient (r)*** |
|---|---|
| Perfect Correlation | 1.0 |
| Marginally Correlated | 0.5 |
| No Correlation | 0 |
| Marginally and Negatively Correlated | -0.5 |
| Perfect Negative Correlation | -1.0 |

**Table 2: Relationship Guidelines for Correlation Coefficient**

The first observations made were on the relationships between vibration levels of the individual end-winding monitored. Correlation coefficients ***(r)***, were calculated for the relationships between each individual FOA.

The results are tabulated below:

| *(r)* | **Turbine End** | | | | | | **Collector End** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **TE Slot 29** | **TE Slot 35** | **TE Slot 5** | **TE Slot 11** | **TE Slot 17** | **TE Slot 23** | **CE Slot 29** | **CE Slot 35** | **CE Slot 5** | **CE Slot 11** | **CE Slot 17** | **CE Slot 23** |
| **TE Slot 29** | 1.00 | 0.69 | 0.73 | 0.46 | 0.74 | 0.66 | *0.07* | *-0.27* | *0.47* | *-0.46* | *0.37* | *0.35* |
| **TE Slot 35** | | 1.00 | 0.88 | 0.44 | 0.90 | 0.82 | *0.16* | *-0.33* | *0.55* | *-0.46* | *0.44* | *0.41* |
| **TE Slot 5** | | | 1.00 | 0.40 | 0.94 | 0.84 | *0.06* | *-0.30* | *0.64* | *-0.57* | *0.51* | *0.41* |
| **TE Slot 11** | | | | 1.00 | 0.29 | 0.15 | *0.33* | *-0.28* | *0.13* | *-0.04* | *0.13* | *0.07* |
| **TE Slot 17** | | | | | 1.00 | **0.93** | *-0.01* | *-0.20* | *0.70* | *-0.59* | *0.55* | *0.48* |
| **TE Slot 23** | | | | | | 1.00 | *-0.12* | *0.01* | *0.71* | *-0.48* | *0.56* | *0.48* |
| **CE Slot 29** | | | | | | | 1.00 | 0.07 | 0.03 | 0.49 | 0.21 | 0.15 |
| **CE Slot 35** | | | | | | | | 1.00 | 0.38 | 0.60 | 0.48 | 0.29 |
| **CE Slot 5** | | | | | | | | | 1.00 | -0.18 | **0.85** | 0.76 |
| **CE Slot 11** | | | | | | | | | | 1.00 | **-0.05** | -0.21 |
| **CE Slot 17** | | | | | | | | | | | 1.00 | 0.81 |
| **CE Slot 23** | | | | | | | | | | | | 1.00 |

**Table 3: Correlation Coefficients Between Individual End-windings**

On first inspection one can see some notably high correlation between numerous measuring points such as TE Slot 17 and 23 and CE Slot 5 and 17. However, the assumption that all monitored points follow each other cannot readily be made as indicated from values between CE Slot 11 and 17.

To make a general assumption about how the measuring points vibrate in relation to each other, the average correlation was calculated of each of the Turbine and Collectors ends as well as the entire generator. The results are as follows:

Avg. ***(r)*** between all FOA data on the Turbine End (TE) = **0.66**

Avg. ***(r)*** between all FOA data on the Collector End (CE) = **0.31**

Avg. ***(r)*** between all FOA data on both sides = **0.12**

It seems reasonable from these values to deduce that there is a closer relationship between vibration levels at each end of the stator than there is across the entire winding. Correlation coefficients were calculated between (each of), MW, MVAR, and average slot temperature *versus* vibration levels.

The results are tabulated below:

| *(r)* | **Turbine End (mils)** | | | | | | **Collector End (mils)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **TE Slot 29** | **TE Slot 35** | **TE Slot 5** | **TE Slot 11** | **TE Slot 17** | **TE Slot 23** | **CE Slot 29** | **CE Slot 35** | **CE Slot 5** | **CE Slot 11** | **CE Slot 17** | **CE Slot 23** |
| ***(r)*$_{\mathbf{MW}}$** | *0.76* | *0.86* | *0.93* | *0.28* | ***0.98*** | *0.89* | ***-0.04*** | *-0.25* | *0.69* | *-0.69* | *0.57* | *0.55* |
| ***(r)*$_{\mathbf{MVAR}}$** | *0.09* | *0.08* | *0.13* | *-0.37* | *0.23* | *0.31* | *-0.14* | *0.23* | *0.36* | *-0.21* | *0.20* | *0.30* |
| ***(r )*$_{\mathbf{TEMP}}$** | *0.74* | *0.82* | *0.94* | *0.37* | ***0.95*** | *0.81* | *-0.04* | *-0.29* | *0.68* | *-0.66* | *0.51* | *0.44* |

**Table 4: Correlation Coefficients Between MW, MVAR and Average Slot Temperature vs. Vibration Levels**

Once again there are some notably high correlations between certain measured parameters such as TE Slot 17 (mils), MW and Avg. Slot Temp. However, it may be premature to associated MW loading with end-winding vibration levels as can be seen when comparing other relationships like that between CE Slot 29 and MW. The following graphs in Figures 9 and 10 depict how the individual vibration levels tracked the temperature vibration levels over the 6-hour period.

Visual comparison of the two graphs seems to validate some of the earlier numeric calculations. In this machine, end-winding vibration levels seem to follow operating parameters more closely on the turbine side rather than the collector side. These are very conservative initial observations however; the ease of data collection from the FOA makes this type of analysis fairly straightforward. An operator concerned with vibration levels as a function of time, operating parameters, or in comparison to other machines can easily make simple or sophisticated studies by taking data directly from the FOA or from any A-D type data acquisition unit.

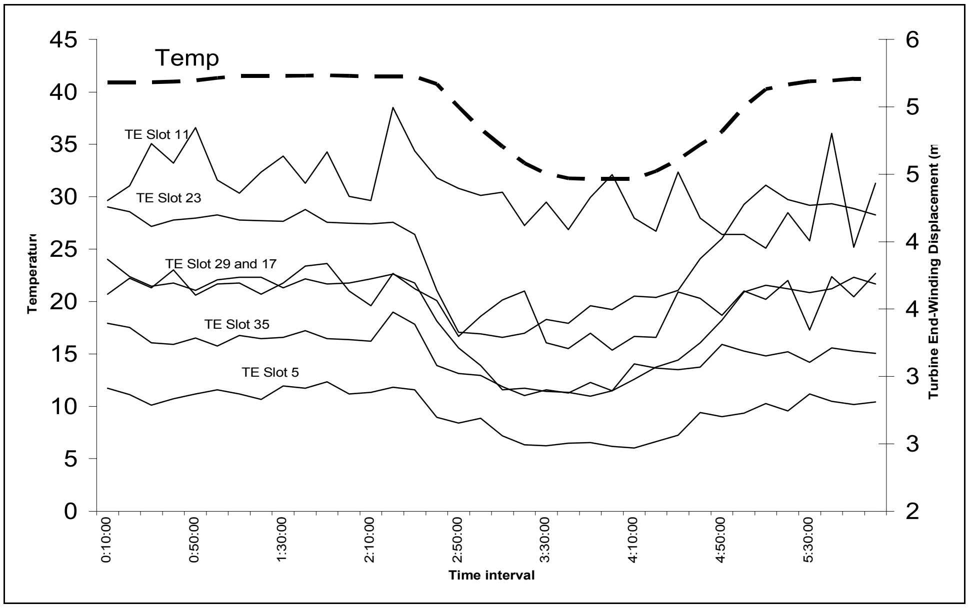


**Figure 9: Temperature vs. Turbine End-winding Vibration Levels**

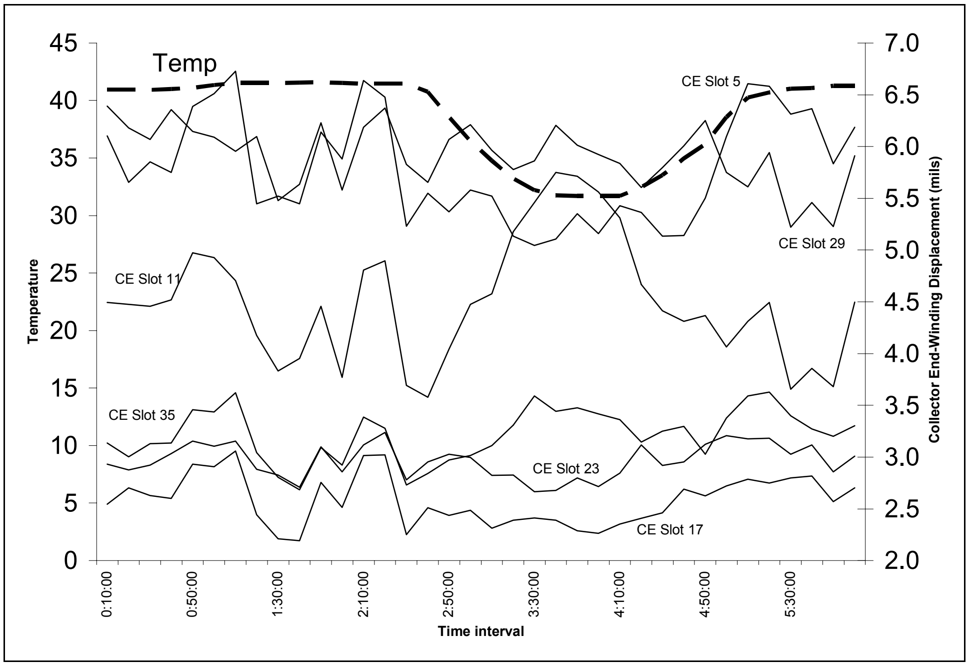


**Figure 10: Temperature vs. Collector End-winding Vibration Levels**

Unit **A** had 12 FOAs installed in a similar fashion to that of **B**. In the summer of 2002, average peak-to-peak displacement values were measured over a 6-hour period (during constant operating conditions). The results tabulated below clearly indicate the bar in TE slot #29 has an unusually high value compared to the others. At this time, an explanation for this situation has not been found. This example clearly demonstrated the importance of close monitoring using the FOA following any repair work done on the stator winding. The end user can now consult with the manufacturer keeping close tabs on any change in levels or evolution of the problem.

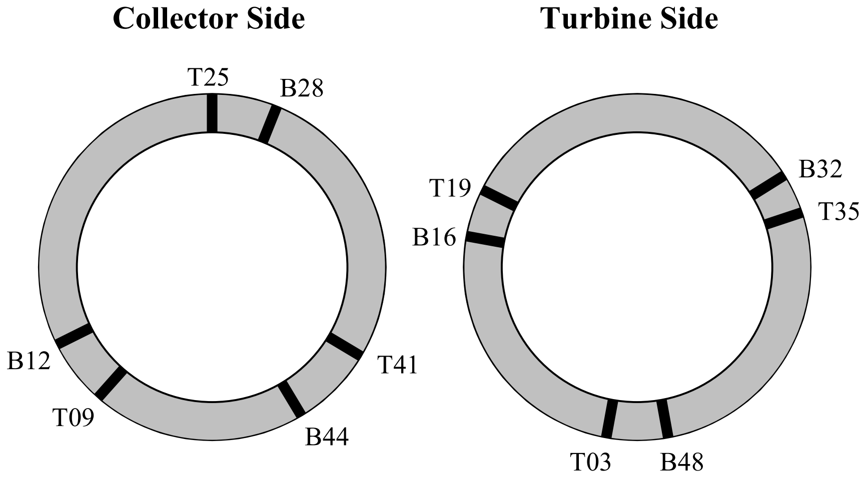
| | **Turbine End Vibration (mils pk-pk)** | | | | | | **Collector End Vibration (mils pk-pk)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **TE Slot 29** | **TE Slot 35** | **TE Slot 5** | **TE Slot 11** | **TE Slot 17** | **TE Slot 23** | **CE Slot 29** | **CE Slot 35** | **CE Slot 5** | **CE Slot 11** | **CE Slot 17** | **CE Slot 23** |
| Avg. Displ. | **9.68** | 2.42 | 2.68 | 3.98 | 3.47 | 2.94 | 2.35 | 1.28 | 2.22 | 2.08 | 2.31 | 2.27 |

**Table 5: Average End-Winding Vibration Levels from 12 FOA Sensors Installed on Unit B**

**SBV Case Study**

At the same site, six SBV sensors were installed at each end of a larger generator with the following nameplate information:

| | |
|---|---|
| **Original Equipment Manufacturer:** | **General Electric** |
| **Year of Manufacturing:** | **1980** |
| **Stator Rewound:** | **1999** |
| **Rating:** | **1025 MVA** |


**Collector Side**

**Turbine Side**

**Figure 11: Placement of Sensors at Both Ends of the Generator**

Measurements were taken at normal operating temperatures and the vibration levels observed were found to be as expected. The recorded vibrations averaged 0.1 mils pk-pk (2,5 µm) at the collector end and 0.25 mils pk-pk (6,4 µm) at the turbine end. These levels are considered satisfactory for a newly refurbished Unit. However, seeing that vibrations at this location have never been measured, the most important factor will be the observation of any positive or negative trending over time.

The specific SBV sensor location has a definite purpose. As can be seen in Figure 3, the sensor is installed at a certain distance (approximately 50 cm) from the end of the stator core. It is believed that stress exerted on the stator bars, originating from the basket or end-winding region, will result in minimum forces closer to the stator edge and maximum forces further down the slot. More simply put, the outer-most wedge acts as a pivot or node to the forces across the bar surface as illustrated in Figure 12.

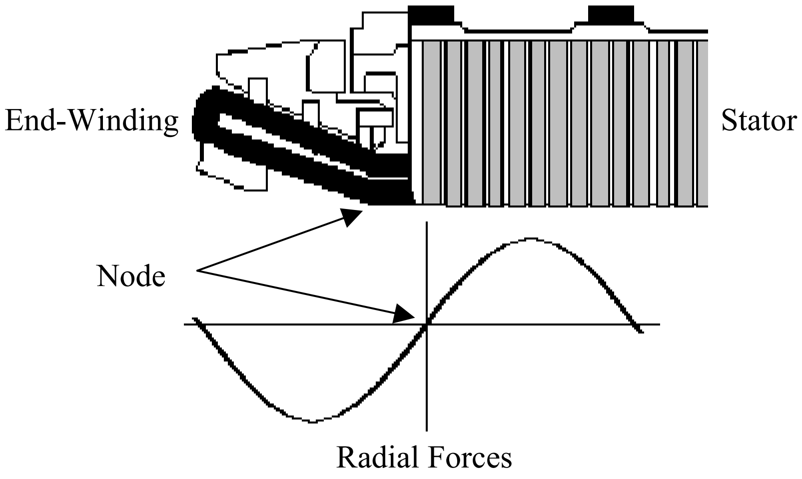


**Figure 12: Distribution Forces Acting on the Stator Bar**

It is also believed that the basket design may also *attenuate* vibration forces present at the stator core level. This attenuation effect may prevent maintenance personnel from getting an accurate picture of all the radial forces acting on the stator bar. It is clearly understood that the vibration level of the stator bars in their slots, and the evolution of this vibration level is a good indicator of winding insulation breakdown. Also, this vibration may be a precursor to major damage due to the growing possibility of phase to phase and/or phase to ground faults. Therefore, any information relating to this phenomenon would be invaluable in establishing the condition of the windings - allowing well timed intervention, and avoiding damage. This is the foundation upon which condition based monitoring programs enable large power producers to better manage and maintain their generation assets.

## Conclusions

A number of conclusions can be made from the observations of both case studies. The most important is that of applicability. The FOA represents a breakthrough in sensor technology regarding safety and noise immunity. The material from which the FOA is made makes it ideal for the harsh environment of end regions in high-voltage rotating machines. The SBV design fulfills a different but equally strong constraint. Its wafer-like shape makes it extremely fitting for installation in air gaps in most sizes of turbine generators.

As well as application, the FOA functionality has proven successful in obtaining accurate diagnostic data and delivering it in a convenient form. Operators have easy accessibility to calibrated analog outputs located within a metal housing used as part of the device penetration. Through the use of a LIN module, the SBV has proven equally successful in delivering data reflecting vibration and displacement without the need for field calibration.

With both technologies, a limited number of measurement points can be selected providing a statistical sample of the entire machine condition. Depending on the size and circuit arrangement, 6, 12, 14 or 20 sensors from each technology can provide the appropriate level of coverage.

Although FOA and SBV sensors function as independent devices (based on substantially different sciences), many machines would benefit from a collective approach using an installation of both systems. For example, in large units (such as nuclear powered), the risk management budget and philosophy calls for a more comprehensive array of devices helping to assess condition, risk and probability of failure. In the case of smaller peaking units where thermal cycling plays a major role in deterioration, winding looseness may exist in either the stator end or core region. Using only one technology might allow the vibration to go unchecked as the vibration magnitude becomes muted when measured at different points than its source.

Even though field tests have shown that vibration phenomena in the slot and end-winding may show some correlation, further investigation into this relationship can be easily accomplished with an installation of both the FOA and SBV technology using one to help confirm the other.

Finally, stronger competition in the energy market is forcing the participants to curb costs. Condition-based and predictive maintenance strategies have contributed greatly to this effort. The success of the FOA and SBV sensors in this application clearly defines their role in reliable and accurate data collection of vibration and displacement – part of any comprehensive maintenance strategy.

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