New low cost fiber optic accelerometer system for stator winding monitoring of hydroelectric generating machines

J.M. López-Higuera, A. Cobo, M.A. Morante, J. Echevarría, J.L. Arce, M. Lomer, R. López

University of Cantabria, Photonics Engineering Group
Avda. los Castros s/n; Santander 39005, SPAIN
Tel: +34-42-201498; *Fax*: +34-42-201873
E-mail: higuera@teisa.unican.es

ABSTRACT

A new fiber optic accelerometer system for stator winding simultaneous multi-point vibration monitoring of hydroelectric generating sets is presented. It is composed of as many sensor heads as points to be monitored, an optical channel and a processing unit distant from the sensing area, which is exposed to strong electromagnetic interference. The evaluation scheme is based on an intensity modulation and differential detection technique so that the measure is not influenced by external perturbations. The system is able to measure accelerations ranging from 30 to 450 Hz, with a maximum amplitude of 200 m/s^2 RMS. Experimental results for the previous prototypes developed are showed. This sensor is intended to be integrated in a new complex system aimed to reach the goals of instantaneous protection, real time detection and evaluation of defects, failures and malfunctions in the above mentioned machines.

Keywords: fiber optic accelerometers, optical fiber sensors, hydroelectric generating machines, stator winding vibration monitoring, real-time multi-point vibration monitoring, intensity modulation.

1. INTRODUCTION

Hydroelectric generating machines are usually subjected to restrictive environmental conditions that prevent traditional sensors from being applied in them. Particularly, they are exposed to large electromagnetic fields that unable any electrical operation in their proximity. Conversely, optical fiber technology exhibits features such as immunity to electromagnetic interference, resistance to humidity and temperature changes and possibility of multi-point and distributed sensing, among others, that make it suitable to be used in such applications. Optical fiber sensors (OFS) are, therefore, appropriate to monitor vibrations in hydroelectric generating plants.

Several OFS for vibration measurement have been presented in the past few years, both academic works and commercially available devices.[1-7] According to the physical phenomenon they employ, they can be divided in polarimetric, interferometric and intensity-based, and, according to the technology they utilize, they can be classified in integrated optics- and fiber optic-based. Among them, the ones which show the lowest cost are the intensity-based sensors made in fiber optic technology. The system presented here uses these techniques, so that it can compete with the more complex and more expensive interferometric sensors. Furthermore, it allows multiple-point sensing.

This new Fiber Optic Accelerometer System[8] is intended to be devoted to the protection of hydroelectric generating machines, particularly to the monitoring of stator windings operation. The main malfunctions to be prevented in these parts of the generators are loosening of the stator wedges and core's radial junctions with increase of the generalized vibration level, and loosening of axial core bolts with increase of core frame vibration.[9] They can lead to frame distortion and lateral displacement first, and if they persist, they can cause the generator breakdown. The system is capable of measuring vibration on several points and it is to be integrated in a new simultaneous multi-point vibration monitoring system aimed to reach the goals of instantaneous protection and real time detection and evaluation of defects, failures and malfunctions in the above mentioned machines. The main goal of the complete monitoring system is to contribute to the knowledge of the

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actual state of the machine and anticipate mechanism failure. It can be of great assistance to the maintenance programs of hydroelectric plants and other factories, and help achieve the long-term reliability of the equipment in them.

2. SYSTEM ARCHITECTURE

A general scheme of the system in one of its applications is shown in figure 1. The electronic unit, on the right, has been separated from the optical one, on the left, integrated by the sensor heads and the optical communication channel. As the very harsh environment (high EMI and temperature) existing on the measuring points can act upon the processing part of the system, the electronic unit is taken apart from the sensor heads by means of an optical channel that can be hundreds of meters long. Since we were looking for a low cost system, an intensity modulation technique was chosen because of its simplicity of fabrication. The acceleration to be measured is derived from the light coupled between optical fibers, which changes with the vibration experienced by the machine monitored.

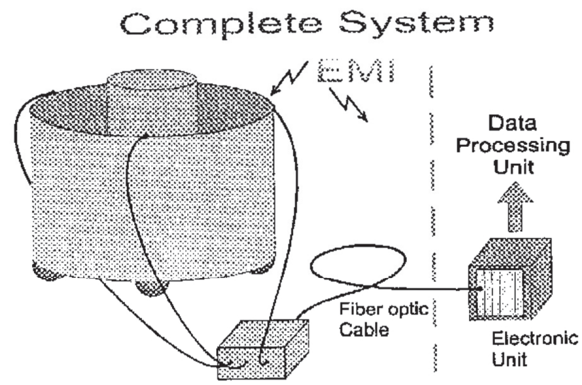

Fig. 1. General overview of the optical fiber accelerometer system.

Next, the transducer heads, the intensity modulation scheme, the optical channel and the electronic unit of the system are presented.

2.1 Transducer heads

The transducer heads are the system elements that convert a vibrating movement into optical signals from which the value of the acceleration can be derived, after convenient processing and conditioning. They are to be fastened to the mechanical parts of the machines whose vibration is to be monitored. They are completely made of dielectric materials so that the electromagnetic fields encompassing the hydrogenerators do not influence them.

The optical transducer head is based on a simple structure with three fibers, one of them emitting light and the other two receiving it. The emitter one is a cantilever beam that moves with the vibration of the whole and its movement modulates the light intensity coupled into the other two. The two receiver fibers permit differential detection of the position of the cantilever in such way that external perturbations are compensated.

The oscillating behavior of a bare fiber optic cantilever beam was theoretically analyzed in an earlier work.[10] Other accelerometers consisting in a vibrating optical fiber cantilever had been previously developed, but they needed a mass at the end of the cantilever.[11] The structure employed in these transducer heads proved to be suitable for accurately measuring vibrations and it allows straightforward processing, since the displacement of the fiber optic cantilever free end is directly proportional to the acceleration to be measured in the frequency range of interest. Besides, the lack of the mass at the free end of the optical fiber simplifies the construction of the sensor head. The cantilever is 7.4 mm long and the operative frequency range runs from 30 to 450 Hz.

Furthermore, experimental results about the performance of the optical fiber cantilever, obtained in more stringent conditions than normal anticipated operation, guaranteed its reliability as a part of a device subjected to vibrations. Several fiber optic beam samples were tested under high levels of vibration at their resonant frequencies for a large period, showing no apparent deterioration on their mechanical behavior.

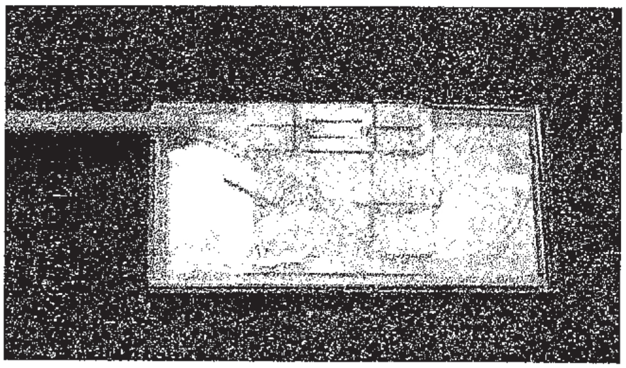

Fig. 2. Photograph of an early prototype of the transducer head.

A laser-processed holder made of hard insulating material was used to place the three fibers composing the optical transducer head, since the fibers have to be precisely positioned in order to obtain correct modulation of the light between them. The holder has one single groove to locate the emitter fiber and a double one for the receiver fibers, and their centers are perfectly aligned. Consequently, in the absence of movement the emitting fiber couples the same amount of power into both receiving ones, and the motion of the former is enclosed in the plane that contains the receiver fibers. Figure 2 shows a picture of an early prototype of the optical fiber sensor head. The receiver fibers were bent inside the head in order to provide only one pigtail containing all the fibers. The dimensions of the transducer are 50x25x5 mm^3.

2.2 Light coupling

Once the fiber optic cantilever beam movement has been proved to be proportional to the acceleration, it is necessary to study how the optical power coupled into the receiver fibers changes according to the cantilever displacement. The light coupling curve, that is, the optical power collected by each receiver fiber versus the position of the emitter fiber, must be obtained for the types of fibers employed. As the optical power coupled between monomode optical fibers is very low, only multimode fibers were considered for evaluation.

There were some theoretical studies on the optical losses in multimode fiber optic connectors due to misalignments[12], but the precision required in sensor applications obliged us to determine the modulation curve experimentally. We did it for various types of fibers and several axial distances between the emitter and the receiver in order to optimize the design of the sensor head. The parameters that were taken into account in order to chose the ideal performance are the following:

- The static collected optical power should be as high as possible to provide a good S/N ratio.
- The modulation index (the slope of the modulation curve) must be high to improve the sensor sensitivity.
- The linearity of the optical power must be high over the total range of displacement of the emitter fiber.

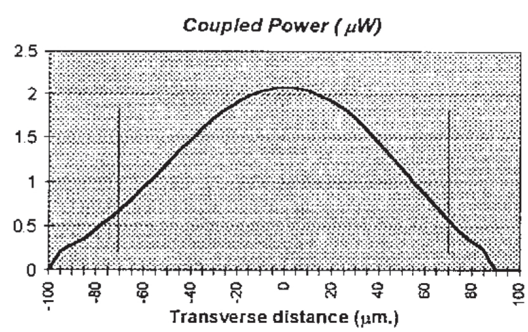

Fig. 3. Power coupled into receiver fiber versus lateral displacement of emitter fiber.

The theoretical study was supplemented with the measurement of the modulation curve in the laboratory. A computer-controlled micro-positioning system with a 60-nm resolution was used to move the emitter fiber, keeping the receiver fiber motionless. The optical power collected by the latter was represented in terms of the position of the moving fiber. Figure 3 shows the modulation curve obtained for the 100/140 fiber experimentally. The static point of operation corresponds to the transverse distance of 70 μm, which is the radius of the receiver fibers.

2.3 Optical channel

The optical channel is used to deliver the optical signal from the light source of the electronic unit to the emitter fiber of the sensor head, and to guide the modulated light from the two receiver fibers to the photodetectors. Thus, the optical channel contains three fibers per sensor head. These fibers are jointly attached in order to be equally affected by the external perturbations, cable bending and temperature changes, mainly.

New optical pigtails for the sensor heads and a new fiber cable for the optical channel were customized and manufactured using materials that meet the requirements of a numerous international specifications for zero-halogen cables.

2.4 Electronic unit

The electronic unit is mainly composed of five parts. The light source chosen is an LED, because it gives less intrinsic noise (between 20 and 30 dB) than the laser. For the detection part, the most suitable light receiver element is the PIN photodiode; the avalanche photodiode is rejected because of the complexity of its associated control electronics. Both electrical signals generated in response of the lights are pre-amplified and filtered and they are electrically processed using a differential pattern based on analog components. The output signal is amplified and filtered within the selected frequency band. The output signal of the electronic unit is then a trustworthy reproduction of the acceleration applied to the remote optical transducer head.

The signal treatment mentioned above allows the compensation of the sensor for environmental perturbations (temperature changes, component aging and changes in the optical path losses), as long as the two paths are equal and are subjected to the same disturbances, that is, they have the same optical path and the same opto-electronic converters.

4. EXPERIMENTAL WORK AND RESULTS

The performance of the complete system was tested in the laboratory, both individual parts and the sensor as a whole, and measured results showed to be in substantial agreement with the expected values. Regarding the mechanical behavior of the sensor head, the feasibility of using an optical fiber beam as an acceleration transducer was proved and published in a previous work.[8] Its reliability in continuous vibration operation was also validated. The resonance frequency of the prototypes fabricated, which determine the frequency region of operation of the transducer, ranged from 2000 to 2050 Hz, while the theoretically calculated value for the 30-450 Hz region was 2045 Hz.

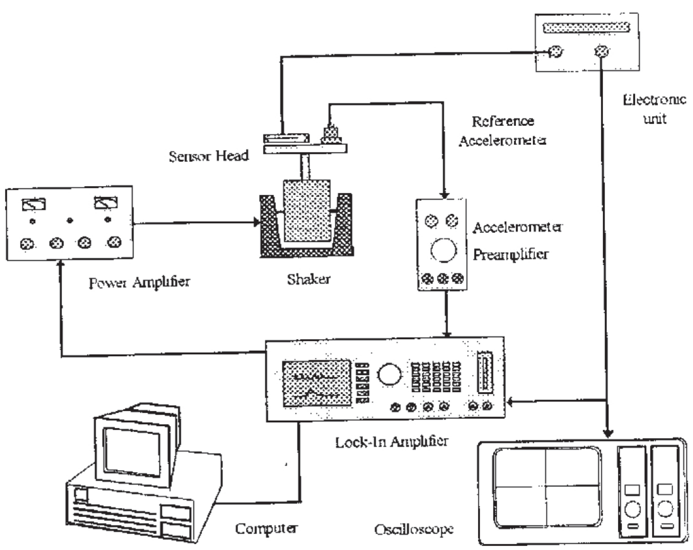

Fig. 4. Experimental setup used in the characterization of the optical fiber accelerometer performance.

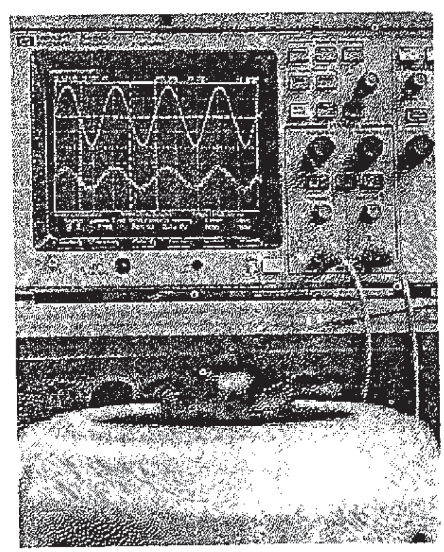

Fig. 5. Outlook of the vibrating sensor head and a comparison between the fiber optic system output (upper signal) and the reference accelerometer signal.

The modulation curves taken into account in the optical transducer fabrication were those obtained experimentally with the assistance of a computer-controlled high-resolution positioning system. Several tests were done with different types of fibers and different longitudinal distances between the emitter and the receiver, in order to chose the fiber-distance pair that provided the best linearity, sensitivity and amount of power coupled. The non-linearity was 0.5 % within the cantilever displacement range, the sensitivity was 23.6 nW/μm and the amount of coupled light power was about 700 nW.

Every single part of the electronic unit (emission, detection, processing, filtering and amplification) was examined individually and they proved to do their function with great linearity and accuracy. The noise output power (RMS) of the electronic unit was -36 dBm. It was also tested in climatic chamber and a maximum temperature drift of 0.07 %/°C was measured within the range 0-50 °C.

In order to characterize the whole optical fiber sensor, the setup shown in Figure 4 was used. A Stanford Research 850-model lock-in amplifier drove the power amplifier which excited a Tiravib 5100-model shaker. The optical transducer head and the Bruel & Kjaer accelerometer were forced to vibrate on the shaker according to the excitation, and their electrical signals were acquired and treated in the computer. Figure 5 shows the signals from the optical system and the reference accelerometer as they were visualized on the Hewlett Packard digital oscilloscope.

The amplitude and frequency responses are depicted in Figures 6 and 7. The amplitude range runs from 0 to 20 g RMS, with a non-linearity, at 70 Hz, of 0.42 %. The minimum detectable acceleration is 0.1 m/s^2. The frequency response is flat within ± 3 % in the range 30-450 Hz. Temperature tests were carried out in an ACS Hygros 15-model climatic chamber. The temperature range is 10 to 90°C for the transducer head and 0 to 50°C for the electronic unit. Finally, the output scale was settled to range from 0 to 10 V, so the accelerometer sensibility is 500 mV/g. The transverse sensitivity of the sensor is better than 5 % in the mentioned frequency range.

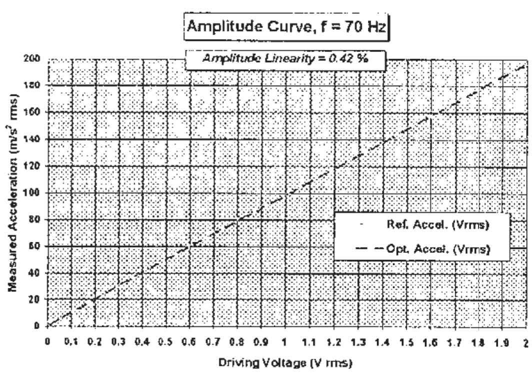

Fig. 6. Amplitude performance of the system at a frequency of 70 Hz.

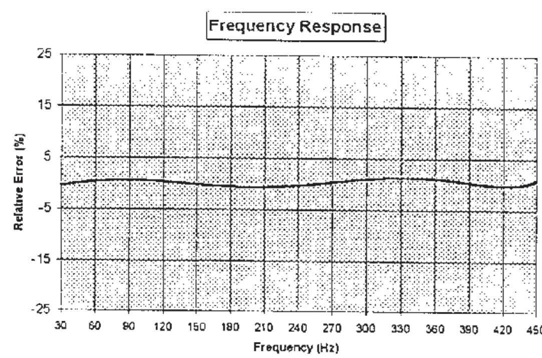

Fig. 7. Frequency response of the optical fiber accelerometer.

5. CONCLUSION

A new optical fiber accelerometer system has been developed. It is intended to be applied in an integral system aimed to detect and evaluate malfunctions in stator windings of hydroelectric generating sets, and anticipate mechanical failures in such machines. It allows multi-point vibration monitoring.

The system was completely implemented and tested in the laboratory. It is composed of several transducer heads (as many as the number of points to be monitored), an optical channel and an electronic unit. The sensor heads are made of