The danger of vibration in power transformers

Online detection of windings distortion by direct vibration measurement using a thin fiber optics sensor

ABSTRACT

A thin fiber optics sensor, VibroFibre, has been developed to fit into a 2 mm gap in transformer windings for directly measuring the winding vibration. The new innovation is aimed to help the transformer users to safely extend service lives of their assets and to mitigate risk of unscheduled shutdown due to premature equipment failure. The optic fiber based vibration sensor can be installed inside a transformer and the resulted vibration measurement is no longer affected by various noise sources from peripheral equipment. The vibration frequency spectrum measured inside an oil-filled transformer, shows a signature of wider band ranging between 20 Hz to 1000 Hz. The new sensor has shown superior performance, especially in its response to frequencies below 100 Hz. When combined with the new Long Gauge technology, the response goes as low as 5 Hz. The sensor's small size makes it possible to install the sensors in the winding spacers with built-in cradle-like slots, which helps avoid possible disturbance to the cooling oil flow.

KEYWORDS

vibration, diagnostics, VibroFibre, Internet of Things, oil-filled transformers

1. Introduction

The key to a sustainable power grid rests on high voltage power transformers. Transformers used in the North American power networks are currently over 30 years of age on average, and many are approaching the end of designed service lives. In managing the power grids safe operation, partial discharge (PD) is considered a best indicator for the transformers' residual lives. PD monitoring is currently the most persuasive tool used to forecast a transformer's remaining life. In this respect, the industry relies on using piezoelectric-based PD sensors, which are mounted on a transformer's tank walls to collect the PD related vibration signature analysis. The difficulty

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of signature analysis, which lies with poor signal quality, curbs the accurate life prediction. This paper proposes and describes an innovative method based on thin fiber optics sensor technology. The new optic fiber sensor can fit right into transformer windings, thus achieving the desired direct measurement of winding vibration without the signal attenuation and degradation associated with external sensors. The development of this new technology has been inspired by extensive academic research, in which a rigorous finite element modeling was employed to simulate the magnetic force interaction and the mechanical vibration inside a transformer. The new sensor is not only capable of measuring the vibration behavior, but also simultaneously obtains the operating temperature in the core of a transformer. A showcase of the technology's application was conducted in collaboration with an industry partner, which came out with successful results that have proved the technology's capability in providing a cost-effective monitoring and diagnostic tool. To serve for extending the installed transformers' safe operating lives, some further field testing has been arranged with an aim to adapt the sensor's design structure and to make it compatible with OEMs' manufacturing process.

2. Why is transformer monitoring necessary?

Drastic changes are happening in the power industry as everybody is trying to adjust to the new Environmental Protection Agency (EPA) regulations issued in the United States to reduce the greenhouse gas emission as a major cause of climate change. One outcome is the rapid growth of renewable energy such as solar and wind power. The intermittent nature of these renewable sources requires an adaptation of fast-response power sources to balance the grid. Luckily, shale gas is now abundantly available and inexpensive in the USA, which allows the utility sector to switch from coal to gas. On the other hand, there are utilities that wish to address the reliability and the performance of the existing grids. Many of them have started building extensive transmission networks, for which the key equipment is the high voltage power transformer.

Transformer faults exhibit various different modes such as winding distortion and displacement, interconnect loosening, etc. A minor fault can develop to become major and severe, such as winding breakage and insulation breakdown. The faults can be attributed to the material and structural deterioration, which are usually caused by the mechanical movement and vibration-induced winding wearing and tearing, chemical corrosion and manufacturing defects, etc. Windings are a major structure component in the core of a transformer. The dielectric, thermal and mechanical stresses the windings are subjected to during the transformer's operation will cause material deterioration, shape distortion and displacement and interconnect loosening, etc., which all contribute to the decrease of the transformer performance. Windings distortion can be mechanically induced during the transport of a transformer, or electrically by large transient current surges during a lightning event or by a short circuit, or by aging-induced gradual clamping looseness under constant load cycling. Winding distortion can create extra electromagnetic force between the windings and the core, and in turn give rise to the change in the transformer vibration signature. The signature information is a tool for online condition monitoring of the transformer. The partial discharge (PD) monitoring has been widely used as an indicator of the transformer residual life, yet the piezoelectric based PD sensors comprise electrically conductive parts, which hinders the operation of such sensors inside a transformer. As a compromise, the PD sensors are in common practice installed on the external walls of a transformer tank. The signals so received are consequently highly dependent on the positions where the sensors are mounted, and are contaminated by the noises from oil pumps, cooling fans, or the tank itself. As a result, a transformer's frequency signature such as the PD counts and the intensity distribution can hardly be analyzed effectively to tie to a unique degradation process, although the frequency analysis does work sometimes if a transformer happens to operate in a resonance condition.

With the direct measurement of winding vibration, the signal attenuation and degradation associated with external sensors are avoided

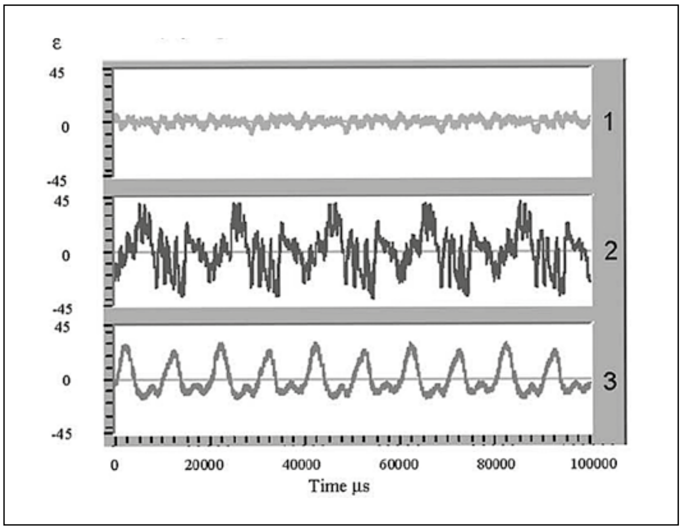

Figure 1. Low frequency plot of a used transformer [8]

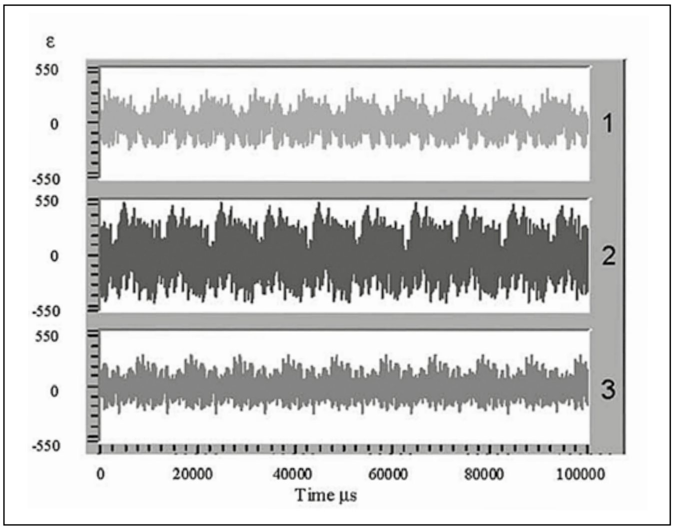

Figure 2. High frequency plot of a used transformer [8]

Vibration analysis can detect undesirable winding movement caused by transportation or large current surges due to short circuits or lightning strike

3. Challenges

According to a CIGRE report [1], 41 % of the failures found in power transformers are connected with the on-load tap changer and another 19 % with the windings. Given that excessive vibration is a major cause that leads to winding displacement and deformation [2], connection looseness and insulation deterioration, vibration monitoring can act as a very good indicator of the upcoming winding failures. The winding looseness is a leading cause of internal short circuits. The amplitude change of the vibration signal can be a good indication of the loss of winding clamping. The winding movement as another winding fault is also hard to detect as the windings are usually encased within the oil tank. Visual inspections are useful, but not very practical since they require service interruption. Dissolved gas analysis (DGA) offers a snapshot, yet it provides no information about the rate of transformer degradation. Vibration analysis can detect undesirable winding movement caused by transportation or large current surges due to short circuits or lightning strike [3].

Frequency Response Analysis (FRA) has recently attracted much interest. As a previous study reported, by comparing the frequency spectrum with a reference state, an FRA [4] may indicate structural movement in the windings. It has been shown that transformer natural frequencies tend to decrease as the clamping pressure reduces and windings become loose overtime. Indeed, during the transformer manufacturing process,

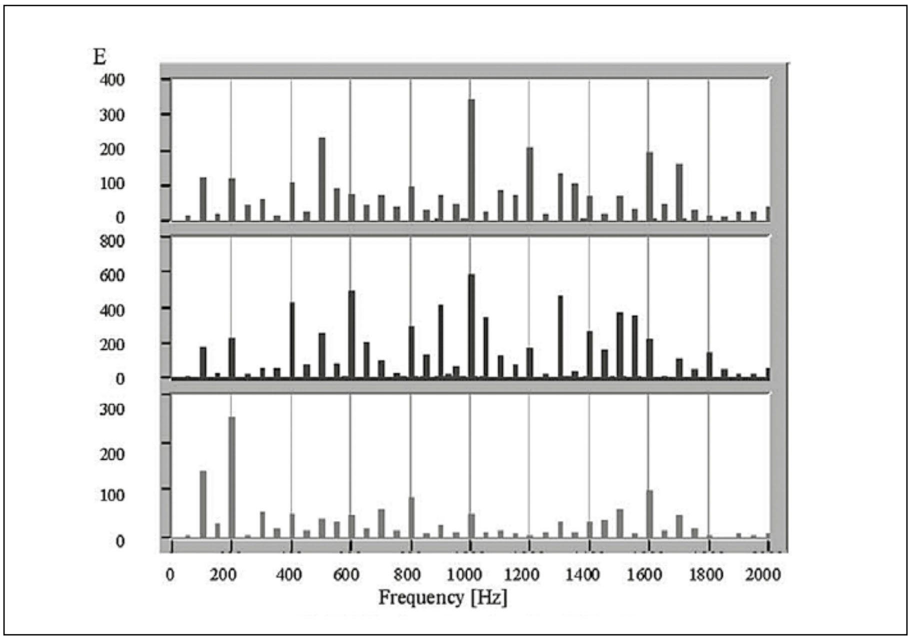

Figure 3. The Discrete Fourier Transform showing the signature of winding distortion [8]

Figure 4. Photograph of windings that underwent deformation [9]

the winding assembly is clamped to an intended pressure. While amplitude diminution is perceived, the frequency shift remains quite small. FRA remains a popular method to detect winding movement, but it is very difficult to interpret the results. Detecting winding motion and clamping looseness requires more sensitive vibration sensors with higher frequency measurement resolution. In addition, the frequency spectra of a fleet of transformers usually differ from one another, which contributes to additional complexity in identifying a defective transformer by comparing the spectra of all the units. Furthermore, the commonly practiced FRA has to be performed on offline transformers, which implies revenue loss due to the required downtime. This loss of revenue has become a deterrent. The frustrations of trying to achieve a simpler method have led to the development of new vibration sensors that can work inside the oil tank, becoming an online tool that can detect the ongoing dynamic electromagnetic and mechanical force interaction [2, 3, 5, 6 and 7].

The proposed new sensor is 2 mm thick, 50 mm long, and 20 mm wide in size. It is the thinnest vibration sensor in the world, yet it can measure vibration between 5 Hz and 1000 Hz. The work is underway to show that the significant faults such as the winding distortions including buckling and bulging, the open and short circuits, and clamp looseness can be detected and identified (see Figures 1, 2, 3 and 4).

Missing inter-winding separation can also be identified as the sensor trends the vibration amplitudes at twice the line signal frequency (2xLF). The capability of simultaneous measuring temperature provides a cost-effective monitoring solution for extending transformer life while providing online diagnostics. In the following, it will be described how VibroFibre sensor was adapted to make it fit between the narrow gap of the winding turns inside a transformer (see Figure 5).

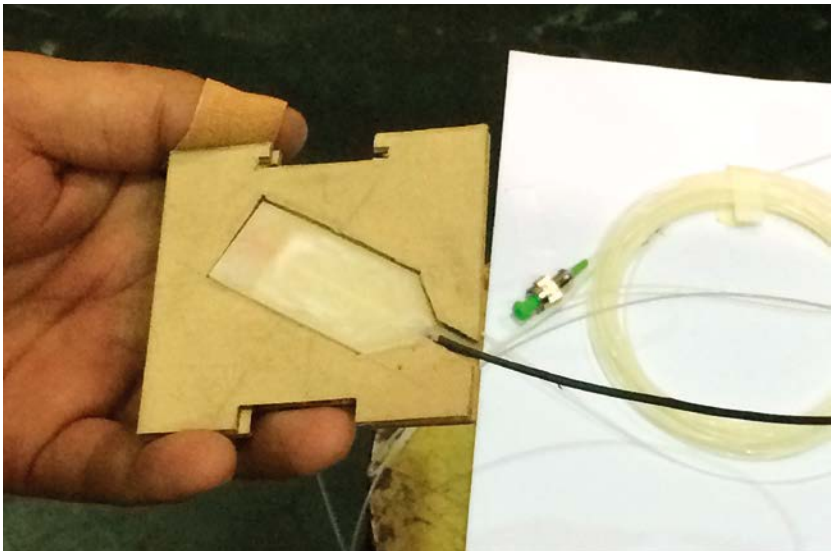

Figure 5. Long Gauge VibroFibre thin head set into a press wood spacer

4. Long Gauge Vibrofibre technology

The VibroFibre, originally developed to monitor vibration at the end windings in large power generators, is mainly used for capturing the vibration signature via the sensor head (discrete sensor). VibroFibre is an extended version of the Fabry-Perot fiber optics vibration sensor.

The latter has been deployed around the world for monitoring generator Stator End Winding (SEW) vibration. With a small modification that acts like a signal enabler, the Long Gauge VibroFibre was born as a distributed sensor [10]. The interrogator emits a narrowband laser signal, whose central frequency is phase-locked to one of the interference fringes. With these new features a Long Gauge VibroFibre can detect environmental effects such as vibration and temperature via the observed interference pattern shift in terms of the voltage sensed by embedded photo-electric transducers. The electrical changes can then be trended and compared. The original VibroFibre design contains a diving board acting as a mechanical amplifier to enhance its sensitivity. The sensor has a thickness of 8

The low frequency resolution and difficulties in identifying the frequency signatures require usage of multiple sensors on the tank walls (up to 50), making such tests expensive for commercial use

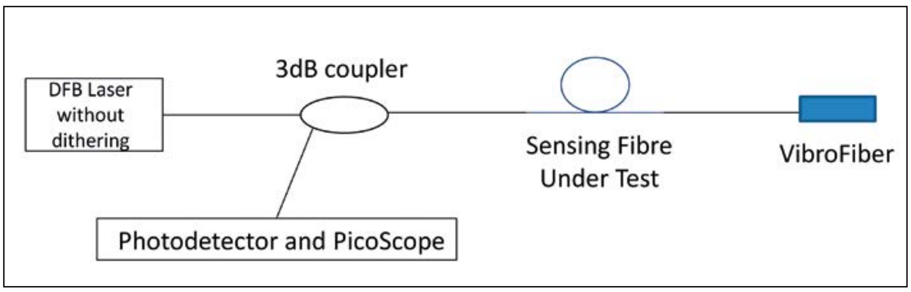

Figure 6. Block diagram of the distributed vibration sensor: a laser source interrogates the sensing fiber and feedback is returned to a photodetector via the VibroFibre

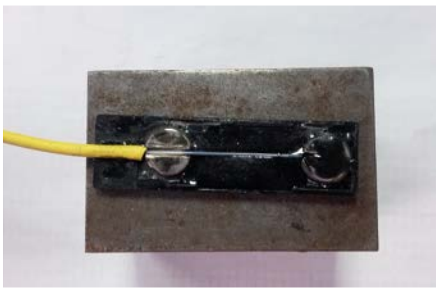

Figure 7. Example of internal structure of the VibroFibre with emphasis on the fiber optics

For sensors to work inside the oil tank, the sensor cabling must not allow any air bubbles to be trapped in and introduced to the mineral oil

mm, which makes it unfit to the narrow gap between winding turns of the transformer. This sensor has been modified by splicing a length of single-mode optical fiber into the cavity, and as a result, the whole fiber became a distributed vibration sensor (Figure 6). The innovation has turned the vibration sensor into a wideband one since the fiber is now resting freely inside a 900 µm Teflon tube. Figure 5 illustrates how we cut a slot into the press wood spacer to fit the thin sensor. The spacer acts like a package and protects the sensing fiber without obstructing the flow of the cooling oil. In doing so, a small size fiber can readily be used to reduce the size of the vibration sensor (see Figure 7).

5. Vibration measurement outside and inside the transformer

Figure 8 demonstrates how the new sensor can measure the vibration inside a transformer. In contrast, if the vibration sensors are mounted on an external wall, as seen in Figure 9, they are disturbed by the vibration noise coming from peripheral equipment such as the pumps and cooling fans. Also, the sensor-received vibration signals depend very much on the sensor location [7, 11 and 12]. Some earlier work has shown the difference among the vibration signals received at the top and the bottom of the transformer tank, as shown in [6]. More extensive analysis succeeded in differentiating the time domain of the signals that were received from new, used and anomalous transformers (see Figure 10 and [5]). It seems that the lower frequency signals (below 1 kHz) are more discriminating in comparison to the higher frequency signals since the latter were heavily affected by the large background noise floor. For transformers under suspicion, the high frequency side of the signal is less continuous in time, displaying instead ephemeral bursts of periodic signals similar to those caused by partial discharges. Coping with the low frequency resolution and the difficulties in identifying the frequency signatures, many researchers opted to mount multiple sensors on the tank walls; as many as 40 to 50 sensors were used in one transformer test. The signals received by the sensors were mainly in lower frequencies between 120 Hz and 240 Hz [2 and 13]. This made such test overly expensive for commercial deployment.

Figure 8. The press wood spacer is inserted between the winding turns. The coupled sensing fiber picks up vibration signature.

6. Winding vibration monitoring in field tests

In studying Stator End Winding (SEW) vibration of a power generator, the main signal received is the 2xLF. The sensors are installed inside the generator on the end winding. An aging generator will suffer from severe structure looseness, resulting in the increased structure vibration amplitude. This phenomenon can be utilized as a criterion in the vibration monitoring. According to the published literature the vibration signatures inside the oil tank of a transformer have a wideband frequency ranging from 20 Hz to 1000 Hz. In our previous collaboration with Manchester University as it was shown in [12], we compared the VibroFibre with the conventional piezoelectric sensor. The results proved that the VibroFibre had a superior performance in monitoring frequencies lower than 100 Hz. In a field test conducted in China, the new sensor was installed inside a test transformer (110 kV, 350 MVA) in a location between the winding turns to measure the windings axial vibration. A built-in slot was prepared in a winding spacer to act as a cradle of the sensor body. The scheme provided physical protection to the sensor, yet no disturbance was exerted on the flow of the cooling oil as the result of the sensor installation. This filed test was the first on-site demonstration, and it successfully showed the technology's unique capability in observing various vibration signatures in relation to the winding looseness, movement and distortion, etc. (see Figures 1, 2, 3 and 4).

7. Proposed solutions

Companies in the power generation industry are typically conservative in that they barely allow internet connections in their control room. The fear is that a cyber-attack, if happened, could turn off their generators. When we installed the vibration monitoring solution for the stator end windings, it was very difficult to obtain the final data that we helped collect and trend until some personal relationships were built with individual technical staff at the plant to send the data offline.

In the last five years we were unable to provide an optimal value of our solution due to this lack of data. Given that the timely information and diagnostics are critical for optimizing the maintenance programs, the recent emergence of the Internet of Things (IoT) is proving to be one of the best solutions. In addition to the sensor innovation, the architecture of the Transformer Guard – a system whose embedded laser interrogates the fiber optics based sensor – also underwent application adaptation. While keeping many features for interrogating the VibroFibre, new elements had to be implemented to optimize the quasi-distributed ability of the Long Gauge VibroFibre.

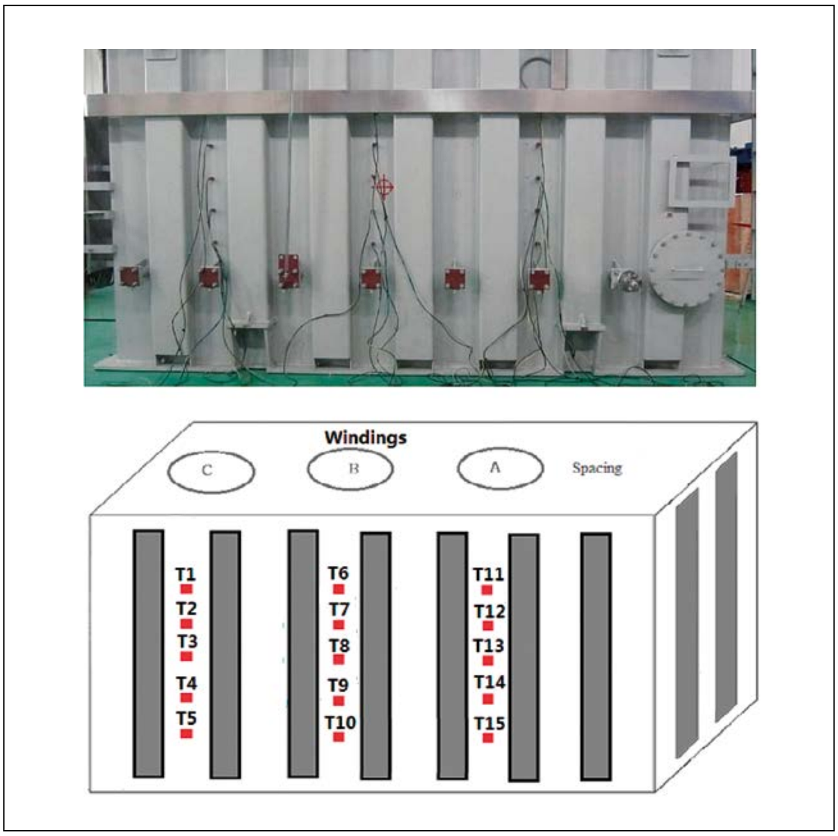

Figure 9. Accelerometer locations on a transformer tank [7]

Regarding the optical networking, the sensors are placed inside the oil tank and output optical signals are transmitted via a hermetic junction plate to a composite optical cable. The latter can drive the signals to the control room located at a distance up to several kilometers. The optical form of the data prevents any possibility of electrical interference and noise contamination of the original signals. The interrogation unit used is equipped with an interface module to enable data transmission to a cloud. The module is also built with the connection to the conventional standard Modbus via RS-422/485. The edge module has a processing power sufficient to perform data processing and data summary, which means it is unnecessary to send a huge amount of raw data to the cloud. The proposed solution will also employ a Supervisory Control and Data Acquisition (SCADA) system, which is a control system architecture that uses computers, networked data communications and graphical user interfaces to provide a high-level process supervisory management. The obtained test data is correlated to the operating data from the customer's SCADA system and other external sources. The present technology, the Long Gauge VibroFibre, picks up vibration excitations along the optical fiber and the sensor head can measure temperature. Provided another transduction model is added, such as moisture sensing via fiber optics and trending of current load, correlation analysis enables a most complete picture of the transformer aging condition. Via the cloud, the said raw data will be turned into useful information for the management decision making, and become accessible by all relevant units in a customer's organization. Another module acts as a cloud-based sensor node at the tank wall in order to transmit data to the cloud such as tank temperature, DGA and PD measurements. An operator or technical staff equipped with a cellphone or a tablet can obtain warning and detailed information that is sent from the system via the cloud while physically being off site, where the hostile environment temperature could go from -40 °C to 60 °C. Some other critical issues need to be tackled in order to enable the new sensors to work inside the oil tank, including that the sensor cabling must not allow any air bubbles to be trapped in and introduced to the mineral oil. The air is easy to break down to the oil, triggering arcing events inside a transformer.

As the industry is headed towards using higher voltage transmission to reduce the transmission loss, there will be more technical problems associated with this. In addition, different forms of adapted Long Gauge vibration sensor are needed to measure the vibration of the windings along the radial as well as the lamination directions of the core. Indeed, similarly to the sensors set to the tank wall showing dependency to location, measuring different directions (phases) of winding along its different components displays various signature facets. In these cases, the vibration sensing head will need to consist of single-mode fiber enclosed inside the perforated Teflon tubes. In fact, the sensors being developed such as the moisture sensor and PD sensors for working inside the transformers need to be equipped with the porous cables, since the dense pores along the cable could allow air to escape during the vacuum process in manufacturing.

The solutions will be first introduced to transformer OEMs who can integrate them into their manufacturing process to contribute to timely service and maintenance of their products in order to extend service life. In the meantime, we have plans to approach service companies and help the customers rework and repair the existing transformers. These results will be reported later.

Conclusion

The adaptation of the vibration sensor technology is aimed to work inside transformers. The currently available solution is capable of providing an integrated monitoring platform for improved predictions of the residual lives of transformers. A large step forward has been made beyond the sampling of the insulation oil with neither reference nor

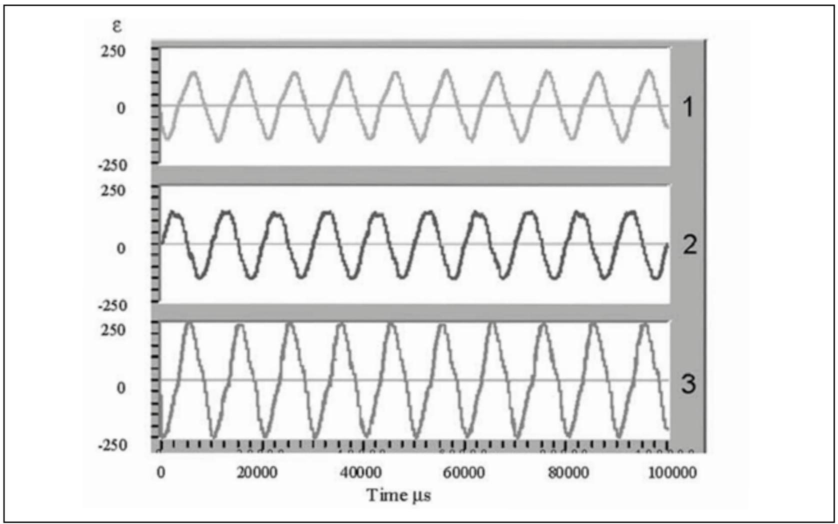

Figure 10. Low frequency plot of a new transformer [8]

The currently available solution is capable of providing an integrated monitoring platform for improved predictions of the residual lives of transformers

correlation to the operating temperature and the loading information. Further field tests will enable design adaptations of the sensor structure to make it compatible to the OEMs' manufacturing process.

The next challenge is to develop a trace moisture and temperature fiber optics sensor. Once the capability of collecting the failure relevant data is enabled, focus will be shifted to help the customers measure the logistics of moisture transport in oil and to understand the mechanism that the moisture goes back and forth from the oil to the pressed wood holding frame and the cellulose paper wrapped around the windings. The transport mechanism is apparently dependent on the operating temperature of the transformer, which is in turn affected by the ambient temperature and the loading.

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Peter Kung obtained his MSEE degree from the University of Minnesota. He is currently the president of QPS Photronics Inc. in Canada. Peter has 20 years of semiconductor experience and another ten years in Telecom. He invented the phase masks in 1991 and spent 15 years developing the fiber grating technology, process and products. His latest invention is the VibroFibre – vibration sensors used to monitor vibrations in the stator end windings inside high power turbine generators. His objective is to work with partners to adapt this technology platform towards greenhouse gas monitoring, enhancing the reliability of the power grid.