TRANSFORMER VIBRATION MONITORING USING A WIRELESS SENSOR NETWORK

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Abstract. Transformer vibration monitoring is often at present implemented under laboratory conditions. If it is to be used for preventative maintenance in the field, remote access, limited energy usage and data communications have to be taken into consideration. The present work describes results of a system using an IEEE 802.15.4 based wireless sensor network, a matrix of accelerometers and a communications gateway to measure the distribution of frequency amplitudes across a transformer tank surface. Frequency spectra at different positions on the surface show harmonics and the variation of vibration amplitudes across the surface are presented. With a change in load conditions the distribution of frequency amplitudes varies. The system can be installed on a remote transformer with only minor adaptations to ruggedise it.

Key Words. transformer monitoring, vibration sensing, wireless sensor network

1. INTRODUCTION

Electrical power network downtime due to unscheduled interruptions in the supply line can cause major economic disruption. Transformer breakdowns can cause such interruptions and a system that can act as a predictor for imminent transformer breakdown or failure would allow preventative maintenance or replacement of faulty equipment. Before such a predictive system can be implemented a system has to be developed that can monitor the performance of a transformer in the field under varying load conditions. A wireless sensor network (sensornet) that can remotely monitor the performance of power line transformers is proposed here.

Transformer condition monitoring through sensing various characteristics has been an ongoing area of research [1] and can be implemented by various methods. Abu-Elanien and Salama [2] published a survey of all methods such as thermal, vibration, partial discharge, dissolved gas and frequency response analysis. They concluded that dissolved gas analysis was "well defined, well understood and no more enhancements are to be expected" but the special arrangements it required limited its application to on-line monitoring. They furthermore concluded that other techniques needed more development before an on-line system of condition monitoring and fault diagnosis could be realised. This project initially concentrates on vibration analysis.

Remote monitoring of equipment has been greatly enhanced in recent years through the application of sensornets. Applications to power transformers have recently been explored by Baker et. al. [3] who sensed partial discharge and Nasipuri et.al. [4] who sensed temperature and bushing voltage phase differences. Behaviour of transformers in the field (not only in the laboratory) can be determined in much greater detail due to (a) smaller sized sensors, (b) wireless remote monitoring, (c) low power requirements and (d) long term monitoring. Considerations that have to be taken into account on vibration monitoring of power transformers are discussed in part 2. The system described in part 3 goes some way towards this goal. In part 4 experimental results are presented and part 5 concludes that the proposed system could greatly enhance real-time vibration condition monitoring on power transformers in the field.

2. VIBRATION MONITORING OF POWER TRANSFORMERS

There have been several studies into using vibration methods to check conditions of power transformers [5], [6], [7], [8], [9]. Magnetostriction and electrodynamic forces acting on the core and windings of the transformer cause vibrations that are transmitted through the transformer oil to the tank walls. The tank walls therefore oscillate and the two-dimensional distributions of these oscillations are to some extent influenced by the normal modes of the tank wall. The mechanical deformations in the transformer are non-linear causing the generation of harmonics of the fundamental frequency. There is little evidence for significant harmonics above 1000Hz [5], [6], [7] when high frequency responses (up to 1MHz) used for diagnostics [8] are not considered for on-line monitoring. The distribution of amplitude vibrations over the tank surface has not been investigated in any detail other than positioning sensors over each core [5], [7].

In the system presented here we sampled the vibrations at about 500 samples per second restricting the frequency range to 250Hz. In order to determine the two-dimensional surface distribution of vibration amplitudes a matrix of accelerometers were deployed over the surface.

3. SYSTEM DESCRIPTION

To effectively map the vibration behaviour across the tank of a transformer, a low power, low maintenance, wireless sensor network was required that could easily be deployed in remote locations. The architecture for this system was developed using a sensornet of IEEE 802.15.4 nodes (motes) capable of

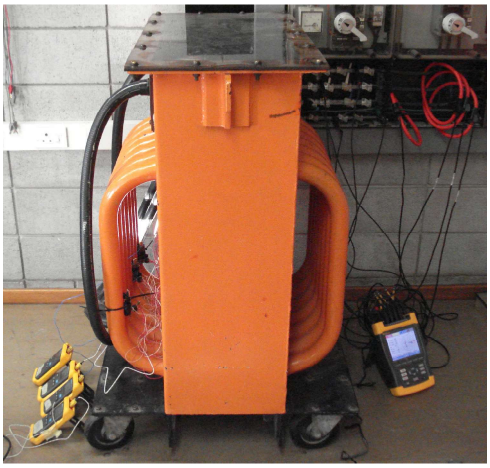

Fig. 1: Transformer during testing.

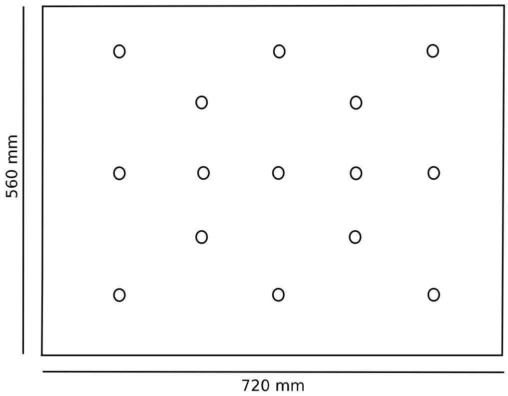

Fig. 2: Positioning of accelerometers in the area underneath the transformer cooling tubes.

communicating data across a gateway to a PC for post processing.

The sensornet was designed using TelosB wireless sensing nodes, each running an MSP430 processor and using the 2.4 GHz Chipcon CC2420 radio for spread spectrum 802.15.4 communication. Attached to the 12 bit ADC of each mote were five LIS352AX 3-axis accelerometers capable of measuring 0-2 g within a bandwidth of 2 kHz. The sensors were chosen predominantly for their operating voltage range and relatively wide sensing bandwidth.

The laboratory transformer under test was a 3 phase, star-delta, 47 kVA, 220 V, 50 Hz, isolation transformer with dimensions 720 mm by 960 mm by 335 mm (see figure 1). Each of the 15 sensors were mounted on small PCBs that were attached in a grid-like pattern to the side of the transformer tank (as in figure 2) on an area between the cooling tubes using thin double-sided tape. Lightweight wires were used to connect the sensors to individual motes mounted on the cooling tubes surrounding the plate. By placing the motes away from the vibrating plate, any additional mass loading effects were minimised.

The software for the network was implemented using TinyOS in which a designated mote was chosen as a master. This mote polled for the required number of motes to be active, before sending out a synchronisation packet. The synchronisation packet informed each mote of the time period before a sample set is to be taken.

Sampling is performed at approximately 500 Hz with 600 samples recorded per channel. All ADC channels are sampled sequentially as fast as the ADC permits facilitating almost instantaneous sampling. The sample sets from each mote were then transmitted to a computer for logging and post processing at intervals of approximately 9 seconds.

Matlab was used as a post-processing tool to map the sampled acceleration data as a snapshot of displacement. The method used for this involved capturing the time domain sample sets for each sensor and performing a Fast Fourier Transform on the data. Absolute magnitude and phase were calculated and the dominant resonant modes for the plate were extracted by performing a maximum amplitude search of the power spectrum. Initial observation revealed distinct mechanical resonances caused by magnetostriction and interwinding vibration [5] typically present at around 100Hz. By dividing the absolute magnitude spectrum by $-\omega^2$ it was possible to transform the acceleration data to displacement. In order to display a smoothed two-dimensional surface plot of amplitude vibrations an array of data points was created with dimensions those of the unencumbered tank surface (the area inside the cooling tubes). This array was populated at each sampling point with the measured amplitude at that point of each selected frequency. Convolving this "bed of spikes" with a Gaussian kernel yielded a smooth surface distribution of the vibration amplitude.

Power density spectra contain no information on the relative phases of the deviations at different positions. To determine this the amplitude and phase of the vibrations at each accelerometer site were determined and could be compared.

4. Vibration Spectra

Data from each of the fifteen accelerometers show the fundamental vibration frequency at close to 100 Hz and harmonics at close to 200 Hz. In order to get a clear estimate of the spectrum a separate experiment was performed to sample 3000 data points at 1000 samples per second at one sensor. This data provided a frequency spectrum plot as shown in figure 3. This is similar to spectra reported elsewhere [5].

The natural modes of vibration of the transformer tank surface were unknown. To investigate the amplitude distribution over the surface using fifteen accelerometers the sampling rate had to be reduced to 500 samples per second. Amplitudes as a function

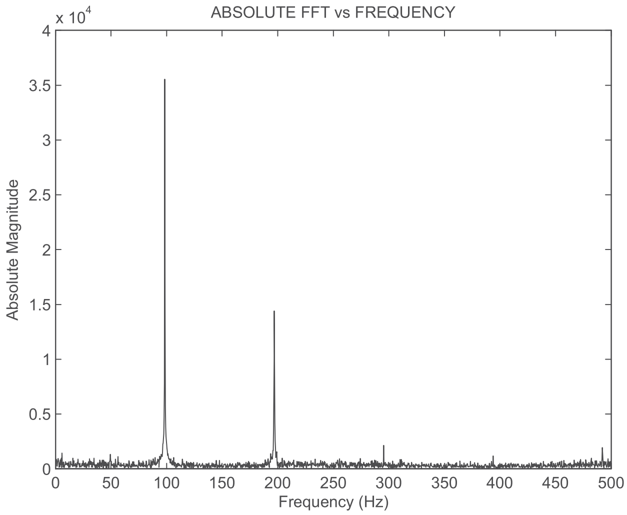

Fig. 3: Frequency spectrum plot from an accelerometer near the centre of the transformer tank surface.

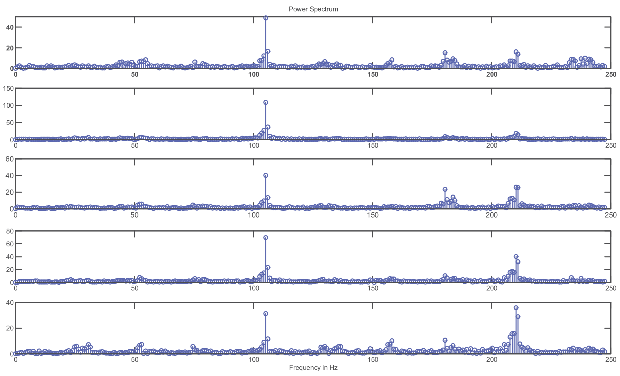

Fig. 4: Power spectral density plots of a mote's 5 accelerometers.

of frequency were calculated and these showed the fundamental frequencies at about 100 Hz and second harmonics at 200 Hz as shown in figure 4. The corresponding amplitude displacements could be positive or negative and hence the phases of the displacements were calculated. From the phase values the signs of the displacements were determined. Figure 5 shows the phase difference evident from readings sampled from two accelerometers.

Selecting the peak amplitude near 100 Hz for each position allowed a surface amplitude distribution plot to be generated. By changing the loading on the different phases of the transformer, different amplitude distributions were observed. Examples of these distributions are shown in figures 6 and 7. In figure 6 the top plot shows no-load condition with the lower plot showing only the white phase loaded. Figure 7 shows only the blue and red phases loaded in the top and bottom plots respectively. Notice the marked difference in amplitude distributions in the unloaded and loaded plots.

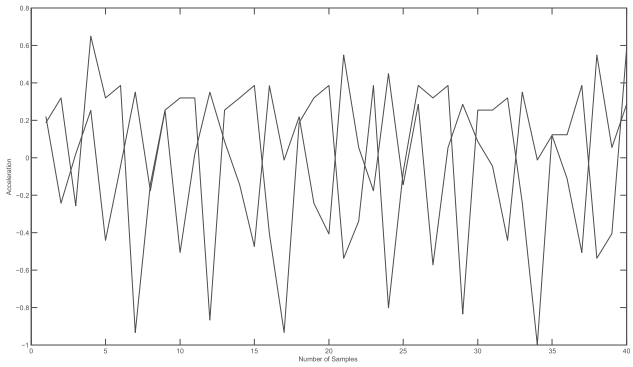

Fig. 5: Data from two accelerometers indicating phase differences.

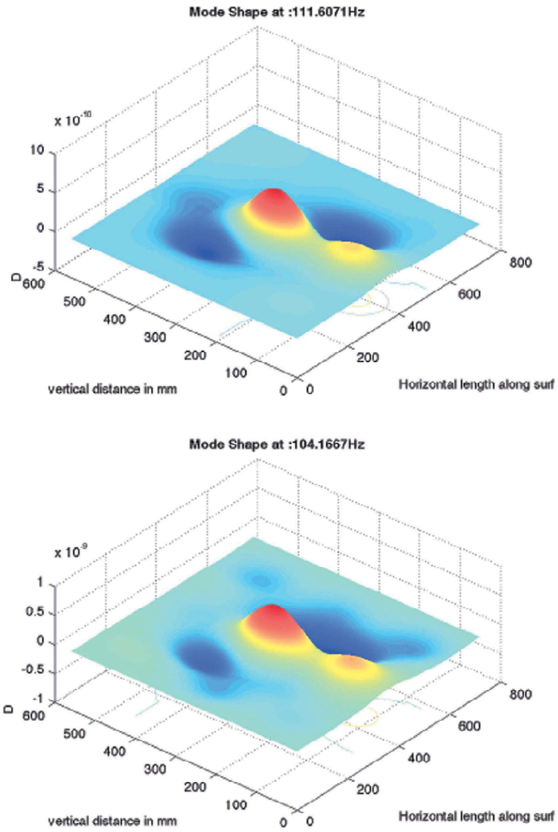

Fig. 6: Amplitude distribution plot for the transformer under varying loads.

5. Conclusions and Future Work

We have implemented a sensornet to evaluate a transformer whilst online using a grid of accelerometers. From this we are able to measure the vibration over a surface of the transformer tank and visualise the amplitude and frequency of its vibration. It can be seen that the amplitude distribution changes under varying conditions.Further analysis of the data is required.

Future work includes modifying the sensornet and logging and analysis software to facilitate long term

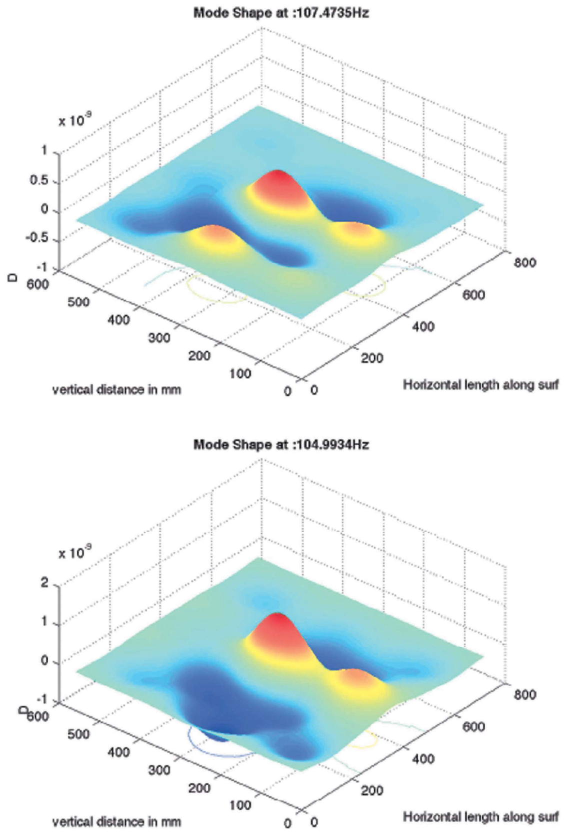

Fig. 7: Amplitude distribution plot for the transformer under varying loads.

unsupervised monitoring to further analyse the state of the transformer over time. Ruggedisation will be required to move the system out into the field.

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