Cost-effective wireless-controlled motor failure prediction for HVAC system in large buildings using demodulated current signature analysis

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Abstract: Monitoring electrical motors performance can be of a highly financial significance, particularly when downtime, production losses and premature equipment replacement or repairs are involved. Trending, benchmarking and being alerted when conditions deteriorate improve the ability to perform predictive maintenance and prevent unscheduled downtime. In industrial maintenance technology, many predictive maintenance methods are available, each best suited to a specific application. Vibration analysis of the motor is used to prevent failure in rotating machinery. However, motor current analysis supports the diagnosis of electrical problems that might be missed by vibration monitoring, which has proven to be a highly valuable predictive maintenance tool. Mechanical faults related to belts, couplers, alignment and more are also easily found through the use of a demodulated current spectrum. Electrical faults include over or under-current, short circuit of windings or electronics components and over-heating. The proposed system consists of hall-effect current sensors connected with the mains supply for each HVAC system in the building. The real-time output of the current sensor is sampled and wirelessly transmitted to the building control room. The received signal of each HVAC system is transformed into frequency domain and analyzed for any mechanical or electrical fault by comparing it with data of similar healthy machines. Upon detecting any recorded fault, a message will be displayed identifying the machine number and the fault type.
[Ahmed N, Atta R. **Cost-effective wireless-controlled motor failure prediction for HVAC system in large buildings using demodulated current signature analysis.** *Life Sci J* 2014;11(10s):33-39]. (ISSN:1097-8135). http://www.lifesciencesite.com. 6

Keywords: Predictive maintenance, HVAC, current signature analysis

1. Introduction

Motors are devices used to convert electrical energy to mechanical energy and thus providing a driver source for most of systems. Usually, alternating current (AC) induction electric motors are used in the air handling unit (AHU) as a part of heating, ventilation and air conditioning (HVAC) systems to drive the blowers which circulate the air. The blower may operate at a single speed or driven by a variable voltage drive to allow a wide range of air flow rates. The flow rate can also be controlled using a variety of inlet vanes, the opening of which can be controlled to reduce the flow. The typical placement of blower is at the end of AHU and the beginning of the supply ductwork. AHU has got heating and/or cooling elements which form a type of heat exchanger. As the air pass through this area, it get hot/cold and is circulated to the usage area using these blowers.

Maintenance is needed periodically to keep these systems running and any sudden failure can bring the whole system to halt. The major source of shutdown in AHU is the electrical motor. On-line condition monitoring is usually performed in electrical motors which can detect a device potential problem early before it turns into a serious problem. The early fault detection can ensure smooth running of the system and also prevent a major damage to the system. Keeping in mind the importance of on-line monitoring towards preventing such disruption and losses, many researchers have been working in this area. A usual on-line monitoring system typically includes components such as sensors, means of data collection, fault analysis and diagnosis. Depending upon the intent of data collection, the sensors vary from simple current sensors to vibration and temperature sensors. So far the most challenging part of the studies had been the diagnosis of the faults.

A model-based method for detecting and isolating faults in electro-mechanical systems was presented in (Zell and Medvedev 1998). The method utilized sensor data from the induction machine to extract information about the operating conditions of the mechanical process. The authors observed that the faults that occurred in the mechanical system resulted in periodic fluctuations in the load torque on the motor's rotor axis. An investigation about the efficiency of current monitoring for diagnostic purposes is presented in (Benbouzid, et al. 1999). The current signature of some asymmetrical motor faults was identified using advanced signal processing techniques. Experimental result demonstrated that the stator current high-resolution spectral analysis, proposed as a medium of induction motor faults detection, has finite advantages over traditionally used Fast Fourier Transform (FFT) special analysis.

Signal-based and model-based techniques were combined for detection of induction motor faults in (Parlos, et al. 2002). An empirical model-based fault diagnosis system was developed for induction motors using recurrent dynamic neural networks and multi resolution signal processing methods. The effectiveness of the diagnosis system was demonstrated through motor faults of electrical and mechanical origin staged in small and large motors. It was concluded that the use of standard motor electrical measurements and speed for detecting and diagnosing the most commonly encountered faults was possible and that no knowledge of detailed machine or bearing parameters was needed.

An overview of the most common expectations from modern instrumentations used in predictive maintenance of induction motors was presented in (Wiedenbrug, et al. 2002). Power conditioning problems was investigated in a controlled laboratory environment and the most important effects of overvoltage and undervoltage conditions, unbalanced voltage conditions and distortion were investigated. The conditions were created using a programmable power supply, offering unprecedented control over the voltage conditions an integral horse power motor was subjected under load. It was shown that existing technologies were capable of clear representation of the dynamic phenomenon on the shaft using the current and voltage signatures.

A new method for accurate three-phase induction machine fault detection using a simple torque excitation technique with the electrical drive was presented in (Henao, et al. 2003). The authors presented a technique to increase the low frequency side-band harmonic magnitude in induction drives. The method allowed detecting more accurately the small magnitude faults without deterioration of the overall torque quality.

An algorithm for detecting mechanical conditions in induction motors under any load condition using spectral analysis of the stator current was presented in (Obaid and Habetler 2003). Their proposed algorithm considered the load related abnormalities and resonance by classifying the load-levels into bins and calculating the baseline for each load bin. The algorithm then determined the load-level, when the motor was in operation and compared the monitored current frequency components to the appropriate baseline to detect the presence of a mechanical fault conditions.

The change in machine vibration due to excitation of voltage harmonics was studied in (Raj, et al. 2013) that helped in electrical fault detection in induction motors. A novel methods for detecting faults occurring due to mechanical origin such as mechanical looseness and misalignment in motor shaft coupled to brake drum was proposed with the help of MEMS accelerometer used as a vibration sensor. Experiment results confirmed that misalignment and looseness in mounting created additional amplitudes and frequency modulations. The phenomenon were detected and characterized by analyzing the vibration spectrum.

A modified version of music algorithm was developed based on the faults characteristic frequency in (El Bouchikhi, et al. 2012). The method was used to estimate the stator current spectrum. An amplitude estimator was proposed and a fault indicator was derived for fault severity measurement. Simulated stator current data issued from a coupled electromagnetic circuit approach was used to prove the appropriateness of the method for air gap eccentricity and broken rotor bars fault detection.

A study to detect mechanical irregularities in low voltage random wound induction motor by means of stator current monitoring and spectrum analysis was presented in (Bertani and Knight 2003). In this paper a complete fault system for induction motor of HVAC using wireless sensor network is introduced. The wireless data that carry the irregular power spectral of the induction motor current is transmitted through the network to the central control room where the data is analyzed and faults corresponding to specific motor are identified. A test set up was built where the effect of applying different electrical and mechanical loads on the current signature was studied.

2 Harmonic Analysis Technique

Voltage harmonics induced in the winding by the air gap flux density harmonics results in harmonics in the current spectra of a machine. Measuring the frequencies of air gap flux density harmonics can help determining the frequencies of induced current harmonics. At these selected frequencies the corresponding power spectrum amplitudes of the motor current data indicate the current signature of the motor. Therefore a current signature method is used to detect motor faults by investigating the sideband components around the supplied current fundamental frequency.

Theoretical analysis of the induction motor current has shown that faulty machine frequencies of interest are given by (El Hachemi Benbouzid 2000)

$$f_k = f_s \pm k f_c, k = 0, 1, \ldots, L \quad (1)$$

where f_s is the electrical supply frequency, f_c corresponds to the fault characteristic frequency, and k is the sidebands number. In steady-state condition, the supply and the sideband currents are constant. These frequencies are associated with different motor mechanical faults such as air gap eccentricity, bearing failures or broken rotors bar.

Whenever faults due to electromagnetic origin occur there will be an electromagnetic driving force. This force therefore builds up and dies away twice during each cycle of voltage change and. This will induce a driving force that will produce a frequency exactly twice that of the voltage supply. This driving force causes a periodic distortion of the flux. This justifies how voltage even harmonics created in the power spectrum due to electrical faults.

3 Methodology

The proposed motor current monitoring system consists of a wireless sensor network platform with multiple nodes grouped in a star topology, as shown in Figure 1. Each sensor node is connected to one motor of the air-conditioning unit. Each node consists of current sensor, microcontroller and RF transceiver. The block diagram of the proposed wireless sensor node is shown in Figure 2.

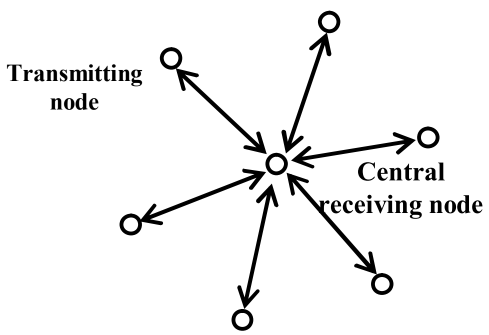

Figure 1: The star wireless sensor network topology used for motor fault detection

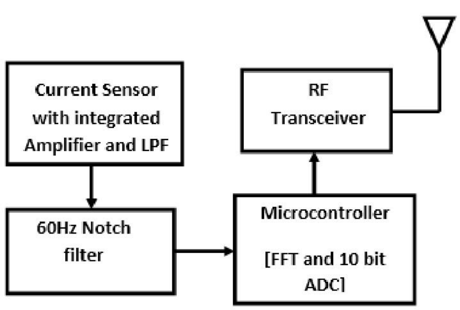

Figure 2: A wireless sensor node functional block diagram

The stator current supplied to a single phase induction motor is monitored using electronic current sensor. The Allegro ACS712 Hall Effect current sensor integrated with amplifier and low pass filter (LPF) is used to measure the motor current. These series of ACS71X integrated currents sensor have range of measuring currents varying from 5A to 200A and have a highest sensitivity of 185mV/A for the 5A measurement range. The higher the current the sensor detect, the lower the sensitivity it has. The resulting analog signal of the Hall Effect current sensor is then amplified and low-pass filtered. The undesirable high frequencies components can be removed using the RC filter. These undesirable high frequency components can otherwise produce aliasing of the sampled signal while the amplification maximizes the use of the next stage analog to-digital converter (ADC) input range.

This process is accomplished by removing the 60-Hz excitation component through notch filtering, where the fundamental component is reduced, and sampling the resulting signal will increase the ADC sensitivity. The output of the current sensor is digitized using the internal ADC of the Microchip PIC18F4550 microcontroller with resolutions of 10 bits. This 8-bit nano-watt-technology microcontroller has 32 KB of flash memory for storing embedded programs and 2KB of SRAM for temporary storing measurement data.

The A/D converter samples the filtered current signal at a predetermined sampling rate. This is continued over a sampling period that is sufficient to achieve the required FFT. The microcontroller will convert the sampled signal to the frequency domain using an FFT algorithm on the selected time domain window. The spectrum generated by this transformation includes the magnitude information about each frequency component

In order to reduce the large amount of spectral information to a usable level, an algorithm, in fact, a frequency filter is applied. It eliminates those components that provide no useful failure information while keeping only those components that specify the characteristic frequencies in the current spectrum that are known to be coupled to particular motor faults. The algorithm will only consider those frequencies whose levels exceed a predetermined threshold.

To provide wireless communication link between sensor nodes, the RF-Solutions ZULUM-868 wireless radio modem is integrated in each node. This radio frequency transceiver module operates in the 868 MHz radio band and can communicate at a host data rates up to 38,400 Baud and RF data rate of 115Kbps over a range up to 2Km. The circuit diagram of a transmitting node is shown in Figure 3.

A data file is constructed which contains a node identifier number followed by the fault parameters. Other variables such as motor speed which indicates the locations of the interesting power spectrum frequencies may also be recorded.

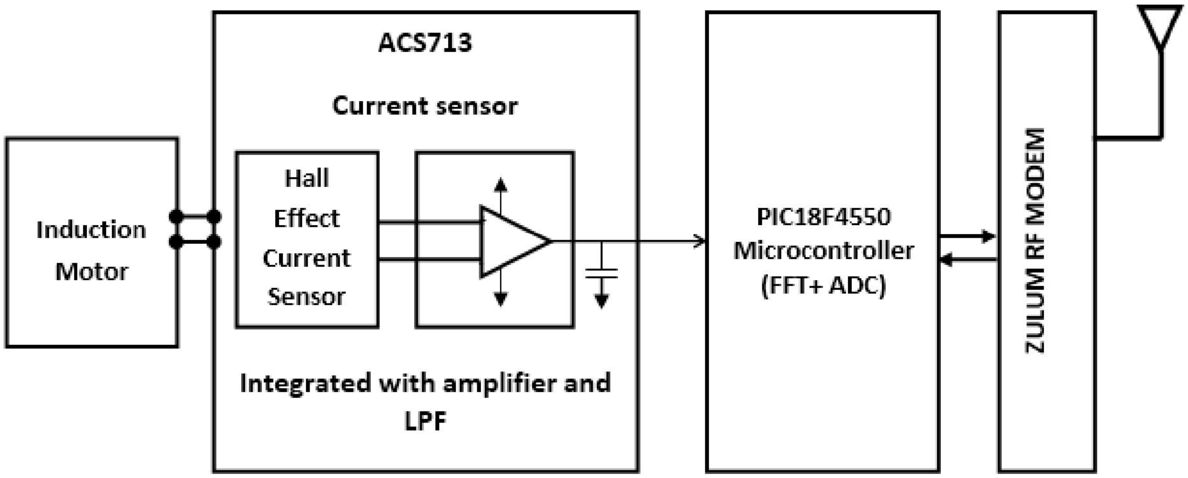

Figure 3: Wireless sensor node circuit diagram

All the transmitting nodes data will be received at the central node which contains a ZULUM-868 RF modem connected directly to a PC which displays the transmitted data from all nodes together with their identifying number. The flow chart of the microcontroller firmware is sketched in Figure 4.

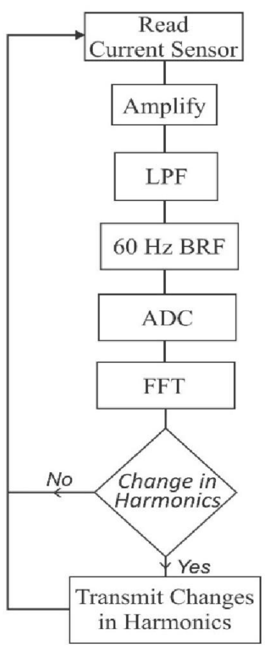

Figure 4: Flow chart of the microcontroller firmware

4 Experiment Setup

In order to test the effect of different load change on the current signature at a specific node, an experiment system was set up and the proposed procedure was applied. A 1KW induction motor was connected to adjustable AC voltage source. The motor shaft was connected to a computer controlled motorized load. The current was monitored using the current sensor probe clamped across the feeding wire to the induction motor. All the data was recorded to the computer through a wired data link and Tektronix DPO 4054 digital storage oscilloscope. The set up picture is shown in Figure 5.

In order to take the best advantage of the powerful microcontroller used at each node, it was programmed to perform FFT, while synchronously performing analog to digital conversions. In order to save computational time, the RF communications module is only activated when there is a noticeable change in the data resolution of the node.

The resolution is defined as the smallest difference between peaks of two successive sets of power spectrum measurements. This represents a statistically significant difference with a specified confidence level. The initial set of measurements represents the normal state for the motor and would be considered as a reference value. If the detected fault is recognized at any time to be of a dangerous type, a feedback signal from the receiving node will be send back wirelessly through the network to the motor controller to stop it for motor protection.

5 Results and Discussion

To test the proposed system, different electrical and mechanical loads were introduced. A series of tests was conducted to verify the accurate operation of the system. The motor was started and was running at a speed of 1700 rpm for some times. A 10 second snapshot of current was reviewed to view the operation over that time period. To view the condition of the rotor and identify any load-related issues, low frequency demodulated current was reviewed, while determining other faults including electrical and mechanical health was achieved by examining the high frequency demodulated current. The classical spectral estimation techniques which have been used are among the most robust ones, allowing computationally efficient FFT algorithms. For the FFT a Hanning window with 50% overlapping percentage among the partitioned segments was applied, which was reported to be an efficient implementation of the algorithm (Bertani and Knight 2003).

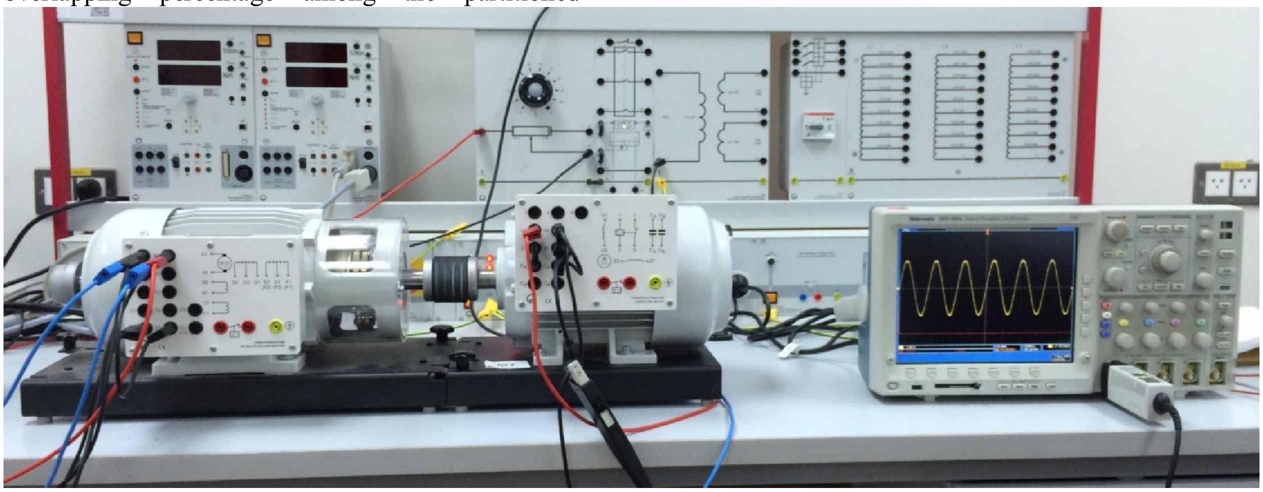

Figure 5: Set up of motor current signature record over one node of the HVAC

The expedients begin by recording motor current signature of every machine in the network. This data is stored as a signature of healthy machines that will be used for further comparison with future data of expectedly faulty motors. The recorded spectra for this snap shot showed only a second harmonic which was noticeable at the start and very small at the steady state. Almost all other harmonics went unnoticeable, as shown in Figure 6.

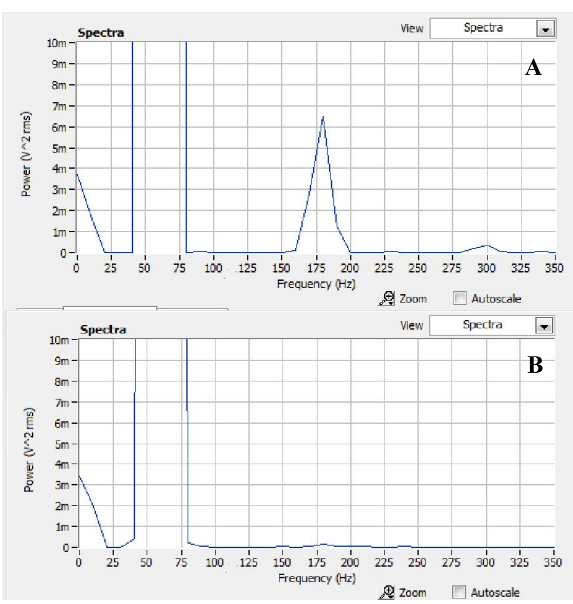

Figure 6: Power spectra of the healthy running motor at; A. the start and B. the steady state

The analog signal and their corresponding 10-bit converted digital signals for the motor start-up data in Figure 6, is shown in Figure 7. The high starting current in Figure 7A was corresponding to a high second and fourth power harmonics in Figure 6A. These harmonics disappeared after the motor reaches the steady state as shown in Figure 6B and Figure 7B.

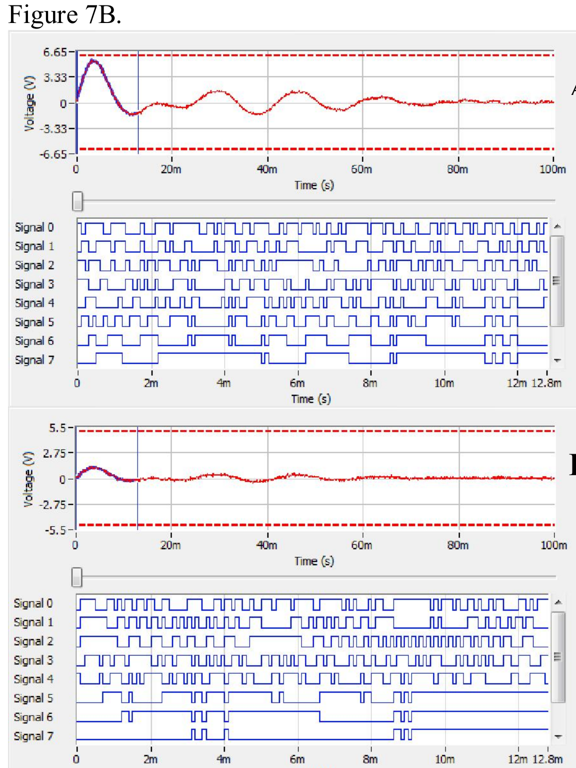

Figure 7: Current signal in time domain and their corresponding 10-bit digital signal of the healthy running motor at; A. the start and B. the steady state

To have a fast wireless transmission data rate, the study was limited to the first and second harmonics. The motivation in choosing the first and second harmonics around the fundamental supply frequency is due to a higher signal-to-noise ratio (SNR) of these harmonics, which contain more reliable and discriminative information with compared to other harmonics. The higher frequency harmonics have a relatively low spectrum amplitude and are thus more sensitive to noise. This is clear from the spectra shown in Figure 6.

At no-load condition these harmonics will interfere with the main monitored frequency or its harmonics. The current detection schemes will thus not be able to perform efficiently for the no-load condition of the motor. On the other hand, signatures that are not dependent on the main frequency harmonics and carry discriminative information, can be included in the analysis in order to make the detection schemes provide reliable fault decision in the no-load condition of the motor. This is shown in Figure 8. Figure 8A shows a healthy running motor at no load while Figure 8B shows a heavily loaded running motor with a torque of 0.5 N-m. This load added extra harmonics (90, 110 and 130 Hz) which is independent of the mains harmonics in addition to the obvious increase in the amplitude of the main frequency.

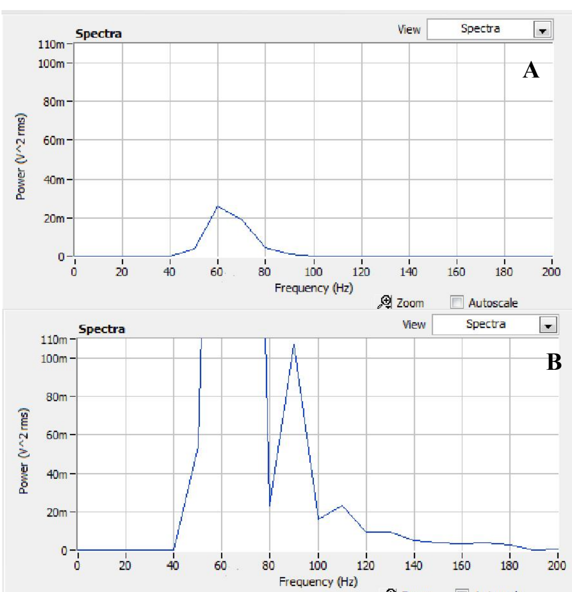

Figure 8: Power spectra of a running motor at; A. no load and B. heavy torque of 0.5 N-m

A sudden break test was also applied to the no load running motor. The power spectrum of such a break is recorded in Figure 9, which shows an obvious increase in the second harmonics amplitude.

Another test was performed by connecting the starting coil of the motor while the motor was running to imitate a faulty starting coil or a faulty starting coil switch. The power spectrum in this case contains multiple of different high amplitude harmonics both dependent and independent on the mains fundamental frequency, as shown in Figure 10. This figure shows clearly the first and third harmonics as well as some independent harmonics at, for example, 130 and 150 Hz.

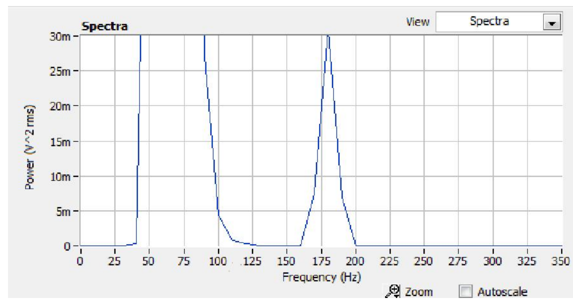

Figure 9: Power spectrum of a running motor at sudden brake

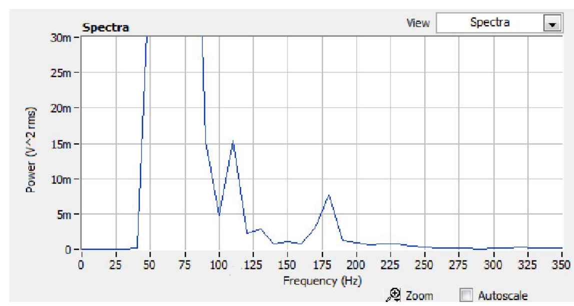

Figure 10: spectrum of a running motor with faulty starting coil switch

Conclusions

In this paper a simple and cost effective system is proposed to monitor the operating conditions of running motors of HVAC systems in big buildings. The proposed system consists of hall-effect current sensor to detect the change in signature of the motor current and wirelessly transmit it through a wireless sensor network to the building control room, where it get analyzed for any mechanical or electrical fault by comparing it with data of similar healthy machines. Upon detecting any recorded fault, a message will be displayed identifying the machine ID and the fault type. Different faults caused by changing mechanical and electrical loads were studied. The results showed a clear change in both dependent and independent harmonics which varies with the type of induced fault.

Since faults degrade the motor, post-diagnoses the frequency components and their classification for each specified fault is necessary. Additional analyses can then be performed using standard packages such as Matlab to investigate pattern recognition issues of the collected data. A feedback signal from the control room can be sent back through the network to stop the motor in case of identified dangerous faults like overload or sudden breaks.

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5/29/2014