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The Application of Wireless Sensor Networks for Condition Monitoring in Three-phase Induction Motors

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ABSTRACT

A commonly used technique for the detection of faults in large three-phase induction motors is to measure the supply current to the motor and analyze the signal spectrum. This technique is well established and has been shown to be indicative of a faulty condition. However, current signature analysis is usually used by very skilled technicians using expensive equipment. A cost effective condition monitoring technique is needed for smaller motors (those smaller than 200 HP). A motor's heat signature tells more about its quality and condition. For heavy-duty motors, it is very important to detect overheating because hot windings deteriorate rapidly. This paper explores the possibilities of using wireless sensors inside the motor. Wireless sensors are gaining popularity in condition monitoring applications because of their relatively low cost and ease of installation. This paper proposes a system of condition monitoring of the three-phase induction motor using wireless sensor networks (WSN) to measure the temperature and the vibration signals. The sensor nodes are placed on the rotor and the stator. The data acquisition is accomplished at a base station located at a distance of 6 feet. Issues related to electromagnetic interference between the wireless devices and the magnetic fields present within the motor are investigated.

INTRODUCTION

Condition monitoring is important to maintain sustained operability of machinery. The ability to effectively and efficiently monitor the condition of industrial machines allows the user to have a clear understanding of any problems that may arise during machine operation. Condition monitoring has the clear advantage of offering the ability to perform just-in-time maintenance i.e. before failure occurs but only as necessary. This aspect allows companies to reduce downtime when repairing machinery and ensures that productivity does not suffer.

The U.S. Department of Energy estimates that electric motors consume 63% of all electricity used in industry. In an effort to reduce power consumption, condition-based maintenance employs many different technologies [1, 2] to monitor the performance of motors used in industrial applications. It is believed that a reduction in machine failures increases plant efficiency and productivity. Wireless sensors are becoming a much more feasible monitoring option because of their desirable characteristics. They are small and lightweight, allowing for placement in limited spaces. Since they are wireless, they can be mounted on moving parts, thus eliminating the need for flexible connectors, slip rings etc. The sensors require very little power and are very low cost. The low power requirement makes energy scavenging from the environment attractive [1]. Their ability to continuously observe the vibrations and temperature provide the continuous monitoring of the performance and efficiency of the motor. This allows the motor to be repaired quickly and effectively as and when needed.

A commonly used technique for the detection of faults in a large three-phase induction motor is to measure the supply current [4] to the motor and analyze the signal spectrum. For heavy-duty motors, it is very important to detect overheating because hot windings deteriorate rapidly. Excess heat may be generated in motors due to increased load, worn-out bearings, clogged vents etc. Input current may indicate impending failure of stator winding by overheating. However, there are a number of motor failures that are not associated with stator winding overheating. A survey explaining motor failures by Austin Bonnett and Chuck Young [5] estimate that roughly half of motor failures that occur are due to the rotor and the bearings. These failures cannot be easily predicted by merely monitoring current. Implementation of sensors to directly measure the phenomena in the rotor are not easy because of the rotation of the rotor. A wireless sensor network containing temperature and vibration sensors would be ideal in collecting the necessary information to determine maintenance requirements. We have built a prototype system, which is comprised of two thermistors and two vibration sensors. This prototype wireless sensor network will be used to monitor a three-phase induction motor.

Wireless sensors have not yet been widely used in manufacturing applications [6]. One of the main reasons is the magnetic field present in the machine, which can block the signal transmitted between the wireless sensors. This paper studies the electromagnetic interference between the wireless devices and the magnetic fields present within the motor. We will investigate the packet loss of the wireless sensors located in different positions.

ELEMENTS OF WIRELESS SENSOR NETWORKS

In condition monitoring, wireless sensors can help alleviate the problems of embedding a data acquisition system into existing machinery. It is not always easy to install new, wired sensors into existing machinery because of wiring requirements and limited accessibility. Machine condition monitoring systems include measurement hardware and software that acquire and interpret signals generated by the machine being monitored. Figure 1 provides an overview of the motor monitoring system components.

A three-phase induction motor is our signal source. The measurement hardware that we used is comprised of thermistors and accelerometers. They are mounted outside the motor as well as inside the motor. Power is supplied to these sensors via batteries. Almost all of the power that the sensors consume is due to the wireless communication between the sensors and the base station. The dotted lines shown in Figure 1 are the wireless connections between each sensor and the dashed lined rectangles represent the wireless sensor nodes inside the motor. Due to the complexity of the wireless connection diagram, the sensor nodes attached outside the motor are not included in Figure 1.

Sensor Nodes

A sensor node is comprised of a sensor board and a sensor mote. The sensor motes host an Atmel 128L CPU that runs the Tiny Operating System (TinyOS). The operating system executes programs independently written in the programming language nesC [7]. Our sensor motes and programming board are commercially available from Crossbow, Inc. Temperature is measured using a thermistor that has a range from 0°C to +50°C.

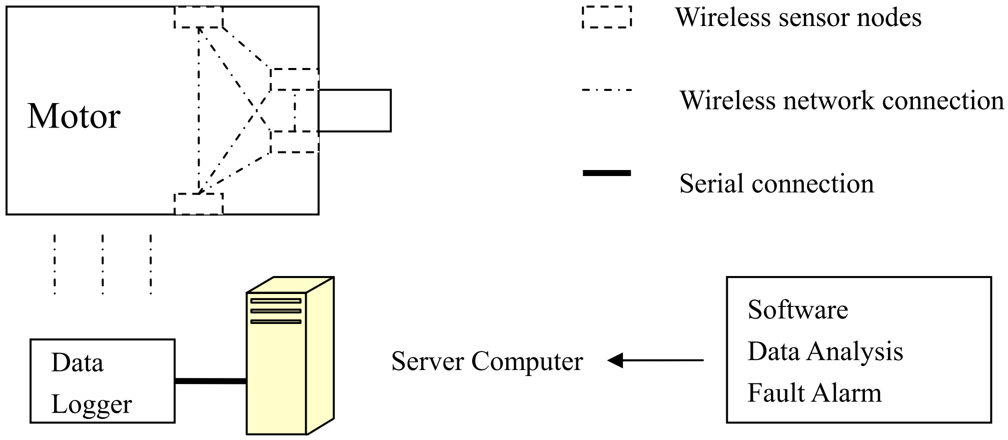

Fig.1 Motor Condition Monitoring System Elements

Fig.2 Accelerometer sensor node

The accelerometer has an analog output and has a measurement range of +/- 2g with a sensitivity of 2mg at 60Hz.

Base Station

The data acquisition task is achieved by a data logger, which consists of one sensor node and a programming board. The programming board is connected to the computer server by a serial cable. The sensor node and the programming board together are called a base station. The purpose of the base station is to collect the data from each sensor node.

PACKET LOSS

Wireless sensor networks can be used to undertake the task of condition monitoring in a wide variety of environments. Many of these environments can be harsh for wireless communication, especially in manufacturing environments. The most basic aspect of wireless communication is the packet delivery performance: the characteristics of packet loss, and its environmental dependence [8] . In our three-phase induction motor, there is a strong magnetic field inside the motor when it is running which can cause more packet loss during the period of data transmission from sensor nodes to the base station. By tracking the packet loss of the sensors which are placed at different positions, we can investigate the strength of the magnetic field and its effect to wireless communication.

We now present a brief description of the packet sending and receiving mechanism to provide the context for our experiments. To send a packet, the application layer (in our case, this will be the data acquisition and processing application that runs on the sensor nodes) implements the communication stack with the packet to be sent and the address of the destination node of the packet. After performing medium access control (MAC) to ensure that there is no other communication in progress on the wireless channel, the MAC layer begins sending the packet one byte at a time. Each byte is coded and sent over the channel. Simultaneously, a cyclic redundancy check (CRC) code is computed over the entire packet and is appended to the transmission. The receiver receives the coded bytes and decodes them, correcting any single bit errors and flagging double bit errors. When the entire packet has been received, a CRC code is computed by the receiver on this packet and is compared to the CRC that was computed and transmitted by the sender. If the two do not match, the packet is rejected as spurious. CRCs are popular because they are simple to implement in binary hardware, are easy to analyze mathematically, and are particularly good at detecting common errors caused by noise in transmission channels. TinyOS networking stack uses the CRC coding scheme to drop the corrupt packet. In order to determine packet corruption, we investigate both the individual bytes that are corrupted as well as the packets that fail the CRC check. By keeping tracking of these packets, we can determine the effect of the EM field on the transmission.

EXPERIMENT SETUP

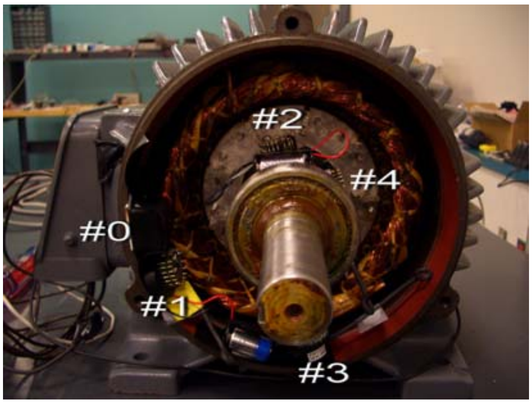

Fig. 3 Sensor placement

A three-phase induction motor from Newman Electric Motors, Inc. is mounted on a steel plate. It is a 1 hp three-phase induction motor and is connected to an adjustable speed drive from Toshiba International Corporation. The running speed can range from 0 to 900 rpm. Our data are collected under the running of the motor at 900 rpm and 750 rpm.

Figure 3 shows the placement of our wireless sensors and one wired accelerometer, which are also listed in Table 1. One temperature sensor i.e. the thermistor is attached on the bottom shell of the motor (#3 in Figure), the other temperature sensor (#4 in Figure) is attached on the shaft beside one of the vibration sensor. One vibration sensor (#1 in Figure) is placed beside the wired one (#0 in Figure) on the left side, the other one (#2 in Figure) is attached on the shaft. The vibration sensor is a two axis accelerometer. We make the x axis perpendicular to the shaft axis and the y axis along the shaft axis.

Table 1. Sensors and position

id	Sensor type	Position
0	wired vibration	left stator
1	wireless vibration	left stator
2	wireless vibration	shaft
3	wireless temperature	bottom stator
4	wireless temperature	shaft

Fig. 4 Magnet mounting

The mounting method in this application is to use a small magnet on the bottom of the mote, as showed in Figure 4. This makes our set-up quick and easy to change.

Our base station of the wireless sensors is setup at a distance of 6 feet away from the rotor face. The distance between the wireless sensors and the base station is the same for all sensors.

In our prototype system, an electrical load is applied to the motor by connecting the output shaft of the motor to the input of a 3/4 hp generator. The generator supplies power to adjustable resistance with a capacity of 225W. The potentiometer provides different loads to drain the power of the motor which can induce different condition modes of the system. We measure the voltage at two sides of the resistor load and the resistance using a multimeter. By calculating the current through the resistor and measuring the voltage generated by the generator, we can estimate the power drained in the motor by simply multiplying the voltage and the current. The formulae of calculating the current, the voltage and the power generated are given by

$$I = V / R \tag{1}$$

$$\varepsilon = I * (r + R) \tag{2}$$

$$P = \varepsilon * I = \frac{V^2}{R}(1 + \frac{r}{R}) \tag{3}$$

Where I represents the current passing through the load, R is the resistance adjusted by the potentiometer, V is the voltage drop of the load resister, ε is the voltage generated by the generator, r is the internal resistance of the generator and P is the total power generated.

Testing Wireless Sensors inside the motor

A well-designed motor does not have much space inside. To keep the motor safe and to reduce the influence by the sensor motes, we need to insulate the motes by using insulation tape when we fix the motes onto the stator or the rotor. The measurement of temperature inside the motor is performed by two thermistors integrated on motes, which sense the environment temperature changing. The vibration sensors are placed on the static part and the rotating part of the motor. We will compare the packets' loss rate during outside testing; inside testing without power to the motor; and inside testing with the motor running. Then we can inspect the magnetic field effect to the motes.

Testing Wireless Sensors inside motor driving a load

The magnetic field present in the motor is governed by the current passing through the windings. We apply the electrical load to change the current through the windings, which also changes the strength of the magnetic field. When using one potentiometer, we adjusted the resistance to 4Ω, 3.5Ω, 3Ω, 2.5Ω, 2Ω and 1.5Ω respectively. To achieve 1Ω load safely, we use 2 potentiometers adjusted to 2Ω each and connected in parallel.

DATA ANALYSIS AND DISCUSSION

Calibration of Accelerometer

We set up a wired vibration sensor as a reference to our wireless sensors which helps us verify the reliability of wireless sensors. It is easier to set up a wired sensor to a static part inside the motor compared to the rotating part. However, the wire arrangement is still difficult because we want to have the wire extending out to connect to its data acquisition board without drilling any hole on the shell of the motor.

The accelerometer sensor can also be calibrated by itself. To do this, the accelerometer is first oriented vertically facing up and the output voltage (Vp) is measured. It is then turned 180 degrees to point vertically down and the voltage is again measured (Vn) The calculation of acceleration from ADC output is as follows:

$$a(g) = 1 - 2 * (Vp - Vout)/(Vp - Vn) \tag{4}$$

Where Vp is the +1g calibration reading and Vn is the -1g calibration reading, a is the acceleration, $Vout$ is the ADC output reading.

The self-calibration is intended to calibrate the sensor before testing and the wired sensor calibration is to verify that the wireless sensors are operating during the test.

Table 2. Accelerometer self-calibration parameters

Sensor id	Axis	±1g	Calibration reading
#1	x	+1g	617
		-1g	500
	y	+1g	577
		-1g	459

#2	x	+1g	581
		-1g	466
	y	+1g	622
		-1g	505

Self-calibration readings are listed in Table 2 which set the positive calibration reading *Vp* and the negative calibration reading *Vn* in formula (4) for each axis of two vibration sensors. For example, if the ADC output of x axis on sensor #1 is 617, we will get +1g by calculation from formula (4).

The thermistor on the mote is calibrated by the company. The sampling rate is 10Hz. The node's thermistor ADC output can be converted to degrees Kelvin using the following approximation over 0-50 °C:

$$1/T(K) = a + b \times \ln(R_{thr}) + c \times [\ln(R_{thr})]^3 \quad (5)$$

where:

$R_{thr} = R1(ADC\_FS-ADC)/ADC$

$a = 0.00130705$

$b = 0.000214381$

$c = 0.000000093$

$R1 = 10\ k\Omega$

$ADC\_FS = 1023$

ADC =output value from Sensor node's ADC measurement.

The wired accelerometer we used is also from Crossbow, Inc. It is a one axis ±4g accelerometer which has its Zero-G Voltage of 2.419V and the sensitivity of 0.479V/g. Its sampling rate is auto scaled around 200Hz. Our wireless vibration sensors are two axis ±2g accelerometers with bandwidth of 50Hz. We set the sampling rate at 100Hz. It is obvious the wired sensor has a higher sensitivity and resolution. Figure 5 shows the frequency domain signal of wireless sensor #1 and wired sensor #0 when the motor is running at 900 rpm and with no load. #1 only uses its x axis data.

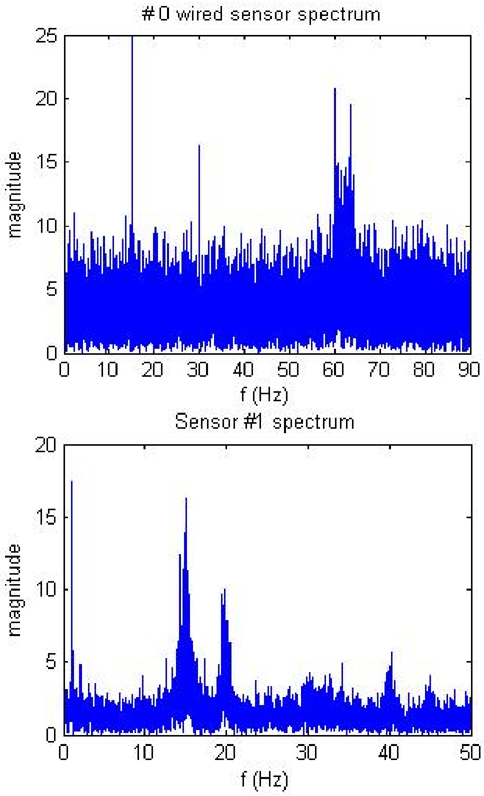

Fig. 5 Spectrum of sensor #0 and #1

Due to their different positions and different sensitivity, the data collected when the motor is running produces a big difference. However, in frequency domain, we can easily find the fundamental frequency governed by the rotation speed which is 15 Hz when the motor is running at 900 rpm.

Vibration signal and Temperature signal

The wireless sensor attached on the shaft gives a clear response signal as displayed in figure 6. The peak frequency known as the fundamental frequency is the shaft rotation frequency which is 15 Hz when the motor is running at 900 rpm. Another frequency peak is the second harmonic.

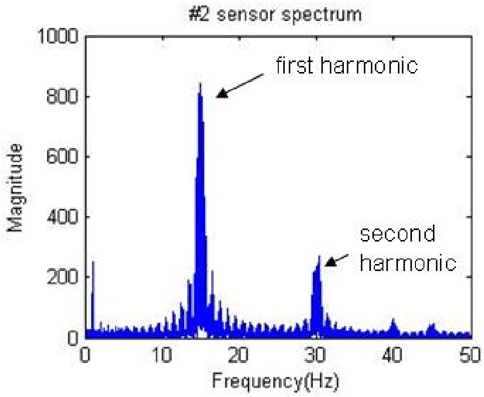

Fig. 6 Shaft vibration response

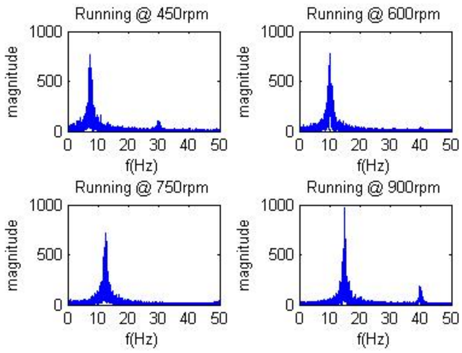

Fig. 7 Vibration vs. Rotation Speed

Figure 7 displays the vibration signal spectrum at different rotation speeds of 450 rpm, 600 rpm, 750 rpm and 900 rpm. The fundamental frequencies are captured clearly for each rotation speed.

The thermistor embedded on the mote senses the temperature inside the motor. Figure 8 is the average temperature of sensor #3 and #4 when running the motor at 900 rpm with different loads. Figure 9 is the temperature signal from two thermistors when running the motor at 750 rpm and without load.

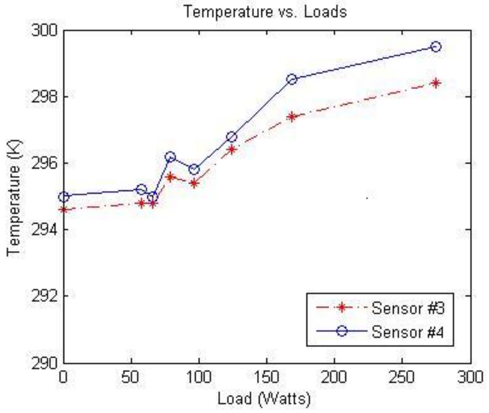

Fig. 8 Temperature vs. Loads

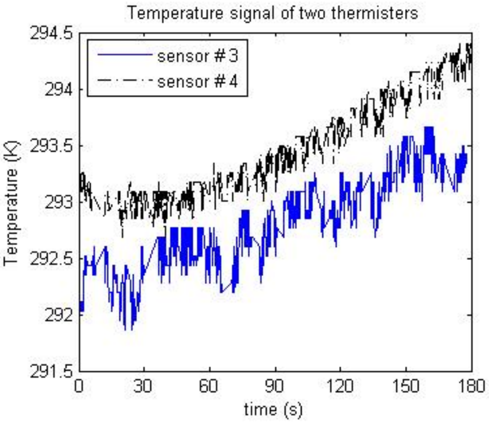

Fig. 9 Temperature vs. Time

Packet Loss

The packet loss of wireless sensors is investigated by setting the sensors at a different place and running the motor with different loads. Table 2, 3, 4, 5 lists the packet loss investigation under different situations. In every test, we collect the data for about 10 minutes. CRC loss rate is calculated by counting the number of packets which have data transition errors divided by the total number of packets received. Data loss rate is calculated by dividing the number of packets received in each buffer by the total number of packets we should receive in these buffers.

From Table 3, it is obvious that the packet loss is increased by setting the #2 sensor inside more along the shaft. While Table 4 shows that the packet loss of #1 sensor has no big change for different positions along the circumference. This is as may be expected due to symmetry. The packet loss of both #1 and #2 sensor inside the motor shows some difference between the two situations of when the motor is running or not (Table 5). It indicates that the magnetic field generated when the motor is running does affect the wireless communication between sensors and the base station. The further inside along the shaft, the stronger the magnetic effects are. During the loading tests, we set sensor #2 and #4 inside more along the shaft axis and change the battery power every about 30 minutes. The results of the test with loading (see Figure 10) show a small difference of CRC packet loss rate when we apply different loads. Although the increased load increases magnetic fields in the motor, a well-designed motor confines its fields to within the iron core and the air-gap. This explains this rather weak dependence on applied load. The temperature sensors which have a lower sampling rate do not have much packet loss. A small trend of getting more packet loss with more driven load is shown in Figure 10.

Table3 #2 sensor Packet Losses no load

Situation (900 rpm, no load)	Data loss rate (%)	CRC loss rate (%)
Inside more along shaft axis	4.51	2.03
Inside less along shaft axis	2.70	0.91

Table 4 #1 sensor Packet Loss no load

Situation (900 rpm, no load)	Data loss rate (%)	CRC loss rate (%)
Left side beside wired sensor	1.82	0.49
Bottom of inner shell	1.43	0.34

Table 5 #1 and #2 sensors Packet Loss no load

Situation (inside)	Sensor	Data loss rate (%)	CRC loss rate (%)
running	#1	1.82	0.49
not running	#1	1.36	0.21
running	#2	4.51	2.03
not running	#2	3.49	0.65

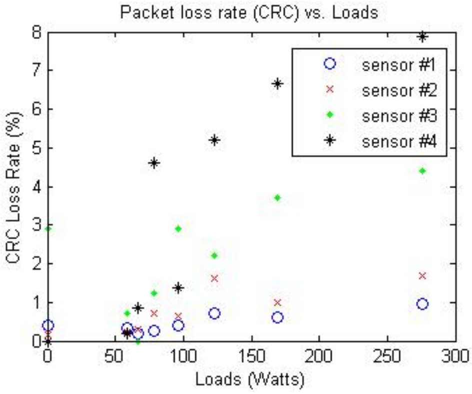

Fig. 10 Packet Loss vs. Loads

CONCLUSION AND FUTURE WORK

The possibility of using wireless sensors in the three-phase induction motor condition monitoring is explored in this paper. We have conducted experiments to gather vibration and temperature data from motors. Although the wireless sensor data is not as reliable as wired sensors, it is an important way to collect data when wired sensors can not reach the place. An interesting phenomenon is investigated related to the magnetic field generated when the motor is running. Due to the magnetic field, the wireless communication between the sensor nodes and the base station is affected. Although the magnetic field causes more packet loss of the data transition, there are still enough data to analyze the analog signal. By placing several sensor nodes around the motor, we will also be able to gather enough data to perform accurate data analysis and condition monitoring.

One drawback of the current system is that the thermistors cannot sense the surface temperature of the rotor as they do not directly connect to the surface. Surface mounting thermocouples should be used to design the next version's temperature sensor board. The problem of electromagnetic interference could be solved by increasing the power of the wireless transmission. This has the disadvantage of increasing power consumption, but rotating shafts have enough energy that can be directly scavenged from the environment and used to supply the required energy. Also faster sampling rates need to be achieved to perform accurate monitoring with vibrations.

The paper also only minimally exploits the local processing and storage capabilities of the wireless sensor nodes. More sophisticated signal and data processing algorithms could be employed on the nodes. In addition, local communication networks could be set up within the motor to enable collaboration among the sensor nodes.

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