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ENERGY SCAVENGING FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

Conventional condition monitoring of electrical machinery is conducted by measuring signals such as currents and vibrations outside the motor. Wireless sensors now provide a means of accessing and measuring useful signals inside the motor where the phenomena responsible for failure occur. These sensors are capable of not merely sensing, but also processing, storage and eventually communication. Since all these activities require power that is supplied conventionally by batteries, the useful life of the sensor node is limited by the life of the battery. This paper describes the design of an energy scavenger capable of collecting energy from the fringing field in a three-phase induction motor. The field in the magnetic filed is converted to electrical energy for use in intelligent wireless sensor nodes. The alternating magnetic field in a three phase induction motor is first measured by the hall-effect sensors. A coil wound on a ferrite core harvests the leaked energy. The experimental results are compared to the theoretical calculations of induced voltage. The paper describes results from tests conducted with a prototype coil that is used to power wireless sensor nodes in a motor running at full speed.

1. INTRODUCTION

Wireless sensors are emerging as viable instrumentation techniques for industrial applications especially in condition monitoring applications [1-4]. Condition monitoring provides information on the health and maintenance requirements of industrial machinery and is widely being adopted as an alternative to the more conventional preventive and breakdown maintenance strategies. Measurements and monitoring of parameters such as vibration, temperature, noise level and power consumption could help to detect the trends from developing faults and determine the sources of problems. This can be used to schedule maintenance effectively to avoid unnecessary maintenance and catastrophic failures.

The selection of right sensors is the key to effective condition monitoring [5]. At present, most of the sensors are physically wired. The wires provide both power and communications paths. However, in many applications, wired sensors are impractical or inconvenient. For example, they are difficult to mount on rotating machinery or high temperature applications. In these situations, wireless sensor networks could be a possible solution. These networks can be used in remote locations and also offer inexpensive and flexible installation.

In a very short span of time, wireless sensors have emerged as the sensing technology of choice in a variety of industry instrumentation techniques because of their flexibility, non-intrusive operation, safety and their low cost, low power characteristics [6]. Wireless sensors can be installed inside the mechanical devices, much closer to the phenomena of interest. Since communication is integrated into the sensor setup, they can be installed on moving parts as well as static components.

Batteries are the primary power supply for current wireless sensor nodes [7]. However, when the battery is exhausted, the sensor node becomes non-operational till the battery is replaced. This finite and often limited operational life makes it a burden for plant maintenance. Energy scavenging for wireless sensors thus becomes more important and has attracted considerable research interest in recent years. Glynne-Jones 2001 [8] reviewed a range of self-powered system which uses vibration power sources, optical power sources, thermoelectric and radio power sources and so on. He also published the design of vibration powered, electromagnetic miniature generator in 2003 [9, 10]. In 2005, Paradiso [11] published a survey of energy scavenging for mobile and wireless electronics which introduced various human-powered systems. Several groups of researchers such as Ottman 2002 [12] and Roundy 2003 [13] have published designs for piezoelectric generators. These convert ambient vibrations to electrical signals. Leland also published an energy scavenger constructed from cantilever-mount piezoelectric bimorphs and magnets for household electrical monitoring in 2006 [14].

There are many power sources in a three phase induction motor: vibration, shaft rotation, temperature gradients, air flow, and magnetic field. Vibration energy scavenging may be used on the outside of the motor; however a properly running motor has limited vibration and is thus not the best source of energy inside the motor. Attaching magnets on the rotor and fixing coils close to the magnets could harvest power when it is running, but it is not advisable to attach weights to the rotor since the rotors need to be dynamically balanced before the installation of the motor. Temperature difference is usually not big enough especially when a healthy motor is running under stable conditions. Air flow may be used to harvest energy, but it also requires moving parts. Based on the considerations above, the magnetic field from the extended windings is the easiest way to scavenge power without touching the rotor. Here, we first present our prototype energy scavenging system designed for wireless sensors used in condition monitoring applications. We then analyze the power requirements of wireless sensor nodes. We then investigate the fringing magnetic field inside the three phase induction motor. Sections 4 and 5 describe our design and experimental results and are followed by the discussion and conclusion.

2. Energy Requirements of Wireless Sensors

Wireless sensors are installed in hard-to-reach places and thus long operating life is highly desirable. However, as analyzed in reference [13], at an average power consumption of 100 microwatts (an order of magnitude smaller than any currently available node), given a 1 cm^3 constraint, standard sensor node batteries must be replaced at least every nine months. For example Table 1 lists the power requirements of a series of wireless sensor nodes called motes developed by UC Berkeley (www.xbow.com). [15]. The Mica motes are designed to use 3V batteries as their power supply.

Table 1 Comparison of commercially available motes' power consumption

		Mica2	Mica2Dot	MicaZ	Tmote sky
Microcontroller	Active Power (mW)	33	8	8	3
	Sleep Power (μW)	75	75	75	15
Communication	Receive Power (mW)	29	29	38	38
	Transmit Power at 0dBm (mW)	42	42	35	35
Minimum Supply Voltage (V)		2.3	2.3	2.3	1.8

3. Characteristics of Magnetic Field in a Three-Phase Induction Motor

The main field of a three-phase induction motor exists between the stator and the rotor core. Most of the magnetic flux loops are perpendicular to the rotor shaft. Only some fringing flux comes out at the two ends of the core. Due to the alternating current in each phase of the windings, the magnetic field created by the extended wires of winding out of the core is the main source of leaking magnetic energy. The magnetic field at the two ends is difficult to analyze by classical electromagnetic theory due to its complexity in winding methods. We measure these fields using hall-effect sensors. Figure 1 shows a cross-section view of the motor. Cylindrical coordinates are defined for the convenience of investigating the magnitude of flux density in a three dimensional point of view. The motor is a 1 hp three-phase induction motor from Newman Electric Motors, Inc. It is a class B induction motor with NEMA frame 213, a mid range generally used small motor. The total length is 17.25 inches; the width and height are 10 inches and 10.125 inches respectively. It is connected to an adjustable speed drive from Toshiba International Corporation. The running speed can range from 0 to 900 rpm. Figure 2 shows the variation of B-field with radius. The variation of B-field with Z distance is very small. The hall-effect sensor used is a single direction sensor commercially available from Allegro Microsystems, Inc. The A1321 sensor has a quiescent output voltage that is 50% of the supply voltage (typically 5V) and output sensitivity of 5mV/G.

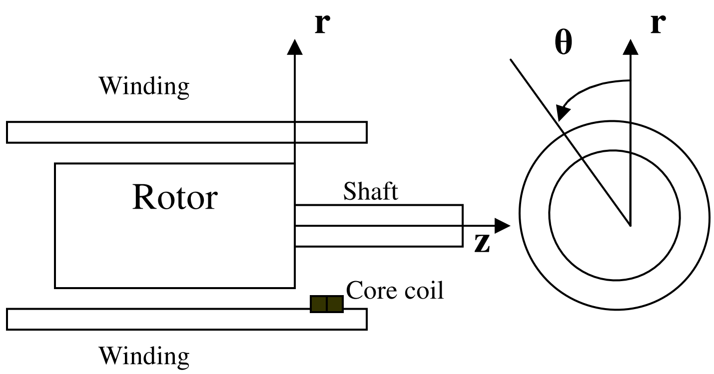

Fig.1 Cylindrical coordinates inside motor

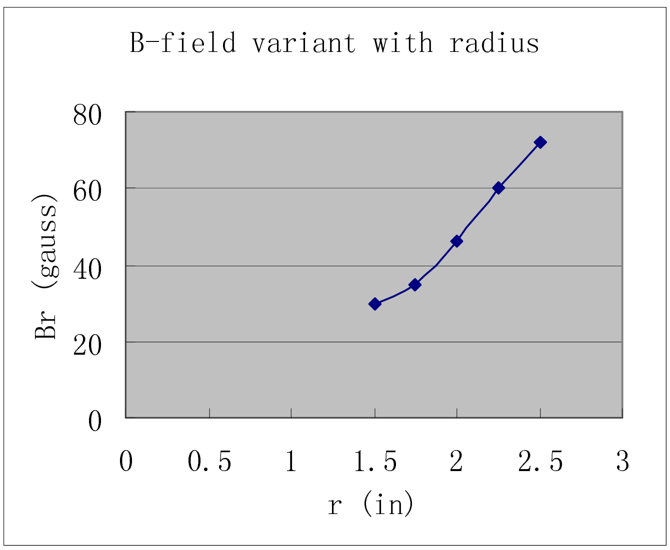

Fig. 2 B-field variation with radius.

The flux density sensed by the hall-effect sensor is a harmonic signal with its primary frequency of the alternating current frequency f. From the observation above, we found the flux density at θ direction is almost same along a constant radius circle. It decreases as r decreases i.e decreases towards the center of the motor. When r is in the range of 2 inch to 2.5 inch, the average is about 60 gauss. The flux density of θ direction at radius of 2 inch can be described as follows:

$$B_\theta(t) = B_m \cos(2\pi ft)\,, \qquad (1)$$

where B_m is the peak value of B_θ measurement which is about 50 gauss.

4. Design of Coil and circuit for scavenger

Based on the Faraday's law, if a loop of wire is subjected to a changing magnetic flux, Φ, through the area, A, enclosed by the loop, then an electromotive force will be induced in the loop that is proportional to the rate of change of the flux:

$$e(t) = -\frac{d\phi}{dt} = -\frac{d}{dt}\int_S \mathbf{B}\cdot d\mathbf{A}\,, \qquad (2)$$

where e(t) is the electromotive force measured by voltage, B is the magnetic flux density through the area dA. Since the flux density in the core is induced by an external magnetic field described in equation (1), the electromotive force or the terminal voltage becomes:

$$e(t) = -\mu_0\mu_e NA\frac{dH(t)}{dt} = -\mu_e NA\frac{dB_0(t)}{dt}\,,$$

(3)

where μ_e is effective relative permeability, N is the number of turns in the coil, , B_0 is the flux density in the air described in equation (1), μ_0 is permeability of free space which is $4\pi * 10^{-7}$ H/m, H is the magnetic field strength. With an air (no) core coil, the effective relative permeability is 1. Inside a 1-hp motor, there isn't much space for the core coils. Due to space limitations, the maximum cross-sectional area of the loop is about 127 mm^2 (maximum diameter of half inch). To achieve an induced peak voltage of 3.82V (V_{rms} = 2.7V), the number of turns in the coil needed is about 16000 when the motor is running at full speed (f = 60Hz). With a ferrite core coil, the effective relative permeability can be increased significantly and the number of turns in the coil can be reduced.

From reference [15], the effective relative permeability can be calculated as follows:

$$\mu_e = 1 + \left(\frac{d_c}{d+t}\right)^2[\mu_a f(l_w/l_c) - 1]\,, \qquad (4)$$

$$f(l_w/l_c) = 1.9088 - 0.8672(l_w/l_c) - 1.1217(l_w/l_c)^2 + 0.8263(l_w/l_c)^3$$

(5)

where d_c is the core diameter, d is the winding inside diameter, t is the thickness of the winding, μ_a is apparent permeability. The function $f(l_w/l_c)$ accounts for the variation in flux density from the middle of the winding to its ends and assumes the winding is centered about the middle of the core.

The core apparent permeability depends on its geometry and initial permeability μ_i, as well as the winding length relative to the core length. A rod becomes magnetized when a magnetic field is applied to it. In response, a magnetic field is created within the rod that opposes the externally applied field and reduces the flux density. The demagnetizing field is proportional to the magnetization and the net field *H'* in the core is

$$H' = H - FM, \qquad (6)$$

where F is the demagnetizing factor, M is magnetization, H is applied external field.

The apparent relative permeability of a core is the ratio of the flux density *B* in the middle of the core to the flux density in air:

$$\mu_a = \frac{B}{B_0} = \frac{B}{\mu_0 H} = \frac{\mu_i}{1 + F(\mu_i - 1)}, \quad (7)$$

The demagnetizing factor F of a rod depends on the length to diameter ratio which can also be found in reference [16]. A typical demagnetizing factor of a rod with its length to diameter of 5 is 0.040. To summarize, the induced voltage depends on the number of turns, the cross sectional area, the current frequency, the field strength, the winding length to core length ratio, the core length to diameter ratio, the core diameter, the winding thickness and the initial permeability of core material.

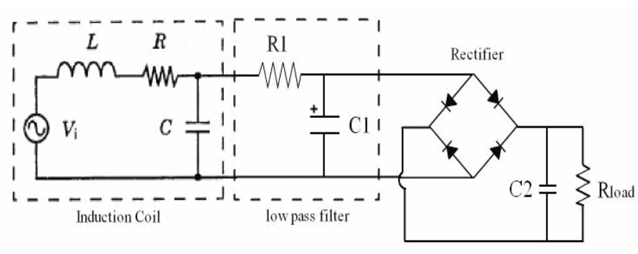

Figure 3 Circuit Diagram for Energy Scavenger

In practical implementations in a three phase induction motor fed by an adjustable speed drive, pulse width modulation (PWM) make the current in the stator winding has a high frequency harmonic with the default setting of 12 kHz. In order to get a clear wave form of the primary frequency, a simple low pass filter is designed to filter out the high frequency noise. To maximize the output voltage, the resistance R1 (in Fig.2) can be designed as small as possible. In our experiment, the resistance R1 we used is 0.5Ω and the capacitance C1 is 26.4 μF. Figure 2 shows the circuit of our design. To smooth the rectifier output, a smoothing capacitance C2 is used.

Table 3 lists the design parameters related to the power scavenging from the leakage magnetic field. Every parameter corresponds to equation (4)-(7) and figure 2.

Table 3. Design parameters

symbol	description
N	Number of turns for coil
l_c	Core rod length
l_w	Coil winding length on core rod
d_c	Core rod diameter
d	Coil diameter
μ_i	Initial permeability of core rod material
R	Low pass filter resistance
C_1	Low pass filter capacitance
C_2	Smoothing capacitance

5. Experiments and Results

To test the calculation of the induced voltage, four coil designs were made and the open circuit voltage was measured by an oscilloscope. . The ferrite core rods are commercially available from Fair-Rite Products Corp. The core material and winding properties are listed in table 4. The magnetic wire is 30 AWG which has its diameter of 0.254 mm.

Table 4. Ferrite core winding coil properties

Core ID	N	l_w (mm)	l_c (mm)	d_c (mm)	μ_i	A (mm^2)
1	93	23.7	38.1	6.35	125	31.67
2	75	19.1	30.0	6.00	250	28.27
3	104	26.5	45.0	8.00	2300	50.27
4	92	23.4	35.0	5.00	2300	19.63

Using the calculations above, figure 3 shows the experimental measurement and the theoretical results (Solid lines are experimental results and the dotted lines are theoretical results). A 1 hp three phase induction motor running at different speeds with no load is used for the tests.

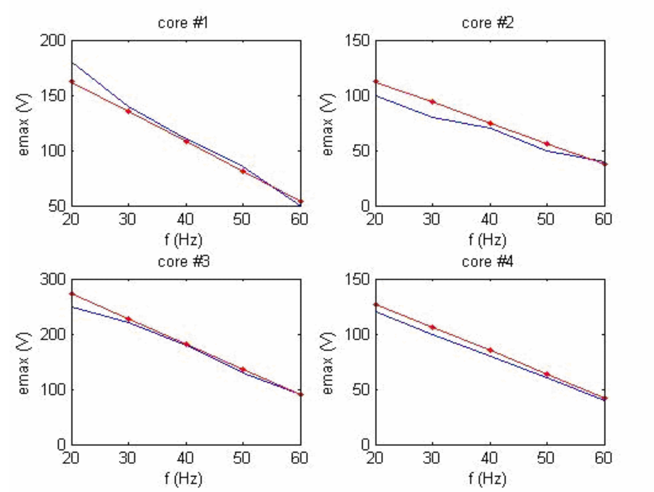

Figure. 4 Induced voltage vs. frequency.

To reach the voltage minimum for the mica motes, the core dimension used reflect core id #3 on table 3, but the number of turns N is increased to approximately 2000. The wire wound ferrite core is placed in the location where the Hall Effect sensor measured the strongest magnetic field. The strongest magnetic field was found perpendicular to the rotor's shaft inside of the motor's field winding (armature). Inductive coupling transfers the energy from the magnetic field to the ferrite core and producing energy. Producing direct current from alternating current required four schottky diodes. The diodes are assembled as a full wave rectifier circuit. Fast switching diodes of forward voltage of 0.3V were used to capture full bandwidth of the carrier frequency. In Fig.4 a filter capacitor is connected in parallel to provide smoothing. The smoothing capacitor provides a continuous voltage with

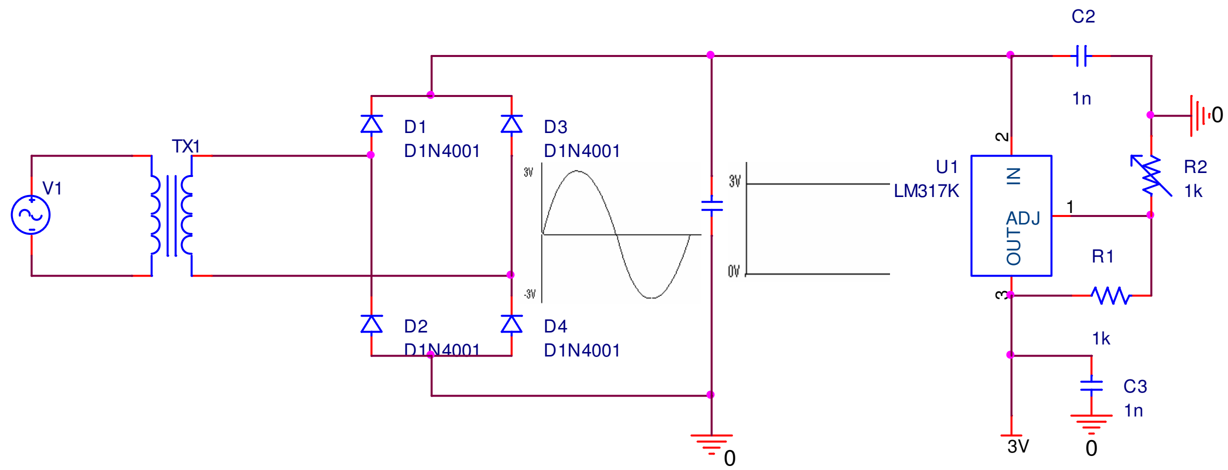

Figure 5 Prototype Setup

vary little ripple effect. The smoothing capacitor for a 10% ripple voltage is calculated

$$C = \frac{I_O + 5}{V_S + f}, \tag{8}$$

where I_o is the output current, V_s is supply voltage and f is driving frequency. Variable voltage regulator LM317 provides a continuous 3V with no ripple effect. We found that in linear voltage regulators, a voltage drop exists because the regulator requires an input voltage higher than the minimum voltage desired. The power loss is associated with the CMOS transistors. Given that a small input voltage is generated, a low power regulator LE30CZ that has a low dropout voltage of 0.2V is proposed for future testing.

The experimental setup is comprised of a three phase induction motor described earlier, mica2dot motes from Crossbow Technology, and the coil prototype. The ferrite core is positioned on the surface of the motor's winding. The wire from the ferrite core is routed outside the motor and connected to the prototype circuit. The mica2dot wireless transmitter is positioned outside the motor along with the prototype circuit. The batteries of the mica2dot are replaced with the 3V output from the voltage regulator in figure 4.

Using the motor controller, the motor was driven at 60Hz. The prototype circuit produced 24mW. To investigate the reliability of the power produced, the motor ran for several minutes and the mica2dot continuously transmitted its power information to the base station at 1 sample/sec.

6. CONCLUSIONS

An energy scavenging scheme for wireless sensor networks is described in this paper. A ferrite core designed with wire winding that can generate electrical current was investigated as an energy harvesting device and a single power supply for mica2dot operations.

In this note, the different sizes and the materials for the core are parameters that demonstrate significant results. Additionally, the winding pattern and the number of turns are characteristics that contribute to the amount of energy generated from the magnetic flux leakage of the motor.

The prototype design provides considerable power for mica2dot's low power applications. Future work will focus on high speed and large power applications. It would also be better to use a hybrid power strategy where a rechargeable battery is used as the primary source and an energy scavenger as the secondary source.

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