On the Application of Wireless Sensor Networks in Industrial Plant Energy Evaluation and Planning Systems

Anubhuti Khare, Manish Saxena, Manorma Kushwah

Abstract- Energy evaluation and planning are important in industry for overall energy savings. Traditionally these functions are realized in wired systems formed by communication cables and various types of sensors. However,the installation and maintenance of these cables and sensors is usually much more expensive than the cost of the sensors themselves. Recent advances in wireless communications, micro-electro-mechanical systems, and highly integrated electronics allowed the introduction of wireless sensor networks (WSN). WSNs have unique functional characteristics that enables low cost energy evaluation and planning in industrial plants. This paper proposes a closedloop energy evaluation and planning system with the WSN architecture. The importance of the proposed scheme lies in its non-intrusive, intelligent, and low cost nature. As the focus of this paper, the properties and architecture of the WSN in this application are discussed in detail. The applicability of the proposed system is analyzed and potential challenges are addressed. Finally, a demo system is constructed and experimental results are presented.

Index Terms— wireless sensor networks, IEEE 802.15.4, efficiency estimation, condition monitoring, experimental implementations.

I. INTRODUCTION

There are many motor driven systems in plants, such as pumping systems, compressed air systems, and fan systems, etc.These motor driven systems use over 70% of the total electric energy consumed by industry. Because of the oversized installation or under-loaded conditions, motors generally operate at low efficiency which results in wasted energy. In the United States, over two-thirds of the total electric energy consumed by industry is used by motor-driven systems. As the cost of energy increases, energy savings in industry are drawing more attention. Obviously, to improve energy efficiency, an evaluation of the energy usage condition of the industrial plant is required. Traditionally, energy evaluation in industrial plants is realized in wired systems formed by communication cables and various types of sensors.The installation and maintenance of these cables and sensors are usually much more expensive than the cost of the sensors themselves.Recent advances in wireless communications, microelectro- mechanical systems and highly integrated electronics have enabled the implementation of very low cost, ultra-low power consumption, multifunctional sensors and actuators. Clearly, the elimination of communication cables and the associated installation cost can greatly reduce the overall cost. This naturally brings the opportunity to investigate the use of wireless systems. However, because of the high cost of commissioning legacy wireless systems, this was infeasible until the appearance of the wireless sensor network(WSN) during the past few years. The deployment of large numbers of these sensors and actuators has resulted in the development of wireless sensor networks.Unique characteristics such as a sensor-rich environment, flexibility, high fidelity, self-organization, rapid deployment, and inherent intelligent capability make WSNs the ideal structure for low cost energy usage evaluation, which is important to industrial plant managers in making planning decisions. It is expected by the United States Department of Energy (DOE) that the widespread deployment of WSNs in industry could improve overall production efficiency by 11% to 18% in addition to reducing industrial emissions by more than 25% by 2010 wherein a WSN is applied as the architecture of an industrial plant energy management system, and especially focuses on the overall system architecture and details of the wireless communications. The non-intrusiveness of the proposed scheme comes from the fact that industrial motor energy. usage evaluation is achieved using only motor terminal quantities through WSN and nameplate information without interfering with the motor's normal operation.

Manuscript Received October 18, 2011.

Dr. Anubhuti Khare, Reader, Department of Electronics and Communication,University Institute of Technology, Rajeev Gandhi Technical University, Bhopal, Email:-anubhutikhare@gmail.com, Mobile:+919425606502

Manish Saxena, Head Of Electronics and Communication Department, Bansal Institute Of Science And Technology Bhopal, Email:-manish.saxena2008@gmail.com, Mobile: +919826526247

Manorma Kushwah Student, Mtech(Digital Communication), Bansal Institute Of Science And technology Bhopal, India.
Email:manupreet.kushwah08@gmail.com Mobile: +917566543074

II. ENERGY EVALUATION AND CONDITION MONITORING

Energy usage evaluation and motor condition monitoring are two basic functions of an energy management system for an industrial plant. They have their unique motivations and requirements, but also share many common needs, such as data collection.

A. Energy Usage Evaluation

It is estimated by DOE that motor-driven systems use over 2/3 of the total electric energy consumed by industry in the United States.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

In industry, motors below 200 hp make up 98% of the motors in service and consume 85% of the energy used. On average, these motors operate at no more than 60% of their rated load because of oversized installations or underloaded conditions, and thus at reduced efficiency which results in wasted energy. As the global energy shortage and the green-house effect worsen, the improvement of energy usage in industry is drawing more attention. Obviously, to improve energy efficiency, an evaluation of the energy usage condition of the industrial plant is required Among all the energy usage evaluation functions, motor efficiency estimation is the most important. Over the years, many motor efficiency estimation methods have been proposed .A common problem of these methods is either expensive speed and/or torque transducers are needed for rotor speed and shaft torque measurements, or a highly accurate motor equivalent circuit needs to be developed from the motor parameters. Generally, these methods are too intrusive, and are often not feasible for in-service motor testing. To overcome these problems, presents a complete survey on motor efficiency estimation methods, specifically considering the advances in sensorless speed estimation and in-service stator resistance estimation techniques during the last decade. Three candidate methods for non-intrusive efficiency estimation are modified for in-service motor testing. The non intrusive characteristic of these methods enables efficiency evaluation with a WSN.

B. Condition Monitoring

Motor condition monitoring gives the health condition of running electric motors and avoids economical losses resulting from unexpected motor failures. Sharing many common requirements with energy usage evaluation in terms of data collection, motor condition monitoring could be naturally added into an energy management system considering that the necessary data are readily available. For example, the motor stator currents need to be measured in the energy management system since they are required by almost all efficiency estimation methods. On the other hand, many condition monitoring algorithms such as rotor bars, worn bearings, and air-gap eccentricities, use the motor current spectral analysis (MCSA) technique, which also requires the stator current waveforms to be sampled and collected. Therefore, it would be natural to incorporate these condition monitoring functions in the energy management system without additional cost for data collection.

C. Additional Requirements

Generally, the measurements needed for each efficiency estimation and condition monitoring method are different, but essentially all require the input line voltages and the line currents. Some methods require the nameplate data (rated voltage, current, horsepower, speed, *etc.*), stator resistance, R_S, or rotor speed, ω_r. Among these, the measurements or estimates of stator resistance and speed have for years been regarded as stumbling blocks. However, recent research has made great progress in the area of stator resistance and speed estimation .Most of these estimators utilize the terminal voltages and currents, which are available in the energy evaluation and condition monitoring system.

III. WIRELESS SENSOR NETWORKS AND IEEE802.15.4 STANDARD

The WSN is a self-organized network with dynamic topology structure, which is broadly applied in the areas of military, environment monitoring, medical treatment, space exploration, business, and household automation (YU HAIBIN et al., 2006). the recent advances in wireless communications, integrated electronics, and microelectromechanical systems (MEMS) technology, new types of wireless networks, such as WSNs, have been developed. WSNs target primarily the very low cost and ultra-low power consumption applications, with data throughput and reliability as secondary considerations. The IEEE 802.15.4 standard is intended to address applications where existing wireless solutions are too expensive and the performance of a technology such as BluetoothTM is not required. Table I compares performance of the 802.15.4 LR-WPANs with 802.11b WLAN and 802.15.1 Bluetooth. While other wireless network standards aim to achieve long distance, large throughput, and high quality of service (QoS) level; the 802.15.4 standard is designed to provide simple wireless communications with short-range distances, limited power, relaxed data throughput, low production cost, and small size. These are exactly the properties of the industrial plant energy evaluation and planning system The IEEE802.15.4 standard is the physical layer and MAC sub-layer protocol for WSN, which supports three frequency bands with 27 channels as shown in Fig. 1. The 2.4GHz band defines 16 channels with a data rate of 250KBps. It is available worldwide to provide communication with large data throughput, short delay, and short working cycle. The 915MHz band in North America defines 10 channels with a data rate of 40Kbps. And the 868MHz band in Europe defines only 1 channel with a data rate of 20Kbps. They provide communication with small data throughput, high sensitivity, and large scales. The IEEE 802.15.4 supports two network topologies as shown in Fig. 2. The star topology is simple and easy to implement. But it can only cover a small area. The peer-to-peer topology, on the other hand, can cover a large area with multiple links between nodes. But it is difficult to implement because of its network complexity. An IEEE 802.15.4 data packet, called physical layer protocol data unit (PPDU), consists of a five-byte synchronization header (SHR) which contains a preamble and a start of packetdelimiter, a one-byte physical header (PHR) which contains a packer length, and a payload field, or physical layer service data unit (PSDU), which length varies from 2 to 127 bytes depending on the application demand, as shown in Fig.3

TABLE I

A COMPARISON OF LR-WPANS WITH OTHER WIRELESS TECHNOLOGIES.

	802.11b WLAN	802.15.1 Bluetooth TM	802.15.4 LR-WPANs
Range	~ 100 m	~ 10 – 100 m	10 m
Data Throughput	11 Mbps	1 Mbps	⩽ 0.25 Mbps
Power Consumption	50	10	1
Cost / Complexity	20	10	1
Size	Lager	Smaller	Smallest

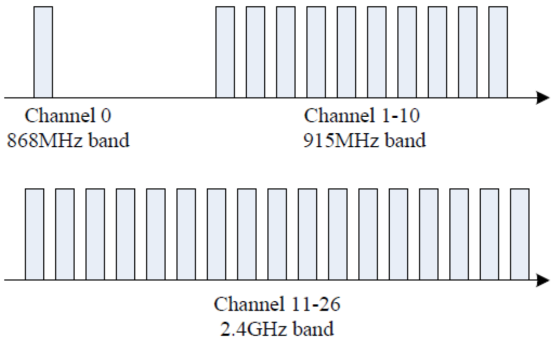

Fig. 1. IEEE 802.15.4 frequency bands and channels

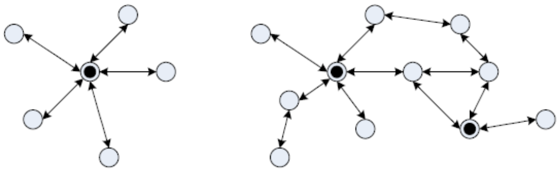

Fig. 2. Star (L) and peer-to-peer (R) topologies

Preamble	Start of packet delimiter	PSDU Length	PHY layer payload
4bytes	1 byte	1 byte	2-127 bytes
SHR		PHR	PSDU

Fig. 3 IEEE 802.15.4 packet structure

IV. A CLOSED-LOOP INDUSTRIAL PLANT ENERGY EVALUATION AND PLANNING SYSTEM USING WSNS

A closed-loop energy evaluation and planning scheme for industrial plants is proposed with a WSN as the back-bone structure. The wide deployment of a WSN results in a sensor-rich environment which allows for a high level intelligent energy management system for industrial plants. The importance of the proposed scheme lies in its wireless, non-intrusive, intelligent, and low cost nature.

B. System Description

In an industrial plant, motor control centers (MCC's) provide power for motors of all different sizes. The motor terminal data are collected and processed in the central supervisory station (CSS). Based on the reports from CSS's, the user can asses the plant operational cost and make decisions. It is necessary to point out that a typical plant usually has more than one MCC and CSS. Traditionally, communication cables need to be installed to collect data from the MCCs or motors and send them to the CSS's. These communication cables could be eliminated by deployment of WSNs. Due to the challenges of WSN technology, such as the relatively long latency, and limited reliability and security, the objective of applying WSN in an industrial plant is not to replace the existing wired communication and control systems completely. Rather the objective is to form a wireless and wired coexisting system; wherein the non-critical tasks such as efficiency estimation, operating cost evaluation, and diagnosis are carried out by the wireless part to reduce the overall cost, while the critical tasks (in terms of time requirement and cost) such as real-time motor controls and overload protection are still performed by the wired system for reliability reasons. The WSN sensor node has both sensing and communication capabilities and can work as a transmitter node, a receiver node, or a relay node. Fig. 4 illustrates a WSN transmitter node. It first measures the motor terminal quantities (*i.e.*, line voltages, line currents, and temperature, if available) and scales them into analog signals in the range of 0-5 volts; then, these scaled signals are passed through an analog to digital conversion (ADC) unit; finally, the digitized signals are passed to the radio unit and the data packets are transmitted through the WSN.

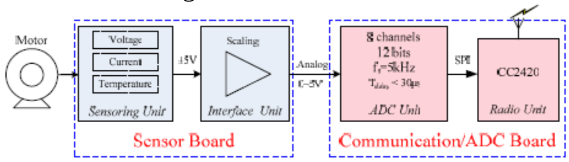

Fig. 4. Description of a WSN transmitter node.

Fig. 5 illustrates a WSN receiver node. It first receives the data packets from WSN; then the raw packets are reconstructed into the original digitized signals in the interface unit; finally, these digital signals are sent to the CSS through an RS232 link. When a sensor works as a relay node, it does nothing but receives data packets and sends the same packets out.

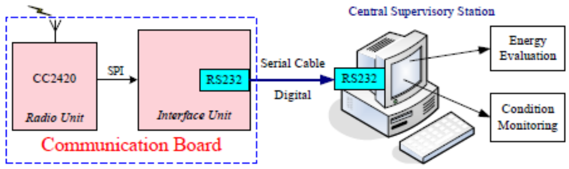

Fig. 5. Description of a WSN receiver node.

The proposed closed-loop industrial plant energy evaluation and planning system with WSN architecture is shown in Fig. 6

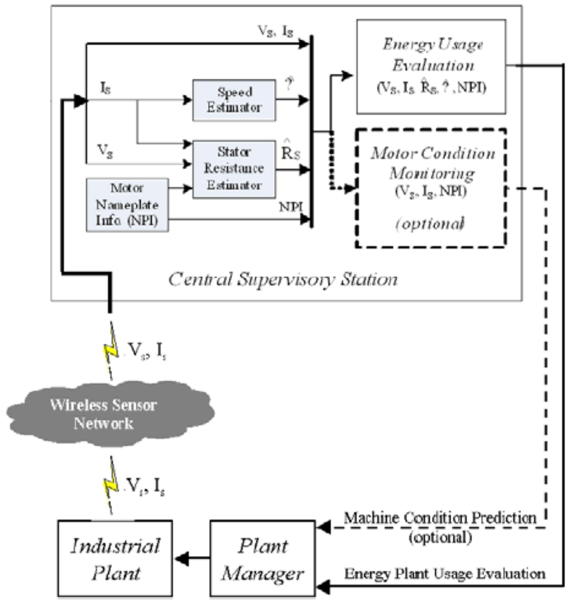

Fig. 6. A closed-loop industrial plant energy evaluation and planning system with a WSN architecture.

As shown in Fig. 6, the motor terminal quantities are measured at the MCC and transmitted to the CSS through the WSN. Using these data, non-intrusive methods are used to estimate the energy usage condition of each motor in the plant, and finally the operating cost of the whole plant. As an

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

optional block, the motor condition monitoring functions could also be applied using the same received data. To close the loop, a plant manager can make planning decisions such as replacing oversized or malfunctioned motors based on the energy usage evaluation and diagnosis results.

B. Energy Usage Evaluation Subsystem

The key of a energy usage evaluation subsystem is the non-intrusive motor efficiency estimation. In this application, the air-gap torque (AGT) method is modified to fit this need. It estimates the motor efficiency using only terminal voltages and currents, and motor nameplate information. Motor efficiency is estimated without interfering with the motor's normal operations respectively

C. Motor Condition Monitoring Subsystem

Motor condition monitoring includes the detection of airgap eccentricities and misalignment, worn bearings, stator winding turn faults, broken rotor bars, winding overheating, and load torque oscillations. These functions can conveniently be added to the energy evaluation system using the data from the WSN. Similar with the requirements of efficiency estimation, non-intrusive methods are required for condition monitoring using only motor terminal quantities.

D. Applicability Analysis

The risk of the proposed scheme is minimized by the fact that several major concerns of WSNs, energy evaluation, and condition monitoring are no longer problems of this specific integrated application. The applicability of the proposed system is improved from the following aspects:

1) Power Consumption

Power consumption or battery life is the dominating factor that affects the design of most WSNs. In this application, power consumption constraints can be ignored because in industrial plant all the WSN sensor nodes are installed either in a MCC or on the motor frame with access to mains power. In both cases, the power can be supplied from very inexpensive ac/dc converters. This also eliminates the implementation of complicated communication protocols and routing algorithms of WSNs, which are primarily intended to reduce power consumption. In this application, a very efficient PSR routing algorithm is used to reduce the overall system cost..

2) Energy Evaluation and Condition Monitoring Accuracy

The energy usage evaluation and condition monitoring results are mainly provided for the industrial plant managers to make their planning decisions. In most cases, rough estimates of motor efficiency or motor health conditions provide allows decision making. This greatly reduces accuracy requirements for the various algorithms in the proposed system.

E. Challenges

However, realization of a WSN needs to satisfy the constraints introduced by factors such as fault tolerance, scalability, signal range, coexistence issues, cost, wireless security, and harsh environment. Investigations are ongoing to solve these problems.

V. EXPERIMENTAL IMPLEMENTATIONS

WSN data transmission, energy usage evaluation, and condition monitoring functions. For the time being, the stator resistance is assumed to be a constant for simplicity.

A. Energy Usage Evaluation - Motor Efficiency Estimation

As a key function of the energy evaluation system, the motor efficiency estimation algorithm is evaluated by both computer simulations and real experiments.

In the experimental setup, a 3-phase induction motor is line connected to a 230 volts mains supply. The motor has the following nameplate information: 4-pole, NEMA- currents. The air-gap flux is obtained through the integral of the stator voltages subtracting the stator IR drop with zero initial conditions. Then the dc offset in the air-gap flux is removed by a 3 cycle (50 ms) moving average window. The actual efficiency is directly calculated from measured speed and shaft torque. Fig. 7 and Fig. 8 compare the estimated and measured motor efficiencies and shaft torques respectively under different load conditions.

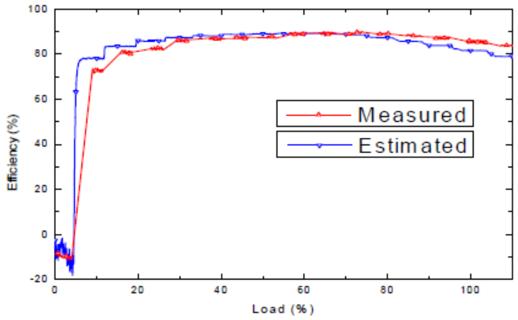

Fig. 7. Comparison of estimated and measured motor efficiency.

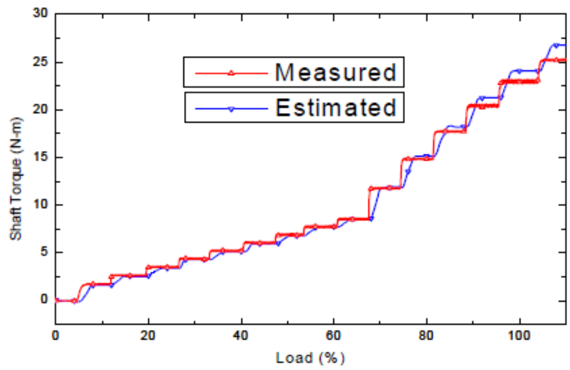

Fig. 8. Comparison of estimated and measured shaft torque.

As shown in Fig. 7, the estimated motor efficiency has a very good agreement (±2% error) with the measured efficiency, especially in the normal motor load range (40% to 90% of rated load). Besides, the proposed system also gives relatively accurate efficiency estimates at underloaded and overloaded conditions, which are useful for industrial energy management. If the estimated temperature varying stator resistance is used, the error in the stator copper loss estimation will be reduced. As a result, the accuracy of the estimated efficiency and shaft torque will be improved.

B. Condition Monitoring – Detection of Air-Gap Eccentricities

A substantial portion of induction motor faults are air-gap eccentricity related. Basically, there are two types of eccentricities: static eccentricity and dynamic eccentricity. In practice, they tend to coexist due to an inherent level of either static or dynamic eccentricity even in a new motor. In general, online condition monitoring of air-gap eccentricity primarily depends on the detection of fundamental side band harmonics located at $f_e \pm f_{rm}$, where f_e is the fundamental excitation frequency and f_{rm} is the rotor rotational frequency. As an example motor condition monitoring technique, an air-gap eccentricity detection algorithm is investigated using only a single phase motor line current. The same experimental setup in section V-A is used. The static eccentricity is created by first machining the bearing housings of the end bell eccentrically and then placing a 0.01 inch shim in the end bell to offset the rotor. The dynamic eccentricity is created by first machining the motor shaft under the bearings eccentrically and then inserting a 0.01 inch offset sleeve under the bearings. A FFT is applied to the measured single phase stator current to obtain its spectrum. When the motor is running at 1752 rpm ($f_e \approx 60$ Hz and $f_{rm} = 29.2$ Hz), the current spectrum is shown in Fig. 8, where, the frequency component magnitudes are shown in a log scale

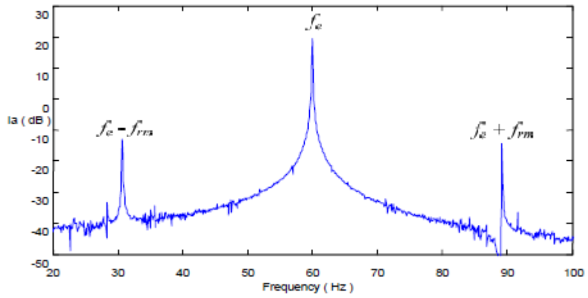

Fig. 9. Stator current spectrum from a motor with a mixed air-gap eccentricity.

Fig. 9 clearly shows that a significant amount of characteristic side-band harmonics appear in the current spectrum. These two current signatures explicitly indicate the existence of an air-gap eccentricity fault.

VI. CONCLUSIONS

In this paper, a closed-loop industrial plant energy evaluation and planning system is proposed in a WSN architecture eliminating the costly installations and maintenance of communication cables. The applicability of the proposed system is analyzed and potential challenges are addressed. The proposed scheme is implemented in a simplified demo WSN system. Finally, the feasibility of the proposed scheme is verified by the experimental results. The unique characteristics of WSNs such as flexibility, high fidelity, self-organization, inherent intelligence, low cost, and rapid deployment make WSN the ideal structure of the low-cost electric machine energy management system incorporating energy usage evaluation and motor condition monitoring functions. The deployment of WSN results in a sensor-rich environment and furthermore constructs a high level intelligent power management system for industrial plants. in the electric machine energy evaluation

ACKNOWLEDGMENT

Mrs.Anubhuti Khare one of the authors is indebted to Director UIT RGPV Bhopal for giving permission for sending the paper to the journal. Manish Saxena Head Of Department is also thankful to the chairman, Bansal Institute of Science &Technology Bhopal for giving permission to send the paper for publication. Last but not least, I would also like to thank our colleagues for supporting us.

REFERENCES

1. B. Lu, T. G. Habetler, and R. G. Harley, “A survey of efficiency estimation methods of in-service induction motors with considerations of condition monitoring,” in *Proc. 2005 International Electric Machine and Drive Conference (IEMDC’05)*, May 2005, pp.1365-1372.
2. IEEE Standard Test Procedure for Polyphase Induction Motors and Generators, *IEEE Std. 112-1996*, Sept. 1996.
3. A. Wallance, A. Von Jouanne, E. Wiedenbrug, E. Matheson, and J. Douglass, “A laboratory assessment of in-service and non-intrusive motor efficiency testing methods,” *Electric Power Components and Systems*, vol. 29, 2001, pp. 517-529.
4. I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: a survey,” *Computer Networks*, vol. 38, no. 4, 2002, pp. 393-422.
5. Department of Energy, “2002 industrial wireless technology for the 21st century,” Office of Energy Efficiency and Renewable Energy Report, Department of Energy, Washington D.C., 2002.
6. B. Lu, L. Wu, T. G. Habetler, R. G. Harley, and J. A. Gutiérrez, “On the application of wireless sensor networks in condition monitoring and energy usage evaluation for electric machines,” in *Proc. 31st Annual Conference of the IEEE Industrial Electronics Society (IECON’05)*, Nov. 2005.
7. B. Lu, L. Wu, T. G. Habetler, R. G. Harley, and J. A. Gutiérrez, “On the application of wireless sensor networks in condition monitoring and energy usage evaluation for electric machines,” to appear in the 31st Annual Conference of the IEEE Industrial Electronics Society (IECON’05), Raleigh, NC, Nov. 2005.
8. J. A. Gutiérrez, E. H. Callaway, and R. L. Barrett, “Low-rate wireless personal area networks: enabling wireless sensors with IEEE 802.15.4,” IEEE Press, New York, 2003.
9. E. Callaway, P. Gorday, L. Hester, J. A. Gutiérrez, M. Naeve, B.Heile, and V. Bahl, “Home networking with IEEE 802.15.4: a developing standard for low-rate wireless personal area networks,” *IEEE Communications Magazine*, vol. 40, no. 8, Aug. 2002, pp. 70-77.
10. IEEE Standard for Information Technology – Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (LRWPANs),” *IEEE Std. 802.15.4-2003*, Oct. 2003.
11. J.R. Holmquist, J.A. Rooks and M.E. Richter, "Practical Approach for Determining Motor Efficiency in the Field Using Calculated and Measured Values", IEEE/IAS PPIC 2003 Conference Record, pp 1-5
12. E. Agamloh, A.K. Wallace, A. von Jouanne, K.J. Anderson and J.A. Rooks, "Assessment of Non-Intrusive Motor Efficiency Estimators", IEEE/IAS PPIC 2004 Conference Record, pp 64-72.
13. J. Hsu and B. P. Scoggins, “Field test of motor efficiency and load changes through air-gap torque,” *IEEE Trans. Energy Conversion*, vol. 10, no. 3, Sept. 1995, pp. 477-483.
14. T. G. Habetler, R. G. Harley, R. M. Tallam, S. B. Lee, R. Obaid, and J. Stack, “Complete current-based induction motor condition monitoring: stator, rotor, bearings, and load,” in *Proc. CIEP 2002 VIII IEEE International Power Electronics Congress*, Oct. 2002.
15. D. B. Durocher, G. R. Feldmeier, “Future Control Technologies in Motor Diagnostics and System Wellness” IEEE/IAS PPIC 2003 Conference Record, pp98-106.