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RESEARCH ARTICLE

TORQUE AND EFFICIENCY MONITORING OF INDUCTION MOTORS USING WSN BASED SYSTEM

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ABSTRACT

The concept praposed here is on the real time automotive application of invigilating the performance of the induction motors which monitorthe torque and efficiency byemploying wireless sensor networks (WSNs). A strong embedded systemis deployed for getting electrical signals from the motor ina constructive manner, and then performing local processing fortorque and efficiency estimation. The values calculated by the embeddedsystem are transmitted to a monitoring unit through an RF-SMD based WSN. Various motors canbe monitored in real time, at the base unit. The relationship between theWSN performance andthe spectral occupancy has been calculated by performing expermental analysis at the operating environment. This thesis specifies that the use of intelligent nodes,with local processingcapability, is essential for the application of motors. A workbench is designed and the embedded system is deployed thereto analyze torque and system efficiency.

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INTRODUCTION

In many automotive industries the load is driven with the help of electric motors in most of the production process. Generally these motors are three phase ac induction motors. These motors are used due to its robustness and cost effectiveness. Induction motors controlled by power electronics are normallysupplied with various chopped voltages or currents. The examinationof their torque qualities is important. In several industry sectors, torque measurement can identify equipment failure, which makes their monitoring essential in order to avoid disasters in critical production process. Researchers and scientists have defined various methods to calculate torque in rotating shafts. There are basically two lines of study for torque estimation as,

Direct Torque Measurement on the shaft:

Direct torque measurement on the shaft using the measuring instrument is more accurate but it is more invasive Theeffectiveness of the proposed intelligent indirect dynamictorque sensor is demonstrated in a typical speed and positioncontrol experimental setup, where the performance obtainedis shown to be superior tu that obtained with conventionalsinusoidal current controllers.

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Estimated torque measurement using motor electric signal:

The estimated torque from the motor's electrical signals (i.e. current and voltage) makes the system less invasive, but it is less accurate when compared to direct measurement systems.There are different methods to measure efficiency in induction motors, which are based on,

- dynamometer
- duplicate machines
- equivalent circuit approaches

However, their application for in-service motors is impractical, because it requires interrupting the machine's operation to install the instruments.

There are some simple methods for in-service efficiency estimation, like

- Nameplate method
- Slip method
- Current method

The efficiency is obtained from an equivalent circuit that is generated from the motor nameplate and the rotor speed measurement. Hsu and Scoggins presented the air-gap torque (AGT) for energy efficiency estimation. The AGT is also used to measure efficiency in a much less invasive manner. The

AGT method can be employed without interrupting the motor operation and it is not based on the motor nameplate. This method generally is more accurate than the other methods described earlier. In this study, the AGT method was used for the estimation of the motor shaft torque and efficiency, because it is the noninvasive method for determining torque and efficiency.Generally energy monitoring and fault detection in industry are performed through wired network which is costlier. Becides the high cost the wired approach offers less flexibility making the network deployment and maintenance difficult.In other context, wireless networks presents, the ease andspeed of deployment and maintenance, and low cost. Inaddition to that, wireless sensor networks (WSNs) provide self-organization and local processing capability. Therefore, wireless network looks as a flexible and inexpensive solution for the industrial monitoring and control systems. This paper presents a strong embedded system for determining torque and efficiency in industrial electric motors by employing WSNs technology. For a set of electric motors, current and voltage measures are gathered for later processing into an embedded system. Torque and efficiency results are then sent to a base unit for real-time monitoring. This way, preventive actions can be taken whenever low-efficiency motors are detected and in cases of torque sudden occurrence.

We have used here RF-SMD for wireless communication. The data transfer has been done with the help of half duplex mode, which specifies the secure communication between two nodes. If we send one signal from the embedded system then the motor detects it and send the information this defines the half way communicationIt is necessary to send a large amount of data when computing the desired parameters. This limits, among other things, the frequency of data acquisition from sensors. In a WSN with a large number of nodes, the situation becomes even worse, since all nodes share the same physical transmission medium. Furthermore, it should be taken into account the unreliability of communication inherent to wireless networks, which can cause the loss of transmitted data, hampering the parameters' estimation process.The system proposed here does all the data processing locally, transmitting to the base unit only the targeted parameters previously calculated. Thus, there is a large reduction in the amount of transmitted data, enabling real-time and dynamicmonitoring of multiple motors, even with a high data rate acquisition in the analog-to-digital converters (ADC).

Previous work

KyusungKim, Associate Member, IEEE, and Alexander G. Parlos, Senior Member, IEEE proposed Early detection and diagnosis of incipient faults is desirablefor online condition assessment, product quality assuranceandimprovedoperational efficiency of induction motors runningoff power supply mains. In this paper, a model-based fault diagnosissystem is developed for induction motors, using recurrentdynamic neural networks for transient response prediction andmulti-resolution signal processing for nonstationary signal featureextraction. In addition to nameplate information required for theinitial setup, the proposed diagnosis system uses measured motorterminal currents and voltages, and motor speed. The effectivenessof the diagnosis system is demonstrated through staged motorfaults of electrical and mechanical origin. The developed systemis scalable to different power ratings and it has been successfullydemonstrated with data from 2.2-, 373-, and 597-kW inductionmotors. Incremental tuning is used to adapt the diagnosis systemduring commissioning on a new motor, significantly reducing thesystem development time.

John Hsu (Htsui) Senior Member Center for Electro mechanics, the University of Texas at Austin Austin, Texas 78712 proposed the analytical and experimental studie of the capacitoreffects on the steep rising and falling voltage spikes and the currentharmonics in induction motors fed by quasi rectangular currentsources are conducted through the case of a motor fed with a sixpulse current source. The phase current of the motor fed by the sixpulsecurrent source goes through various regions of harmoniccurrent (and voltage) variations. The analytical and experimentalresults show that as the value of the capacitor reactance is reducedgradually toward the motor magnetizing reactance, the motorencounters the higher frequency current amplifications first, andsubsequently. The seventh-harmonic amplification and then the fifthharmonicamplifications. Analytical result also shows that it ispossible to encounter a severe fundamental-frequency currentamplification when the capacitor reactance is less than the motormagnetizing reactance.

T. H. Lee, T.-S. Low, Senior Member.IEEE, K.-J.Tseng, and H. K. Lim proposed a technique for indirectsensing of the dynamic torque feedback signal which is applicableto permanent magnet BLDC drives. This technique is based on a judicious use of the motor equations and on parameter estimationmethods. It is intelligent in the sense that thl' technique providesself-calibration at start-up, and in the paper, we also present adl'Sign to extend the technique to overcome effects of parameterdrifts by incorporating real-time on-line parameter estimation. The effectiveness of the proposed intelligent indirect dynamictorque sensor is demonstrated in a typical speed and positioncontrol experimental setup, where the performance obtainedis shown to be superior tu that obtained with conventionalsinusoidal current controllers.

John S. Hsu, Senior Member, IEEE, John D. Kueck, Senior Member, IEEE, Mitchell Olszewski, Don A. Casada, Pedro J. Otaduy, and Leon M. Tolbert, Member, IEEE proposed a theory which states that unlike testing motor efficiency in a laboratory,certain methods given in IEEE Standard 112 cannot be usedfor motor efficiency evaluations in the field. For example, it isdifficult to load a motor in the field with a dynamometer whenthe motor is already coupled to driven equipment. The motorefficiency field evaluation faces a different environment from thatfor which IEEE Standard 112 is chiefly written. A field evaluationmethod consists of one or several basic methods. This paperseparates and compares the basic methods according to theirphysical natures. Their intrusiveness's and accuracies are alsodiscussed. This paper is useful for field engineers to select or toestablish a proper efficiency evaluation method by understandingthe theories and error sources of the methods.

Bin Lu, Member, IEEE, Thomas G. Habetler, Fellow, IEEE, and Ronald G. Harley, Fellow, IEEEproposed Energy usage evaluation and condition monitoringfor electric machines are important in industry for overall energysavings. They are often expected to be implemented in an integratedproduct because of many common requirements such asdata collection. Because of the uninterrupted characteristic of industrialprocesses, traditional methods defined in IEEE Standard112 cannot be used for these in-service motors. This paper proposesa truly nonintrusive method for in-service motor-efficiencyestimation based on air-gap torque using only motor terminalquantities and nameplate information, with special considerationsof motor condition monitoring requirements. Rotor speed andstatorresistance, the stumbling blocks of most in-service testingmethods are extracted from motor input currents instead of beingmeasured. The no-load test, which is required for calculating therotational loss and core loss, is eliminated by using empirical values.Stray-load loss is assumed according to the motor horsepoweras suggested in IEEE Standard 112. Finally, the proposed methodis validated by testing three induction motors with different configurations.Experimental results show that the proposed method canestimate motor efficiencies with less than 2% errors under normalload conditions.

Bin Lu, Senior Member, IEEE, and Vehbi C. Gungor, Member, IEEE proposed the identification of the synergies between wirelesssensor networks (WSNs) and nonintrusive electrical-signal-basedmotor signature analysis and proposes a scheme of applying WSNsin online and remote energy monitoring and fault diagnosticsfor industrial motor systems. The main scope is to provide asystem overview where the nonintrusive nature of the electricalsignal-based motor signature analysis enables its applications inaWSN architecture. Special considerations in designing nonintrusivemotorenergymonitoring and fault diagnosticmethods in suchsystems are discussed. This paper also provides detailed analysesto address the real-world challenges in designing and deployingWSNs in practice, including wireless-link-quality dynamics, noiseand interference, and environmental impact on communicationrange and reliability. The overall system feasibility is investigatedthrough a series of laboratory experiments and field tests.First, the concept of a remote and online energy monitoring andfault diagnostic system is demonstrated using a simplified startypeIEEE 802.15.4 compliant WSN in the laboratory. Twowell-established nonintrusive motor diagnostic algorithms are intentionallyused to prove the feasibility. Next, the challenges ofapplying the proposed WSN scheme in real industrial environmentsare analyzed experimentally using field test results.

Vehbi C. Gungor, Member, IEEE, and Gerhard P. Hancke, Senior Member, IEEE proposed that in today's competitive industry marketplace, thecompanies face growing demands to improve process efficiencies,comply with environmental regulations, and meet corporate financialobjectives. Given the increasing age of many industrialsystems and the dynamic industrial manufacturing market, intelligentand low-cost industrial automation systems are required toimprove the productivity and efficiency of such systems. The collaborative nature of industrial wireless sensor networks (IWSNs)brings several advantages over traditional wired industrial monitoring and control systems, including self-organization, rapiddeployment, flexibility, and inherent intelligent-processing capability.In this regard, IWSN plays a vital role in creating a highlyreliable and self-healing industrial system that rapidly respondsto real-time events with appropriate actions. In this paper, first,technical challenges and design principles are introduced in termsof hardware development, system architectures and protocols, andsoftware development. Specifically, radiotechnologies, energyharvesting techniques, and cross-layer design for IWSNs havebeen discussed. In addition, IWSN standards are presented forthe system owners, who plan to utilize new IWSN technologies forindustrial automation applications. In this paper, our aim is to providea contemporary look at the current state of the art in IWSNsand discuss the still-open research issues in this field and, hence, to make the decision-making process more effective and direct.

System architecture

The system comprises of the Induction Motors, Embedded unit, Wireless Sensor Networks and nodes, WSN Routers and a WSN coordinator as,

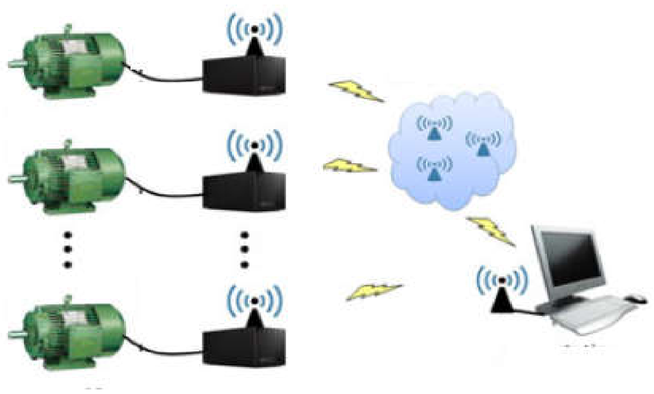

Fig. 1. Embedded System having Induction Motors, WSN and Nodes, WSN routers and a base station (WSN coordinator)

By taking in considerations of the distance between end nodes and the coordinator, it may not be possible to achieve direct communication, due to the radio's limited range and the interference present on the environment, among other factors. Therefore, the communication among nodes and coordinator can be done with assistance of routers.The block diagram of the proposed embedded system is given as,

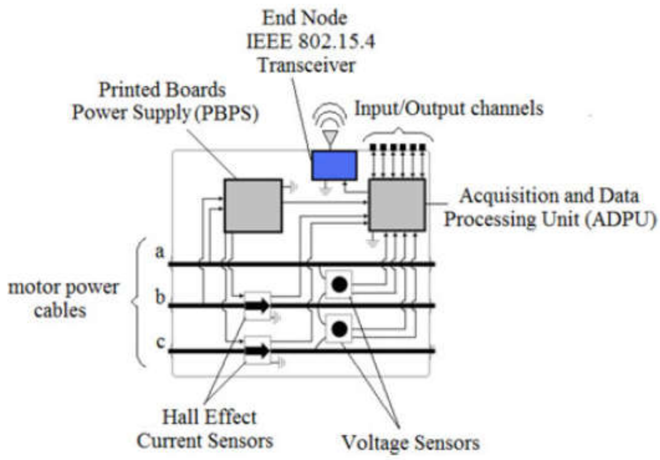

Fig. 2. Block diagram of embedded system

For current measurement, *Hall Effect* sensors are employed due to their robustness and noninvasiveness. Transformerswithgrain-oriented core are used to measure the voltage between phases, which provide the voltages in the secondary and primary without delay. The acquisition and data processing unit (ADPU) is responsible for data acquisition and conversion, besides the data processing. The printed boards power supply supplies the current and voltage for the sensors, the RF-SMD transceiver, and the ADPU. The main element of the ADPU is a dsPIC16F8740, a ATMEL 89C52, which is a digital signal controller designed for applications that require high processing capacity. It has two integrated ADC, which perform simultaneous acquisition of the voltage and current sensors. The input/output channels can be used for user interface, and possible connections to auxiliary sensors and actuators. The values of torque and motor efficiency are transmitted using the RF-SMD transceiver. We have used an RF-SMD having operating frequency 2.4GHz, with 30 meter range. It has a waving voltage of +5V DC. The connection between the transceiver and the dsPIC is accomplished using a Serial Peripheral Interface Bus.The activity diagram is drawn which shows the internal operation of the embedded system. When the system starts, the embedded system parameters are configured. These parameters include the wireless network settings (e.g., address,channel), and the ADC settings. To obtain good accuracy froma simple numerical integration method, such as trapezoidal (used to implement the algorithm), a sample rate greater than 2 kHz should be used. In our system, we set the ADC to operate with 3 kHz and 10 bits of resolution which deals with the good data rate and the accuracy

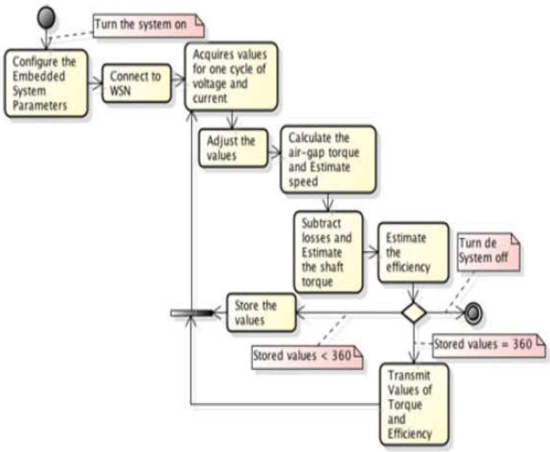

Fig. 3. Activity Diagram

After the first step, the system connects to the WSN. The embedded system only begins to acquire and process data after Successfully connecting to a coordinator operating in the same channel. Then, the system gets into the acquisition loop, processing, and transmitting data, which is repeated until the system shuts down. The voltage and current values, after acquired, must be adjusted to reflect the real values measured from the sensors. After that, the algorithm is executed to compute the AGT. After that, the losses are removed, and the shaft torque is estimated. Using the shaft torque values, the system estimates the motor speed and efficiency. The embedded systems were configured to calculate a set of 360 values (2 bytes each) of torque and efficiency, and then transmit these values aggregated into 20 packets with 72 bytes of payload each. The time necessary to acquire the signals and calculate the 360 values of torque and efficiency is about 11 s (6s to acquire 360 cycles of current and voltage, and 5 s to perform the calculations). Thus, the system transmits data in burst mode spending only about 8% of the time transmitting data, at a rate of 20 packets per second.

Mathematical formulation

1 Calculation of the Shaft Torque :

Air Gap is the region between the stator and the rotor, in induction motor. The AGT is the conjugate formed between the rotor and the stator magnetic flux. In this study, the AGT method is used to estimate the motor shaft torque, by taking the current and voltage measurement from the electric motor.

$$T_{ag} = \frac{p\sqrt{3}}{6}\{(i_a - i_b)\int[v_{ca} + r(2i_a + i_b)]dt + (2i_a + i_b)\int[(v_{ab} - r((i_a - i_b)]dt\} \quad (1)$$

Where,
$p$is the number of rotor poles
$i_a, i_b$are the motor line currents, in ampere
$v_{ab}, v_{ca}$are the motor power line voltage , in volt
$r$is the resistance of motor armature, in ohm

The torque on the shaft can be estimated by subtracting the losses occurring after the process of electromechanical energy conversion from AGT as,

$$T_{shaft} = T_{ag} - \frac{L_{mec}}{\omega_r} - \frac{L_{Rsl}}{\omega_r} \quad (2)$$

Where,
$L_{mec}$are the mechanical losses
L_{Rsl} are the stray load losses
$\omega_r$is the rotor speed in rad per second

Mechanical losses (i.e., friction and windage*Lmec*) vary according to the particular motor and the industrial process to which it belongs. If it is not possible to estimate the losses, then it is necessary to perform a no-load test. The additional losses (i.e., stray-load loss, *LRsl*) result from nonlinear phenomena of different natures, difficult to quantify. These can be approximated by a percentage of motor power

2Calculation of the Shaft Speed :

Several methods of sensor less rotor speed estimation have been proposed. These methods follow two categories:

- Induction motor model,
- Analysis in the frequency spectrum of voltage and electric current

The method proposed by Ishida and Iwata, based on the electrical voltage, uses techniques of digital signal processing to detect the harmonics generated due to the rotor slots. However, it requires high rotor speed and stability. Ferrah*et al.* and Hurst and Habetler used the fast Fourier transform to extract harmonics due to the rotor slots from the electric current spectrum. Some limitations of such method are that it requires a high acquisition rate from sensors and high processing power. The method also requires information from the motor, which do not appear in their factory specifications. The methods mentioned earlier do not work well when the speed is close to the synchronous speed and in dynamic systems with variable torque and vibration.

3Calculation of the Efficiency:

The motor efficiency η can be estimated by the relation between the electrical power supplied to the motor (i.e., input power P in) and the mechanical power supplied to the shaft by the motor (i.e., output power P out), according to the following equation:

$$\eta = \frac{P_{out}}{P_{in}} \qquad (3)$$

Where,
P_{in} is the input power of the three phase induction motor calculated by the instantaneous current and voltage

$$P_{in} = i_a v_a + i_b v_b + i_c v_c = -v_{ca}(i_a + i_b) - v_{ab} i_b \qquad (4)$$

P_{out}can be determined by the estimated shaft toque and the rotor speed as follows:

$$P_{out} = T_{shaft}\omega_r \qquad (5)$$

Thus by putting the values of equation (4) and (5) in equation (1), we will get the efficiency as,

$$\eta = \frac{T_{shaft}\omega_r}{-v_{ca}(i_a+i_b)-v_{ab}i_b} \qquad (6)$$

Where,
$v_{ab}, v_{bc}, v_{ca}$are the stator line voltages
$i_a, i_b, i_c$are the stator phase currents

Conclusion

This review paper has considered different methods which can be used to enhance the monitoring of the torque and efficiency of the induction motor. Use of the WSN results the time management as well as cost reduction. The faults detection and recovery has been done in accurate and non-invasively with time saving, cost efficient and no labor cost.AGT method to estimate shaft torque and motor efficiency. The calculations for estimating the targeted values are done locally and then transmitted to a monitoring base unit through an RF-SMD WSN.In spite of some difficulties in WSN, the system was able to provide useful monitoring information. We are able to use WSN due to the local processing capability for better communication performance.

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