The Application of Wireless Sensor Networks to In-Service Motor Monitoring and Energy Management

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Abstract

This paper presents an application of wireless sensor networks (WSN) to an in-service motor monitoring and energy management system. Based on the IEEE 802.15.4 standard, wireless sensor devices are developed in the proposed system. The motor current and voltage signals are acquired and analyzed by a DSP device to get the condition of motors, and the results are transmitted over the wireless network to a central supervisory station (CSS), where they are stored, displayed and analyzed to meet the requirement of motor monitoring and energy management. This approach greatly reduces the transmission time. That makes the proposed system acceptable in real-time cases. The wireless sensor devices are demonstrated and the test results are given.

1. Introduction

Induction motors are the essential driving machines in industry. The motor driven system used in industrial plants consumed about 70% of all electrical energy consumed by industry [1]-[2]. As an amount of energy loses by the inefficient motors every year, it's important to develop a low-cost in-service motor monitoring and energy management system.

The energy evaluation system in industrial plants is usually implemented with wired communication networks so far. Because of the high cost of installation and maintenance of these cables, it is desired to look for a low-cost, robust, and reliable communication network.

The wireless sensor networks (WSN) is a self-organized network of small sensor nodes with communication and calculation abilities [3]. As an open architecture, self-configuring, robust, and low cost network, it is suitable to meet the requirement

Nathan Ota and Paul[4] discussed the application trends in wireless sensor networks for manufacturing. WSNs can make an impact on many aspects of predictive maintenance (PdM) and condition-based monitoring. WSNs enable automation of manual data collection. PdM applications of WSNs enable increased frequency of sampling. Condition-based monitoring applications benefit from more sensing points and thus a higher degree of automation.

James et al.[5] discussed the robust, self-configuring wireless sensors networks for energy management and concluded that WSN can enable energy savings, diagnostics, prognostics, and waste reduction and improve the uptime of the entire plant.

Bin Lu et al.[6]-[10] applied wireless sensor networks in industrial plant energy management systems. A simplified prototype WSN system was developed using the prototype WSN sensors devices, which were composed of a sensor unit, an A/D conversion unit, and a radio unit. However, because the IEEE 802.15.4 standard is designed to provide relaxed data throughput, it is not acceptable in some real-time cases for the large amount of raw data to be transmitted from the motor control center (MCC) to the central supervisory station (CSS) [8].

In this paper, wireless sensor devices are developed and applied in an in-service motor monitoring and energy management system. A DSP is used for data processing at the MCC, and only the results are transmit to the CSS. This approach can greatly reduce the transmission time.

2. In-Service Motor Energy Management

The energy usage evaluation is one of the basic functions of an in-service motor energy management system. And motor efficiency estimation is the most important among the energy evaluation functions.
In order to evaluate the energy usage, the motor current signature analysis method (MCSA) is used to estimate and/or calculate 8 motor condition parameters, including the current root mean square (Irms), the voltage root mean square (Urms), the input power (PE), the power factor (\(\cos \varphi\)), the rotor speed (n), the shaft torque (T), the output power (PM), and the efficiency (\(\eta\)), as shown in Figure 1.

Figure 1 Motor condition parameters calculation

The MCSA is a non intrusive method by which only current and voltage sensors are installed at the power supply of the motors. Without the installation of sensors, such as speed, torque, and temperature ones, on the motor body, it is easy to monitor the in-service motors in industrial plants.

Based on the MCSA technology, the in-service motor monitoring and energy management system consists of some front-end devices, which are installed at the MCC to acquire and analyze the motors current and voltage signals, and a back-end CSS, which gathers and stores the analysis results from the front-end devices and estimates the motor conditions. The communication between them is based on WSN architecture. The system architecture is illustrated in Figure 2.

3. Wireless Sensor Network

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 [3].

The IEEE802.15.4 standard is a physical layer protocol for WSN, which supports three frequency bands with 27 channels as shown in Figure 3. 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.

Figure 3. IEEE 802.15.4 frequency bands and channels

The IEEE 802.15.4 supports two network topologies as shown in Figure 4. 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.

Figure 4. Star (L) and peer-to-peer (R) topologies

An IEEE packet, called physical layer protocol data unit (PPDU), consists of a five-byte synchronization header (SHR) which contains a preamble and a start of packet delimiter, 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 Figure 5.

<table>
<thead>
<tr>
<th>Physical Layer Service Data Unit (PSDU) Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preamble</strong></td>
</tr>
<tr>
<td>4 bytes</td>
</tr>
</tbody>
</table>

Figure 5 IEEE 802.15.4 packet structure

4. Design and Implementation of WSN devices

4.1. The front-end devices

The front-end device is developed with the digital signal processing (DSP) techniques. It is divided into three parts: sensing, signal processing and transmitting unit, as shown in Figure 6.

![Figure 6 The design of the front-end device](image)

The three parts of the front-end devices are designed and implemented separately on individual PCB’s. When constructing the front-end devices, the signal processing unit and the transmitting unit are mounted on the sensing unit and linked by cables with each other, as shown in Figure 7. The flexible design could meet the requirement for different sensors while different motors are monitored. And moreover the sensing unit could be omitted in the case that the current and voltage sensors are already equipped in the MCC’s in industrial plants. In that case, the transmitting unit can be mounted on the signal processing unit.

The sensing unit consists of two current sensors and two voltage sensors. Both of them are highly accurate Hall effect ones. In the prototype devices used in the laboratory, the current sensor is HNC025A with 0-36 amps RMS current range, ± 0.6% accuracy, and <0.2% linearity, and the voltage sensor is HNV025A with 100-2500V volts RMS current range, ± 0.6% accuracy, and <0.2% linearity.

![Figure 7 Implementation of the sensing, processing and transmitting unit (WSN node)](image)

The signal processing unit contains three main subunits. The -5v - +5v analogue voltage signals coming from the sensing unit are firstly scaled into analogue signals in the range of 0-3.3 volts to meet the requirement of the ADC chip. And then an 12-bit 8-channel ADC is used to sample the analogue waveforms at a certain frequency, which can be configured as 2, 4 or 8 KHz in the prototype devices, and convert them into digital signals.

The kernel of the signal processing unit is a 32-bit fixed-point DSP chip TMS320F2812, which has 128KB flash memory, 18KB internal SARAM. It controls the signal processing and spectrum estimation programs running in a μcOS/II system.

4.2. The WSN nodes

The transmitting unit is implemented with a Cirronet ZMN2400HP wireless module to transform motor running parameters from the front-end device to the CSS. The ZMN2400HP consists of an 8-bit Atmel Mega128 microcontroller, which has 128KB flash memory, 4KB EEPROM and 4KB internal SRAM, and a Chipcon CC2420 radio chip, which is compatible with the IEEE 802.15.4 standard and works at 2.4 GHz band. A more detailed structure of the radio unit is shown in Figure 8.

![Figure 8 Design of WSN nodes](image)

Generally there are three kinds of nodes in a wireless sensor network: transmitter nodes, which have both sensing and wireless communicating capabilities, the receiver nodes, which have both wireless and wire
communicating capability, and relay nodes which have only the wireless communicating capability to relay the data packets in the case that the distances between the transmitter and receiver nodes are beyond the communication range.

In the in-services motor monitoring system, most of the WSN nodes are transmitter ones used in the MCC to transmit the processing results to the CSS. As a few receiver and relay nodes are used in the system, all of the three kinds of nodes are implemented based on the same hardware structure to simplify the design. Those full-capability nodes can be configured to act as transmitter, receiver or relay nodes. This gives the reason why the transmitting unit is separated from the signal processing unit in the design of the front-end devices.

Power consumption is the dominating factor in the design of WSN nodes. However in this specific application, the power consumption is no longer a problem to be considered because the WSN nodes are installed at such locations as a MCC or a CSS, where the power supply is available. So the WSN nodes are designed to be powered by AC/DC converters.

Additionally, as the WSN nodes are used either with the DSP unit or individually, it is designed to be supplied either by the DSP unit or an AC/DC converter.

5. The application of WSN to in-service motor monitoring and energy management

5.1. The application of WSN

The in-service motor monitoring and energy management system is constructed based on the DSP devices and WSN nodes presented above.

At MCC, the motor stator line current and voltage signals are acquired by the sensing unit and analyzed by the signal processing unit to estimated/calculated all the 8 parameters mentioned in section 2. At last, the results are transmitted to the CCS by the transmitting unit over the wireless sensor networks.

At CCS, all the 8 parameters are stored in the database and displayed with instantaneous values and wave charts as shown in Figure 9.

5.2. Data throughput

As described in section 3, the PSDU length can vary from 2 to 127 bytes in a IEEE 802.15.4 data packet. In the proposed system, the PSDU is totally 32 bytes long with 1-byte motor ID, 1-byte frame type, 2-byte counting number, 4-byte voltage, 4-byte current, 4-byte speed, 4-byte torque, 4-byte input power 4-byte output power, 2-byte efficiency, and 2-byte power factor. Apparently, one result can be transmitted in one data packet.

To meet the requirement of signal processing, 4 channels of current and voltage signals are sampled synchronously at 4KHz frequency for 1 second to get 50 cycles of 50Hz waveforms. Another 2 seconds are spent on calculating and transmitting the results. So every 3 seconds, a data packet is sent to the CSS from one front-end device.

That transmitting time and data throughput requirement is enough to be implemented in an IEEE 802.15.4 WSN with the standard latency 6-60 ms and data throughput 250KBps.

To check the maximum communication abilities between the WSN nodes, a simple test is made in which real size data packets are continuously send from a transmitter to a receiver in 300ms with each packet sent within an specified interval (Is). The packets sent from the transmitter (Ps) and the packets received by the receiver (Pr) are counted. Then the real receiving interval (Ir), average packets received per second (Pa), and the packets lost rate (Lr) are calculated. The test results are illustrated in Table 1.

<table>
<thead>
<tr>
<th>Is</th>
<th>Ps</th>
<th>Pr</th>
<th>Ir</th>
<th>Pa</th>
<th>Lr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100</td>
<td>2976</td>
<td>2976</td>
<td>0.0101</td>
<td>9.92</td>
<td>0.0000%</td>
</tr>
<tr>
<td>0.050</td>
<td>5887</td>
<td>5887</td>
<td>0.0051</td>
<td>19.62</td>
<td>0.0000%</td>
</tr>
<tr>
<td>0.030</td>
<td>9691</td>
<td>9691</td>
<td>0.0031</td>
<td>32.30</td>
<td>0.0000%</td>
</tr>
<tr>
<td>0.025</td>
<td>11567</td>
<td>11567</td>
<td>0.0026</td>
<td>38.56</td>
<td>0.0000%</td>
</tr>
<tr>
<td>0.020</td>
<td>14310</td>
<td>14310</td>
<td>0.0021</td>
<td>47.70</td>
<td>0.0000%</td>
</tr>
<tr>
<td>0.015</td>
<td>18791</td>
<td>18790</td>
<td>0.0016</td>
<td>62.63</td>
<td>0.0053%</td>
</tr>
<tr>
<td>0.010</td>
<td>22577</td>
<td>19537</td>
<td>0.0015</td>
<td>65.12</td>
<td>13.4650%</td>
</tr>
<tr>
<td>0.005</td>
<td>29718</td>
<td>18851</td>
<td>0.0016</td>
<td>62.84</td>
<td>36.5671%</td>
</tr>
</tbody>
</table>

From the test results, it can be seen that the minimum packets receiving interval is about 0.015 seconds. In other words, maximum 66.7 packets can be received every second on average. If the transmitter sends packets faster than that, the communication becomes worse with packets lost rate getting higher.

**Table 1 Communication abilities test**

**Figure 9 Motor condition monitoring**
5.3. Laboratory Test

A laboratory test is made in a prototype system including an MCC, a CSS, and four Y100L2-4 induction motors (4-pole, 3KW, 380V, 6.8A) with four 4KW DC generators as their loads, as shown in Figure 10.

In the CCS, a WSN receiver node is used as a coordinator of the network. Four front-end devices are installed in the MCC to acquire the current and voltage signals of the four test motors. When started, they search and connect to the coordinator automatically to setup a star wireless network. Then the coordinator sends a query packet to one of the 4 front-end nodes every second and receives a data packet sent back on the request. In this way, the motor monitoring results are successfully transmitted to the CSS constantly.

The motors are tested from no load to full load with intervals of 12.5% load. And signals are sampled and analyzed for 120 seconds at each load point. That means totally 4 (motors) * 9 (load point per motor) * 120 (seconds per load point) / 3 (seconds for one packet) = 1440 packets are transmitted from 4 front-end devices to the CCS. As only one packet is sent to the coordinator from one of the 4 front-end monitoring devices every second, the data throughput is enough to transmit the data packets, and there is no packet lost in the laboratory test.

6. Conclusion

This paper presents the development of wireless sensor devices in the in-service motor monitoring and energy management system which is used to evaluate the condition of motors used in industrial plants.

The front-end device consists of a sensing unit to acquire the motor current and voltage signals, a DSP unit to perform the motor current signature analysis, and a radio unit to transmit the results to a central supervisory station over the wireless networks based on the IEEE 802.15.4 standard. As the analysis and calculation are made at the front end and only the results are transmitted by the wireless network, this approach greatly reduce the transmission time. That makes the proposed system acceptable in real-time cases.

7. Acknowledgment

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8. References