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WSN Based Power Monitoring in Smart Grids

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***Abstract*–Smart grid technology is one of the recent developments in the area of electric power systems that aid the use of non-conventional sources of energy in parallel with the conventional sources of energy. Monitoring and control of smart grids is essential for its efficient and effective functioning. In this paper, we propose an architecture for monitoring power in smart grid applications using wireless sensor network (WSN) technology. A prototype power sensing module is designed and developed to calculate the power for any kind of loads. Using WSN technology, the monitored power is communicated to the sink at periodic intervals. Multi hop wireless mesh network is set up using IRIS motes to enhance the communication between the power sensing nodes and the sink. The data collected is a rich source of repository for data analysis and modelling. A number of smart actions and applications, such as power theft detection, energy efficient building design, smart automation systems and smart metering can evolve out of the proposed model. A novel Power theft detection algorithm is proposed and simulated in this paper. The system is also scaled using GSM technology to extend the range of communication. Load monitoring can aid distributed architecture in smart grids with automated technology to switch between the non-conventional source of energy and the grid.**

Keywords: multihop, smartgrid, power sensing module

I. Introduction

Improvements in power electronics technologies and utilization of renewable energy sources for power generation have given rise to the use of distributed generation and create concept of smart grids and micro grids to overcome rapid increase in the demands for electricity and depletion of conventional energy sources. Monitoring of power system parameters like voltage, current and power at distribution level is crucial for efficient functioning of smart grid.The power exchange between the smart grid and the utility grid happens by switching. This switching needs complete synchronism between the smart grid and the utility grid. An economic & reliable communication backbone along with accurate monitoring system is essential.

Monitoring of the power system essentially has two main modules: communication module which is the backbone and the sensor module for sensing the different parameters like voltage, current and power. The basic communication architecture is simple and the actual network topologies can be very diverse and depend mostly on the field-level network. With respect to the communication requirements, several options are possible [1]-[4]. Wired communication with dedicated data networks connecting the field devices is one possibility. Dedicated wired data networks can be designed to fulfill the requirements, but the installation costs do not permit an intensive use [5].A less expensive option is wireless networks. Technologies for wireless local area networks or Personal Area Networks like IEEE 802.15.4 can, in principle, be used as a replacement for wired links [6, 7].

An alternate wireless technology is cellular networks as used in telecommunications, like global system for mobile communications (GSM) or general packet radio service (GPRS), or worldwide interoperability for microwave access (WiMAX). They have high coverage and low installation costs for the end devices if the infrastructure already exists [5]. The downside is the general dependency on the network provider if public telecommunication networks are used–regarding both costs for the communication channels and quality of service (QoS). A power line communication system is another popular method for communication [7]–[11]. They use the existing power cabling and need only moderate additional network elements but require a more complex technology in order to overcome the rather poor communication channel characteristics. This type of communication needs higher technical effort and cannot be used in case of a disaster where the power lines are disconnected.

Recently, WSNs have been recognized as a promising technology that can enhance various aspects of today's electric power systems, including generation, delivery and utilization, making them a vital component of the next generation electric power systems, smart grids [12]. Wireless sensor networks in conjugation with SCADA have been implemented in wind power plants. The wireless sensor network can provide abundant, real-time data for wind driven generators' reliable running, guaranteeing the steady running of wind power plant [13]. ZigBee based WSN are proven to be more reliable in packet delivery due to mesh based multi-hop networking. The security of 802.15.4 is also proven better than many exiting protocols in the literature. Generally wireless sensor networks have the main constraints of battery power and scalability but these constraints are well addressed in new ZigBee based sensor networks with more sleep mode options and dynamic multihop algorithms. The proposed application is for smartgrids, so with little auxiliary charging circuit sensor networks can be made less energy independent.

In India context of application of WSNs to power systems, new ideas and implementation plans are coming up where various parameters in the system, etc., are being dealt with [14]. The harsh environments of the power systems need properly designed wireless modules along with efficient sensing elements.

Generally sensing mechanism for measuring the voltages and currents in a power systems is to use potential transformers (PTs) and current transformers (CTs). This technology for sensing has proved itself over a long period of time in industry and in the field. The commonly available current sensors for higher ratings of current are magnetic core based CTs. In case of lower ratings, different transducers like the Hall-Effect current transducers are also available [15]. The usual method of measuring the voltages is by using the potential transformers.

This paper focuses on proposing architecture for power monitoring system for smart grid applications using WSN technology. The mode of communication used is 802.15.4 protocol with a multi-hop network. Multi-hop wireless communication extends the range of monitoring with the flexibility of easy installation of the monitoring system. A power sensing module is designed and developed to measure the active power consumption of any kind of load. In this paper, we also discuss an algorithm to detect power theft which is one of the novel applications using the proposed architecture of the WSN based power monitoring system. Rest of the paper discusses the system architecture for WSN based power monitoring, design of the sensing module, experimental results, discussion and finally the conclusion.

II. System Architecture For Power Monitoring Using WSN Technology

The power monitoring system using WSN has a modular architecture as shown in Fig.1. The characteristics of the system to be monitored such as voltage and current ratings have to be well defined for the proper design of the hardware platform. Based on the information of system rating, appropriate auxiliary circuit has to be designed to step down the values of the parameters needed for monitoring. The resulting signals after stepping down the values are processed using the power/energy sensing unit to get the information on the power. This information is converted to a suitable form so that the auxiliary circuit can be interfaced to the communication module to transmit the data to the base station or the server.

A. Setting up of Wireless Sensor Networks

In this work, WSN is built using IRIS motes and MDA300 data acquisition board from Crossbow for power monitoring in electrical distribution systems of smart grid.

MDA300 has free ADC channels to be accessed and hence can be used to develop an application. The IRIS motes were programmed to communicate with each other in multi-hop fashion. The multi-hop network was set-up by programming the motes in Tiny OS using nesC [16]. Multi-hop mesh network is capable of dynamic routing which enables the motes to communicate to the base station directly if it were in range (about 250m line of sight) or through relay nodes in between. The base station or the gateway is a sink node connected to a computer that acts as a server. In the following section we describe the sensing module for power monitoring.

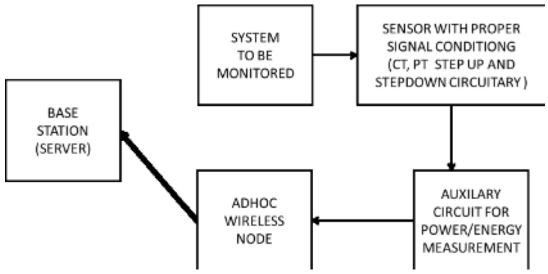

Fig1. System architecture for the power monitoring system

III. Power Monitoring Sensing Module

A. Hardware design and development

Monitoring the loads of a distribution system is an important part of the monitoring system. A prototype has been designed and developed to monitor the energy and power consumption in single phase systems. The basic block diagram of the system is shown in Fig.2. The hardware mainly consists of voltage and current step-down blocks, ADCs, phase correction blocks, multiplier blocks, digital to frequency converters, counters, timing block, DAC, sensor board and the wireless mote.

Some blocks in the hardware are available in the form of energy metering IC ADE 7757 which is a single phase energy metering IC. The IC takes stepped down voltage and current as inputs and gives pulses of frequency corresponding to the energy consumed by the load. Auxiliary hardware was designed to meet the requirements of the inputs of the IC in the form of capacitance potential dividers for the voltage step down for powering the IC from the mains. The voltage and load currents are given as the inputs to the IC for power computation. These inputs along with filters act as the step down blocks which generate the inputs for the ADE 7757. The ADE 7757 IC has internal clock and ADCs with the multipliers and digital to frequency converters. A counter is used to count the number of pulses in the output. The frequency of the outputpulses is proportional to the power consumption of the load.The digital value of the counter is converted to analog voltage level using an R-2RDAC. This analog voltage is fed to one of the ADCs of the sensor board interfaced to the mote. Details of each of the block are given below.

B. Functions of the individual blocks in the sensing module

The energy metering IC has limitations on the inputs that can be given to it. The inputs to the IC for calculating the power are the voltage and the current. The voltage is stepped down using resistance potential divider which is given as the voltage input to the IC. The load current is converted to a proportional voltage using a resistance in series with the load. The basic blocks for the voltage step down and current step down is shown in Fig. 3. The basic equation for the potential divider is the series voltage division principle. In case of the load current it is just converted to a proportional voltage by using a shunt in series with the load to get a voltage proportional to the load current across the shunt.

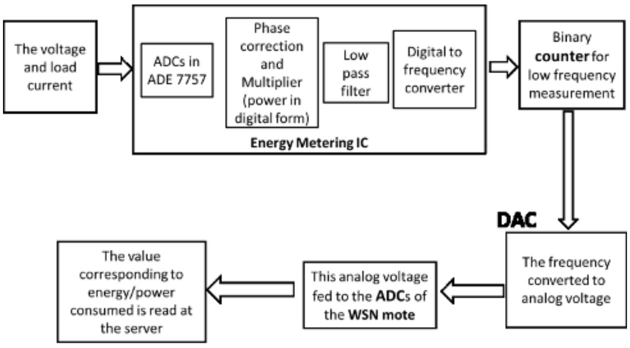

Fig 2. Basic block diagram of the system developed

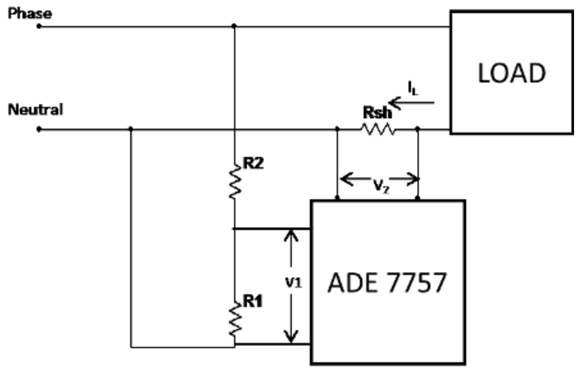

Fig 3. The basic block diagram showing the voltage and current inputs to the metering IC ADE7757

The stepped down and scaled voltages are given as inputs to the ADCs of the energy metering IC. The ADCs in ADE 7757 are 16-bit sigma-delta ADCs with over sampling frequency of 450kHz. TheADCs in ADE 7757enable the direct interface with the voltage and current sensors. A high pass filter (HPF) is present in the input current channel which removes the dc component in the current signal. This eliminates the inaccuracies due to the presence of offsets in the real power calculation. As the HPF is always active, the designed scheme functions only for ac inputs.

The real power calculation is derived from instantaneous power signal. The instantaneous power signal is obtained by direct multiplication of the voltage and current samples. As the instantaneous power is calculated directly by multiplying the samples, the power factor is inherently taken into consideration. All the signal processing is carried out in the digital domain for superior stability over temperature and time. The obtained product of the samples is fed to a digital to frequency converter which generates frequencies proportional to the instantaneous power signal; the analytics of which are being studied.

The counter circuitry consists of an 8-bit binary counter which is clocked by the frequency output of the energy metering IC. The counter is interfaced to an R-2R digital to analog converter (DAC) to read an analog value corresponding to the count. The real power is accumulated for about 48 seconds and then averaged to get the average real power information. The counters are reset every 48 seconds to avoid overflow of the counter. The reset timing functionality is achieved by a stable multi-vibrator using a 555 timer circuit. The 555 timer circuit is designed to generate a negative pulse every 48secs. As the aimed application is for monitoring the real power consumed by every consumer, the frequency of data being sent is chosen to be more frequent (48 seconds was the closest value possible to 50 seconds with the resistor and capacitor values available). The power monitoring system is planned for monitoring even a minimum load. For example, a 12 watt bulb (known as a 0 watt bulb) gives frequency of the output pluses to approximately 50 seconds.

The output from the DAC is given as input to the sensor board through the ADC channels on the sensor boards. The value of the DAC is sent to the server though the wireless sensor network established. The entire hardware can be developed as a smart meter by including a few more auxiliary modules.

C. Extracting the real power information from the DAC output

The value which is sent to the server is the output of the DAC which gives the information about the energy consumed in 48 seconds and hence needs to be averaged to get the average real power information. Every smart meter has a calibration factor which needs to be determined experimentally. Therefore every smart meter has to undergo a one-time calibration. The server is programmed to calculate the average power from the information it receives from the motes.

1) *Validation of the hardware module developed* :

Experiments were conducted using different known loads to test how the monitoring module behaves. The frequency output which gives information on the instantaneous power was measured using the counter and the corresponding DAC outputs were studied. The frequency output of the energy metering IC isdependent on the supply voltage and load current. The relation governing the output frequency was estimated from the circuit elements and their values and is given by the transfer function mathematically given by equation (1) given in the datasheet [18].

$$F_0 = \frac{515.84 * V_1 * V_2 * F_1}{V_{ref}^2} \quad \text{Hz} \qquad (1)$$

Where,

F_0 is the frequency of the output pulse in Hz

V_1 is the voltage input to ADE7757 in Volts

V_2 is the voltage proportional to load current in Volts
V_{ref} is the reference voltage for internal blocks (3.3 volts) in Volts
F_1 is the frequency generated in the IC and is given as 0.86 Hz for the configuration designed [18].

The equation(2) for the frequency output takes into account the root mean square (RMS) values of the voltages, currents and the scaling factors which need to be considered as the signals are sent through various blocks for several operations. For example, the voltage input to the energy metering IC is taken from a potential divider and hence needs to be scaled accordingly. The equation derived is:

$$F_0 = 1.59 * 10^{-3} * V_{in} * I_L \quad \text{Hz} \qquad (2)$$

Where,
F_0 is the frequency of the output
V_{in} is the RMS value of the input voltage (supply)
I_L is the RMS value of the load current

The pulses generated by the metering IC is then used to drive a counter which is connected to a DAC which has an output equation of

$$V_{out} = V_R * \sum_{i=1}^{8} \left(Ci * \frac{1}{2^i} \right) \quad \text{Volts} \qquad (3)$$

Where,
V_{out} is the output of the DAC
V_R is the reference voltage (1.5 V in this case)
C_i is the value of thei^{th}bit in the counter

The DAC output is then mapped back to the power value based on the counter value, the reset time of 48secs and the derived relation for frequency of pulses to the power and the one time calibration factor is calculated for every board.

For the first board designed, the calibration factor was found to be approximately equal to 316. This means the output power can be calculated by using equation (4).

$$Avg.Power = 316 * V_{DAC} \quad Watts \qquad (4)$$

Where,
Avg.Poweris the average power of the Load
V_{DAC} is the DAC output voltage

The calibration is done experimentally and the value is determined by connecting known loads and checking the DAC output. The maximum DAC output should not exceed 2.5 volts which is the maximum input for the ADC channel of the sensor board [17].

IV. Experimental Results And Discussions

The power monitoring system using WSN technology shown in Fig.5was tested using different loads. The loads that were tested were of known power rating and so the module could be tested to check if the output matched the actual load connected. The module was tested with 60, 100 and 200 watts incandescent lamps and a 14 watt compact fluorescent lamp. For example, a 60 watt bulb connected as a load to be monitored gave pulses approximately every 12 secs, resulting in 4 counts. The DAC output was found to be 189.8 mV also can be verified from equation (3). Theoretically, the time for each pulse is 10.58 secusing equation (2). The difference between the theory and the practice was very minimal.

A three node network was setup to monitor different loads of 60 watts, 100 watts and 200 watts by using the system developed. The data was collected and sent to the base successfully at periodic intervals using the WSN network setup using IRIS motes.

A. Wireless Power Monitoring Using GSM Technology for Range Extension

The same power monitoring modules were used to monitor the power consumed by different loads using GSM technology. The GSM communication module was implemented using 8051 microcontroller with the GSM module. The DAC output is connected to the ADC of the 8051 microcontroller. The 8051 was programmed to sample the ADC channels to measure the DAC's output voltage and process appropriately to compute the power using the calibration equation derived for the respective board connected.

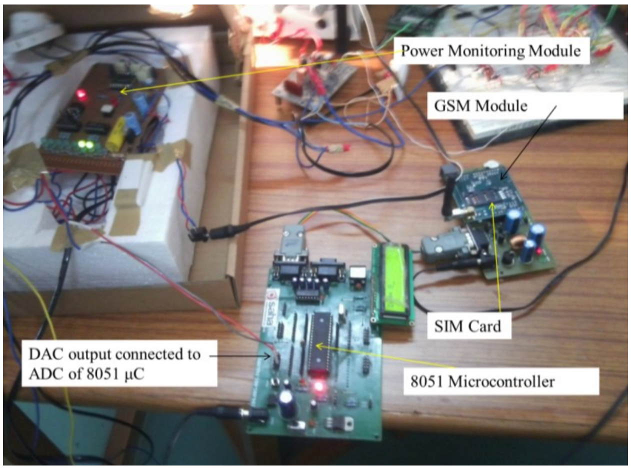

Fig.4. The implementation with the GSM module.

The processed real power information was sent to a GSM SIM card whose number is predefined in the code in the microcontroller via the GSM module connected to the 8051 microcontroller. A GSM module is interfaced to the microcontroller for communicating the power calculated. Fig.4 shows the power monitoring module interfaced to the GSM module through the 8051 microcontroller. The power monitoring using the GSM technology for electrical power distribution system monitoring as the WSN with the sensor nodes has a constraint of distance whereas this constraint is eliminated in case of the GSM technology. The power distribution system monitoring can be enhanced further using the GSM technology to measure various other parameters like currents, voltages, etc. In the present work, the GSM technology was also successfully used to implement wireless power monitoring.

B. Power Theft Application using the proposed power monitoring system

The power monitoring hardware shown in Fig.5 can be used to develop various applications from distributed system monitoring to smart home application. This modules can be used to monitor individual loads, collective loads or a consumer of power entirely. The smart home applications can be developed effectively using this module to have a greener power scenario.

As an extension, a novel application of the WSN based power monitoring system is power theft detection. Preliminary algorithm for the power theft was simulated using Matlab Simulink which is discussed in this section as shown in the fig.6. The model has balanced 3-phase voltage source with the RMS value of 230V. Two balanced 3-phase loads are considered with a lossy distribution line was modeled with resistance of 8 Ω to get a maximum voltage drop of 6% across the line. All the loads were modeled to be 150Ω per phase. The currents and voltages were sensed so that active power could be calculated. The values of voltages and power were transferred through an Additive White Gaussian Noise (AWGN) channel. The information could be sent successfully through the channel. The load powers were calculated with a loss-less line and the power mis-match between the source power and the load power was found to be 0W. The same experiment was repeated with thelossy line and all the loads being monitored. The power mismatch was observed to be equal to the loss in the line which was 153.2 watts as shown in Fig.8, which plots the power mis-match against the time of simulation chosen to be 1 sec. This plot was for the case when there was no power theft and the system had a lossy line which is around 153.2 watts.

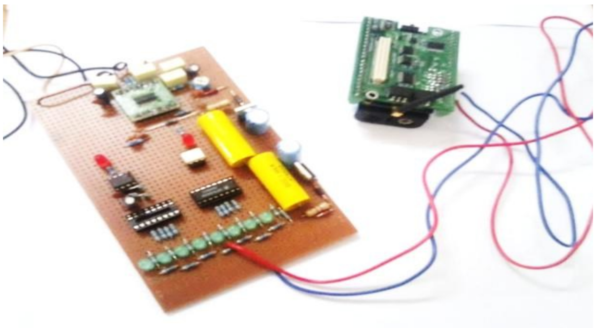

Fig.5. WSN basedPower monitoring system

Experimentation was again carried out with a lossy line and power theft; an un-monitored load was introduced of 150Ω per phase and the power deficit was calculated to be 967.6 watts which was equal to the sum of line loss and the stolen power as shown in Fig.7, which plot the power mis-match in case of theft on a lossy line against the time of simulation chosen to be 1 sec. The time of simulation was chosen to be 1 sec as it can be treated as steady state in case of power systems. The values of power deficit are shown to be negative as the source power is subtracted from the sum of monitored load powers and the losses.

From fig.7 and 8, it can be seen that if there is a theft on the distribution line, it can be easily detected by using this algorithm by calculating the difference which in this case is 814.4 watts (difference of the power deficits).

It was observed that the power supplied was correctly accounted as the sum of powers in loads and the losses in the system. The power equivalence as shown by equation (5) was successfully tested using the above experimentation.

$$P_{supplied} = \sum P_{loads} + P_{loss} \tag{5}$$

The power theft algorithm is planned to be implemented using the proposed WSN based power monitoring system is shown graphically in the fig.9. Wireless nodes with power sensor modules have unique identification numbers. The data sent from the each node is received by local data aggregator on the supply transformer and sent through GSM to local control station. Transformer input power can be measured with the proposed power sensor module. Data under single distribution transformer can be grouped and send to the local control station. The local control station can run a theft algorithm for this data from that transformer. Theft algorithm is simply a algebraic sum of powers at the transformer node as shown in the equation-5. The algebraic sum should be zero when there is no theft with consideration of losses. The algebraic sum of powers don't sum to zero when there is a illegal power consumption shown as red spot in the fig.9 in that transformer area.

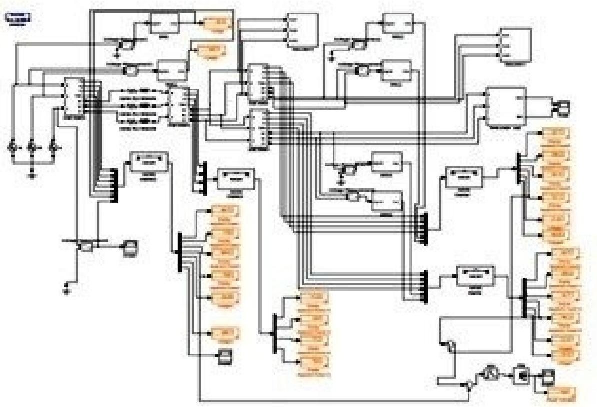

Fig 6. A screenshot showing the model file for the power theft detection

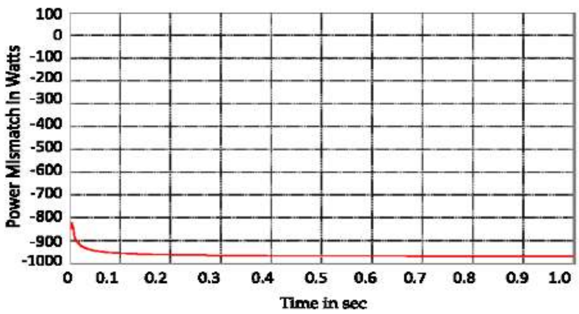

Fig.7. Power mismatch with theft on a lossy line

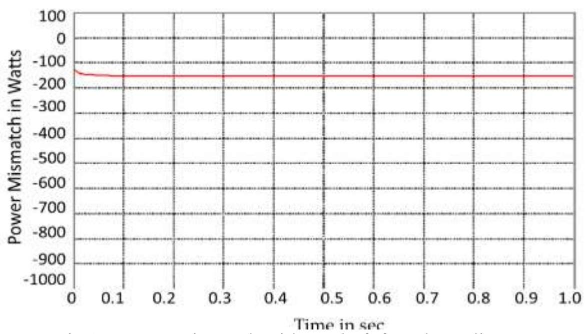

Fig 8. Power mismatch without theft for a lossy line

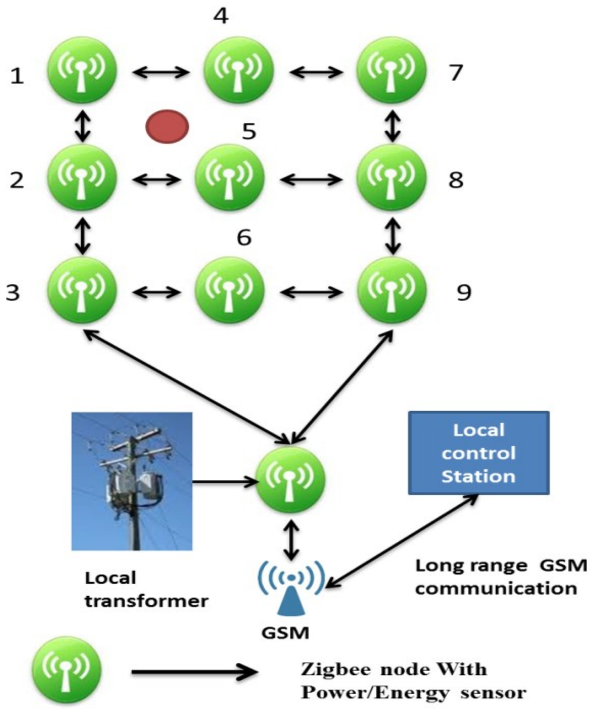

Fig 9. Proposed theft detection algorithm model

V. Conclusion

In this paper, architecture for power monitoring system using the wireless sensor network technology is proposed. Multi-hop mesh network was set up for long range and reliable wireless communication. A prototype for power sensing module was designed and developed for monitoring single phase system. The sensing module is calibrated and tested for the accuracy. The experimentation performed shows that the measured power almost matches the rated power. The calibrated sensing module along with the WSN node communicated the monitored power value to base/sink at periodic intervals. With appropriate scaling this model can be extended to distribution systems also. It is clear from the experimentations that the wireless sensor networks may be successfully employed to smart grids for monitoring purpose. With proper design we also show that WSN can be employed to mitigate power theft and can be effectively used for monitoring the all costly electrical equipment as part of maintenance.

For large scale deployment, cost effective power monitoring system is essential, which requires a reliable and low cost WSN mote design. This system can be extended for smart home automation, online billing and smart metering applications also. This can also be further extended for complete distribution system monitoring with the monitoring of transformers' temperature, oil levels, over-loading, etc.

Acknowledgement

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References

[1] A. Ipakchi and F. Albuyeh, "Grid of the future," IEEE Power Energy Mag., vol. 7, no. 2, pp. 52–62, Mar./Apr. 2009.
[2] F. Lobo, A. Cabello, A. Lopez, D. Mora, and R. Mora, "Distribution Network as communication system," in Proc. SmartGridsDistrib., CIRED Semin., Frankfurt, Germany, 2008, pp. 1–4.
[3] M. McGranaghan, D. von Dollen, P. Myrda, and E. Gunther, "Utility experience with developing a smart grid roadmap," in Proc. Power EnergySoc. Gen. Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, 2008, pp. 1–5.
[4] S. E. Collier, "Ten steps to a smarter grid," in Proc. REPC, Fort Collins, CO, 2009, pp. B2-1–B2-7.
[5] A. Mahmood, M. Aamir, and M. I. Anis, "Design and implementation of AMR Smart Grid System," in Proc. EPEC, Vancouver, BC, Canada, 2008, pp. 1–6.
[6] C. Bennett and D. Highfill, "Networking AMI smart meters," in Proc. Energy 2030 Conf. (ENERGY), Atlanta, GA, 2008, pp. 1–8.
[7] A. Sarafi, G. Tsiropoulos, and P. Cottis, "Hybrid wireless-broadband
[8] over power lines: A promising broadband solution in rural areas," IEEE Commun. Mag., vol. 47, no. 11, pp. 140–147, Nov. 2009.
[9] G. N. SrinivasaPrasanna, A. Lakshmi, S. Sumanth, V. Simha, J. Bapat, and G. Koomullil, "Data communication over the smart grid," in Proc. ISPLC, Dresden, Germany, 2009, pp. 273–279.
[10] M. Bauer, W. Plappert, C. Wang, and K. Dostert, "Packet-oriented communication protocols for Smart Grid Services over low-speed PLC," in Proc. ISPLC, Dresden, Germany, 2009, pp. 89–94.
[11] F. Lobo, A. Lopez, A. Cabello, D. Mora, R. Mora, F. Carmona, J. Moreno, D. Roman, A. Sendin, and I. Berganza, "How to design a communication network over distribution networks," in Proc. 20th Int. Conf. Exhib. Elect.Distrib., Prague, Czech Republic, 2009, pp. 1–4.
[12] Vehbi C Gungor, Bin Lu and Gerhard P. Hancke, "Opportunities and Challenges in Wireless Sensor Networks in Smart Grid", IEEE Transactions on Industrial Electronics, Vol.57, pp. 3557-3564, 10 October 2010e, , 1998.
[13] XingzhenBai, XiangzhongMeng, Zhaowen Du, Maofa Gong, Zhiguo Hu, "Design of Wireless Sensor Network in SCADA for Wind Power Plant
[14] AryadeviRemanideviDevidas, ManeeshaVinodini Ramesh, "Wireless Smart Grid for Monitoring and Optimizing Electric Transmission in India", Fourth International Conference on Sensor Technologies and Applications, 2010 pp 637-640
[15] http://www.allegromicro.com/en/Products/Part_Numbers/0712/0712.pdf
[16] nes C manual provided by Crossbow with the motes
[17] XMDA-MTS manual provide by Crossbow
[18] Datasheet of ADE 7757