

Design and Implementation of Smart Electrical Power Meter System

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ABSTRACT

In recent years, increased importance of Smart Grid, which includes monitoring and control the consumption of customers of electric power. In this paper, Wireless Smart Electrical Power Meter has been designed and implemented which ZigBee wireless sensor network (WSN) will be used for wireless electrical power meter communication supported by PIC microcontroller which used for power unit measurements. PIC microcontroller will be used for evaluating all electric power parameters at costumer side like V_{rms} , I_{rms} , KWh, and PF, and then all these parameters will be send to base station through wireless network in order to be calibrated and monitored.

Keywords: Electrical power meter, PIC Microcontroller, Wireless communications, ZigBee.

نظام لاسلكي ذكي لقياس القدرة الكهربائية المستهلكة

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المخلص

في السنوات الأخيرة، زادت أهمية "الشبكة الذكية"، التي تشمل رصد ومراقبة استهلاك العملاء للطاقة الكهربائية. في هذا البحث، تم تصميم وبناء نظام لاسلكي ذكي لقياس استهلاك الطاقة الكهربائية حيث يستخدم PIC microcontroller لقياس V_{rms} , I_{rms} , KWh, and PF ثم ارسال هذه القيم لاسلكيا الى المحطة الرئيسية باستخدام ZigBee wireless sensor network (WSN) حيث يتم معالجة البيانات ومراقبتها في المحطة الرئيسية.

I. Introduction

In fact, after the 1991 Gulf War, electrical power has been severely damaged in Iraq, where the destroying in the power plants exceeds 90% since that time, Iraq is suffering from a real crisis in providing demand for electric

power, and one of the most important reasons and influencing is a distribution network damaged and irregular consumption of electric power. Now an urgent need for a comprehensive change in the electrical distribution network and especially controlling the

consumption of customers of electrical power and control must rely on an efficient and reliable system for accurate readings which this reduces the cost of measurements, in addition to providing an environment to monitor power factor which is an important factor that increasing consumption or pressure on the network. Change in the national distribution network must include providing a safe environment for measurements and calculations, cost which this matter will increase network efficiency and reduce consumption as well as to increase the value of the financial benefits.

The present system of energy metering as well as billing in Iraq, which uses electromechanical energy meter is error prone and it consumes more time and labor. The conventional electromechanical meters are being replaced by new electronic meters to improve accuracy in meter reading. Still, the Iraqi power sector faces a serious problem of revenue collection for the actual electric energy supplied owing to energy thefts and network losses. One of the prime reasons is the traditional billing system which is inaccurate many times, slow, costly, and lack of flexibility as well as reliability [1]. In recent years, the developments in electric power meter seem to provide opportunities in implementing energy efficient metering technologies that are more precise, accurate, error free, etc. [2-5].

There are many methods for measuring electrical power at home are manual meter, IC Card prepaid meter, wire-line and wireless meter reading system: [6]

- **Manual meter reading:** it is the oldest method and it is weak because; for each house there is its own meter, this method required employers which taking readings of metrics manually, high cost of measurements because it needs a large number of staff, low accuracy of readings, and difficult to monitor gauges that these devices vulnerable to abuses. This method is still used in Iraq so far.

- **IC card prepaid meter:** it is used pay-before use therefore it does not need employers to reading meters on site. It has partially solved the problem of manual meter reading because of no need to be on site and less measurements cost. But some problems exist in the actual operation process: IC card meter is easily damaged due to its direct contact with users and no real-time monitoring. It also fails to avoid theft, damage, and the fault of a meter.

- **Wire-line metering control system:** in this method, the problem of measurements in real time has been solved, so all meters can be monitored and controlled in real time, also this type of meters can be connected to the main station through telephone lines, power line, TV network, etc. therefore it has low measurements cost. But it has problems of long construction period, high installation cost and maintenance cost, expansion of the system upgrade and compatibility with other network.

- **Wireless meter reading system:** it is a process that the meter data is read and processed automatically via special equipment using wireless communication and computer network technology. In this type of meters all

problems of real time measurement, monitoring and control has been solved. Compared with the traditional meter reading, it not only effectively saves human resources, but also save the wiring cost and helps the management department find problems in time and take appropriate measures to deal with. Also, it has easy and low cost installation, easy to extend, and more secure than other methods [7][8].

In this paper, design and implementation of Wireless Smart Electric Power Meter will be achieved which PIC microcontroller will be used as the main part for evaluation consumed electric power and PF. The rms value of voltage and current, consumed electric power, and PF will be monitored through LCD at home and also send these parameters through a ZigBee wireless network to the base station in order to monitor electric power demand and evaluate consumed electrical power fees.

The outline of the paper is as follows. The comprehensive structure of a wireless meter system is described in section II. The design and implementation of the electrical power meter are explained in details in section III. System software is described in section IV. Result discussion in section V, while conclusions are summarized in section VI.

II. The comprehensive structure of wireless meter system

The comprehensive structure of wireless electric power meter system is shown in Fig. 1. The wireless electric power

meter has been used for each customer. These meters have been used to measure the instantaneous electrical power per hour (KWh) and power factor (PF) by using Microcontroller circuit which sends the values of (KWh and PF) to the base station through ZigBee wireless network technology.

Normally base station located far away from costumers, in this case routing device based on ZigBee wireless standard have been used in order to arrive the measurements of electrical power meter to the base station. The final stage of the system is located at the base station, which the server based on ZigBee standard has been used to receive all measurements of costumers and store these data in database for managing and analyzing.

In this paper, automatic electric power meter has been designed in order to measure instantaneous voltage and current. The consumed power and PF has been calculated by PIC microcontroller which consumer monitors these values at home by LCD while the same values sends to a base station for monitoring and calculating the consumed electric power. Xbee kit has been used for ZigBee wireless communication. The XBee/XBee-PRO RF Modules are designed to operate within the ZigBee protocol and support the unique needs of low-cost, low-power wireless sensor networks. The modules require minimal power and provide reliable delivery of data between remote devices.

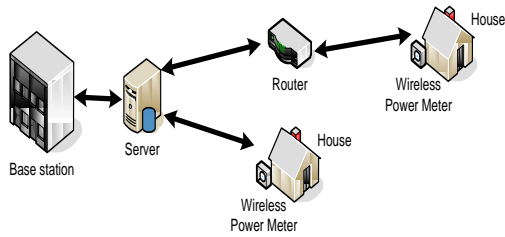


Figure 1: Comprehensive structure of smart wireless electrical power meter.

III. Design of the electric power meter

In this section, the implementation of a basic watt hour meter using microcontroller circuit has been achieved. In the process, ADC with a sample-and-hold circuit can effectively measure both voltage and load current. KWh and PF have been calculated by PIC microcontroller which sends to XBee kit through RS232 serial connection. The design discussed here uses the PIC24FJ128GA010 and Current Transformer (CT) for current sensing.

A. Principles of measurement

Basically, a watt hour meter is designed to measure energy or power consumed over time. In simple terms, electrical power is the product of voltage and current. If measurements of both instantaneous voltage and current, or V_i and I_i has been repeated for N times, the average power (watt) is.

$$\text{Average Power} = \frac{(\sum_{k=1}^N V_{ik} * I_{ik})}{N} \quad (1)$$

The total energy consumed during specific time can be calculated by multiplying the average power by time.

$$\text{Consumed Energy} = \frac{(\sum_{k=1}^N V_{ik} * I_{ik})}{F_s} \quad (2)$$

For alternating current, average power can be calculated by $V * I * \cos(\theta)$, where V and I are average rms voltage and current, and θ is the phase angle between the V and I . Instantaneous sampling does not directly use power factor; the value of the phase angle is essentially embedded in the instantaneous current measurement. Recovering the actual phase angle for the purpose of calculating and displaying the power factor can be done separately and is very calculation intensive.

It is difficult for a microcontroller to make direct measurements when the supply voltage is 230V at up to 50A. This makes it necessary to indirectly measure line voltage and current at a level consistent with a microcontroller, and then rescale these measurements to arrive at the original value. Measuring current here is essentially the same as measuring voltage which transducer has been used to generate a voltage proportional to the load current. The actual voltage and current readings can then be derived.

For this application, the derived voltage reading, V_d , is related to the actual instantaneous line voltage V_i by the expression, $V_d = V_i * K_d / K_v$ or $V_i = V_d * K_v / K_d$, where K_d is the digitization constant for the ADC in this application and K_v is the voltage proportionality constant for the circuit design. Similarly, the derived current reading, I_d , is related to I_i by the expression, $I_d = I_i * K_d / K_i$ or $I_i = I_d * K_i / K_d$, where K_i is the current proportionality constant specific to this design; it is calculated by dividing the CT turn ratio by the

product of the current amplifier gain and the input burden resistance.

By substituting the values of V_d and I_d into Equation 2, the total consumed power of indirect voltage and current measurements will as follow.

$$\begin{aligned} & \text{Energy Consumed (Wattsecond)} \\ &= \frac{(\sum_{k=1}^N V_{dk} * I_{dk}) * K_v * K_i}{F_s * K_d^2} \end{aligned} \quad (3)$$

It is more practical to accumulate up to some fixed amount, and then increment a counter to indicate energy consumption. In this paper, for each accumulating 1000 Wh (1 KWh) the counter will be incremental. This value represents the resolution limit of the meter. It is equivalent to 3,600,000 watt seconds (1000 W x 60 x 60). The resolution limit D can be calculated by Equation 3.

$$D = \sum_{k=1}^N V_{dk} * I_{dk} = \frac{3600 * F_s * K_d^2}{K_v * K_i} \quad (4)$$

Any time that the accumulated sum of the voltage and current products equals or exceeds D, the counter will be increment the KWh. Also, any remainder in excess of D will be saved to be used in the next round of accumulation.

B. Sampling Voltage and Current

Calculating power assumes that the voltage and current are sampled exactly the same time. By using a single ADC with one sample-and-hold circuit makes this impossible. By using an interpolated voltage value that very closely approximates what the voltage would be when the current is sampled.

The principle is graphically represented in Fig. 2.

In this paper, the sampling time t has been taken in order to measure voltage and current. The procedure has been achieved to calculate the voltage for a particular current measurement:

1. Measure the first voltage sample at time t_0 .
2. After an interval of t , measure the current (time t_1).
3. After another interval of t , measure the voltage again (time t_2).
4. Calculate the voltage at t_1 as $(V_{dt0} + V_{dt1})/2$.

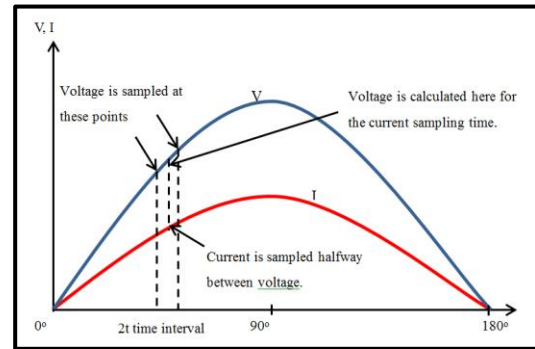


Figure 2: Interpolating voltage for a current sample.

C. Hardware Design

The conceptual design of the energy meter is shown in Fig. 3; a more detailed schematic is presented in Fig.4. This design was prototyped using the PIC24FJ128GA010.

As shown in Fig.4, line voltage and current are sampled sequentially at regular intervals, with voltage and current being presented to different analog input channels. To measure voltage, the AC line is sampled across a potential divider, R1 and R2, which divides the input voltage by about 280. For current measurement, a current

transformer creates voltage signal across burden resistors (R5 and R6) that are proportional to the load current. As the core design of the energy meter will accommodate different types of transducers, the CT is not shown on the schematic.

A fixed offset of approximately 1.5 V is added to both the current and voltage signals. This maintains the signal well above V_{SS} , which is an operating requirement of the microcontroller's ADC. By itself, the ADC does not have the dynamic range or resolution to perform the necessary measurements. For the current signal, an amplifier with two selectable gain stages follows the analog switches; it is used to compensate for the wider dynamic range of the current sample. Single stage gain is set by the values of R7 and R8; together with the turn ratio of the CT and the value of the burden

resistors, these determine the value of the current proportionality constant, K_i .

$$K_i = \frac{CT_Ratio}{R_6} \left(\frac{R_8}{R_7 + R_8} \right) \quad (5)$$

While the voltage proportional constant K_v is

$$K_v = \left(1 + \frac{R_1}{R_2} \right) \left(\frac{R_4}{R_3 + R_4} \right) \quad (6)$$

Information of energy consumption is sent over an 8-wire interface to an external LCD. The current version of the application firmware displays cumulative energy use to date, as well as several other parameters, in a continuous rollover fashion.

The core hardware design also includes a serial RS-232 interface for data communication. The data lines are electrically isolated from the rest of the meter circuitry to reduce the risk of damage to external equipment.

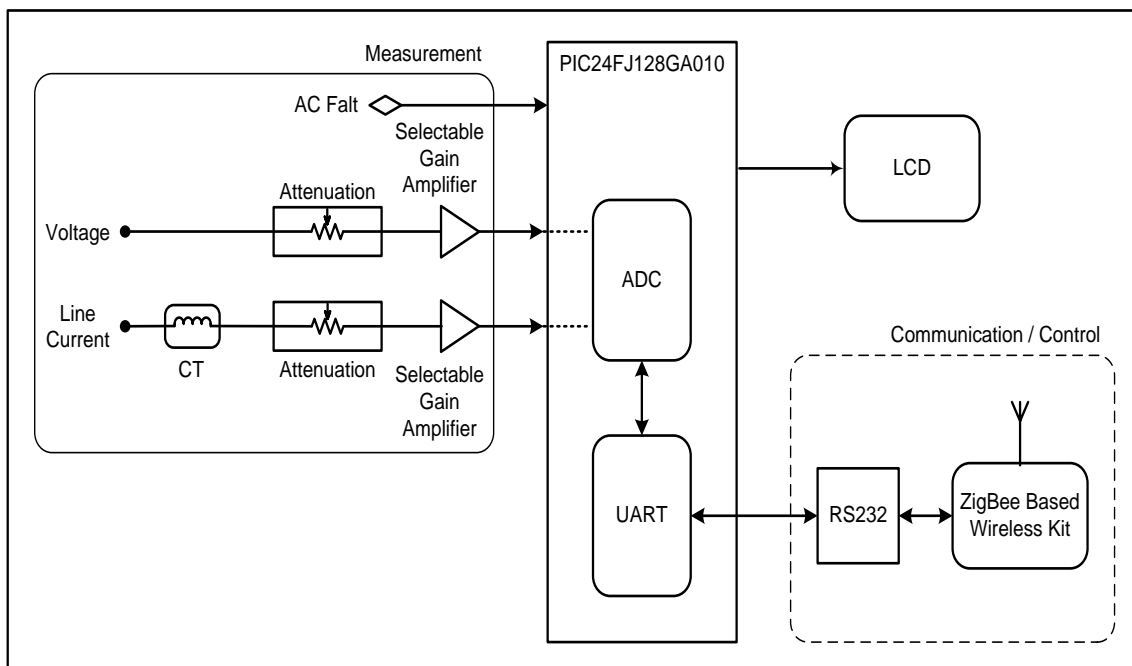


Figure 3: Conceptual block diagram of the energy meter.

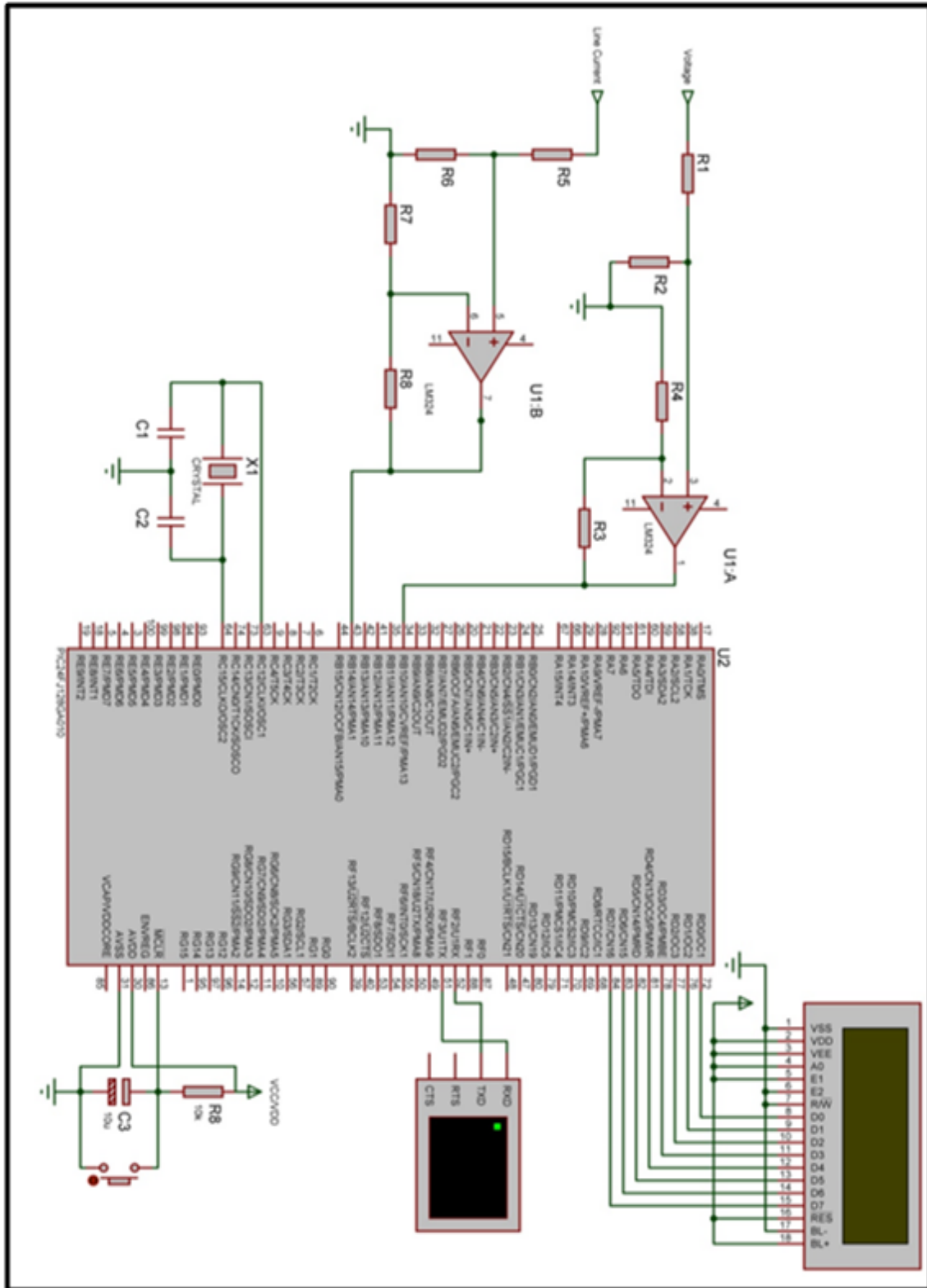


Figure 4: Schematic diagram of electrical power meter.

D. System Firmware:

A high-level overview of the energy metering firmware is shown in Fig. 5. The first step of firmware is initialized

the required procedures for ADC and serial data transmission protocol UART while the second step is to select all suitable value for evaluating

consumed KWh. The main loop is responsible for updating the KWh counter and maintaining the visual display shown on the LCD. The KWh counter is incremented on the basis of a status flag, set in an interrupt driven power measurement routine. A separate display timer is used to determine how long each measured value is displayed before rolling over to the next value.

Voltage and current measurement are performed during an interrupt service routine triggered by the Timer0 interrupt. Measurements are performed in a specific sequence, with the entire sequence being repeated every ($T_s = T/N$ ms). Interleaving samples of voltage and current are taken, with the simultaneous voltage values for the current measurements being interpolated by the application. For each instantaneous voltage and current, the consumed power has been evaluated and repeated for each full time cycle T . The consumed power has been accumulated. When accumulate consumed power exceeding the value of D , the value of KWh counter will be increments.

Also included in the measurement routine is logic to handle reverse-current conditions. Although the energy calculations involve signed operations, the result of the calculation after $2\frac{1}{2}$ cycles should always be positive. This assumes that the current sensors are connected to produce voltage and current signals in phase (or nearly so) at unity power factor (UPF). If this is properly done, the

accumulated energy will always be positive, even across a PF range from 0.5 lag to 0.8 lead. Nevertheless, a reverse-current condition, where voltage and current are 180° out of phase, will still produce a negative accumulated energy result. If this happens, a flag is set to permit the energy algorithm to produce a correct (positive) result from the next cycle onward. Finally KWh will be send to LCD for monitoring, and to base station through ZigBee wireless communication standard.

E. Wireless Communication System

Since wireless communication links can be quickly built, engineering cycle significantly shortened, and has better scalability compared to a wire-line system [9-12]. If a fault occurs, only check wireless data module for causes quickly, and then restores the system back to normal operation. Wireless network system has been used to transfer data to the base station. In this project, ZigBee wireless standard has been used for wireless network.

ZigBee technology is a bidirectional wireless communication technology mainly works on 868 MHz or 2.4 GHz ISM band with $20 \sim 250$ kbit/s data rate, $100 \text{ m} \sim 40 \text{ km}$ maximum transmission range, and a typical 100 m distance [13-15]. The technical features include security, reliability, low cost, power saving, high network capacity, and short delays which enhanced communication delays for delay-sensitive applications.

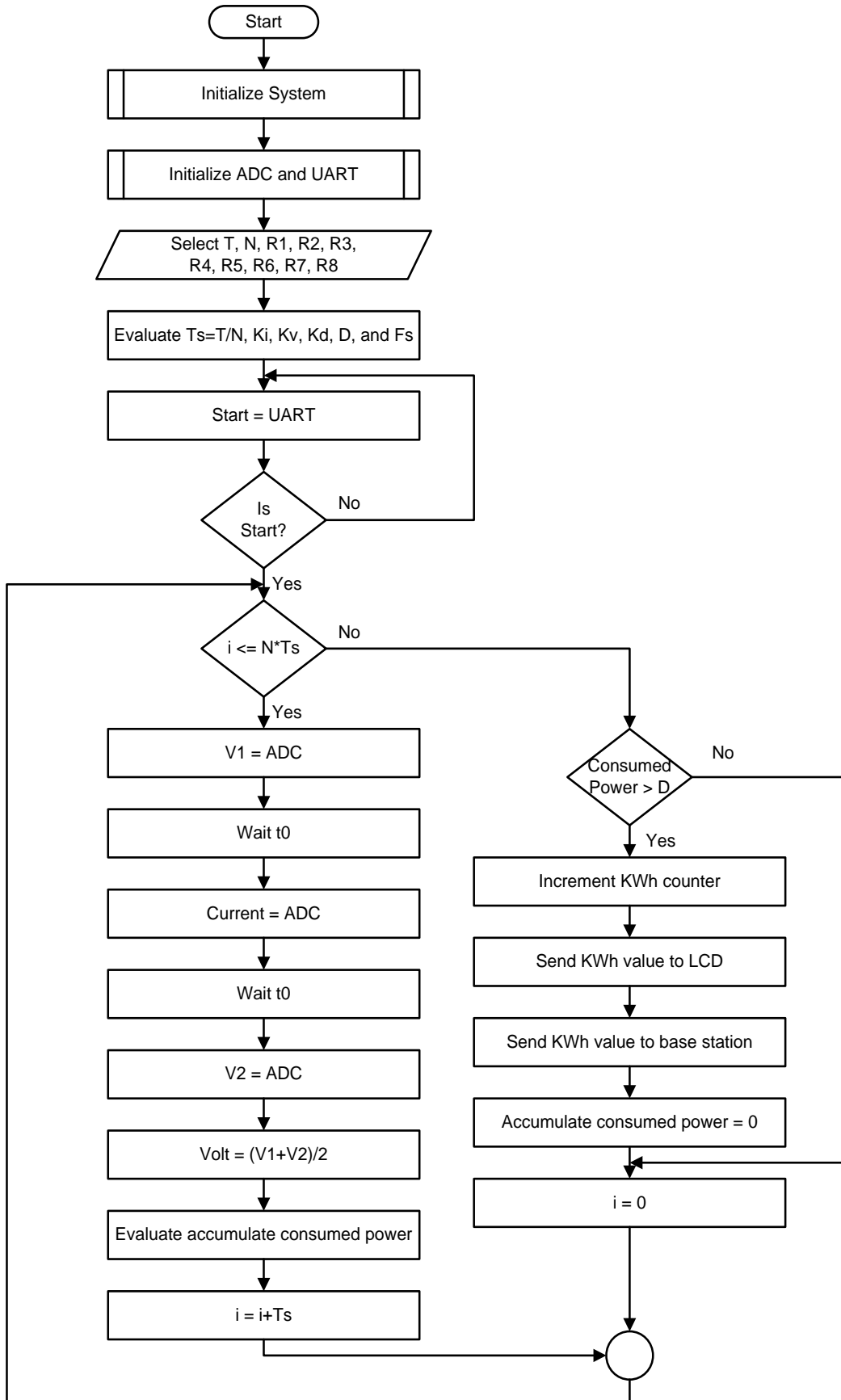


Figure 5: Energy meter firmware.

XBee/XBee-PRO OEM RF module has been used for support ZigBee wireless network. For the applications where robust mesh networking topologies are preferred, XBee/XBee-PRO OEM RF modules provide developers with both ZigBee mesh and the soon-to-be-released proprietary DigiMesh™ topologies. These networks allow devices to harness the entire network of RF modules to effectively extend range beyond that of a single module, and create a more stable and reliable network. Employing dynamic self-healing, self-discovery functionality for reliable communications, XBee/XBee-PRO OEM RF modules make mesh networking simple and easy to deploy [16]. The XBee module is very easy to use, and the interface is based on a simple dialogue with a serial port, which can be easily handled by a microcontroller or a PC as shown in Fig. 6.

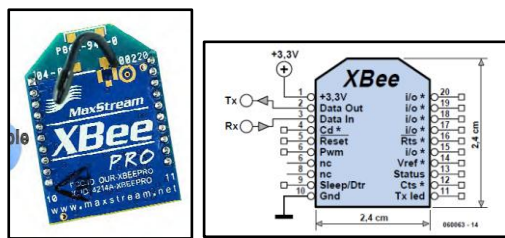


Figure 6: XBee/XBee-PRO OEM RF module [16].

In this project X-CTU software has been used to configure XBee module as:

1. END device which connected to power meter through RS232 to received measurement parameters that will be send to base station.
2. Router device which used to routing messages to destination also it is used

to retransmit messages for long distance communication.

3. XBee has been configured as Coordinator device in base station side which connected to PC server through RS232 in order to receive messages of all END devices.

ZigBee END device reads energy measurement information in multifunction electric meter by UART, and transmits them to the network Coordinator via Zigbee wireless network, thus it can realize the wireless meter reading of the network coordinator. Therefore, the END device must be able to communicate with the electric power meter and Coordinator. The Coordinator also has to know which END node that sends the data so the data can be read accurately. Each of ZigBee modules has a unique 64-bit permanent address, so the addressing won't be much difficult.

IV. Power meter software design

Instantaneous voltage and current have been measured by electric power meter based on PIC microcontroller which rms value of voltage and current, power factor, and KWh have been evaluated by microcontroller. These information have been sent to the base station through ZigBee wireless network. In base station side the information has been stored in PC server for management and monitoring.

At the base station the Graphical User Interface (GUI) of smart electrical power meter is shown in Fig. 7.

The screenshot shows a software window titled 'Form1' with a 'Customer Information' section. It contains a table with the following data:

ID	Customer_Name	Address	City	Phone	Email	Voltage	Load_Current	PF	KWh	KWh_cost
5001	Ali Mohammed	Al Maaqal	Basrah	077073627789	ab45@yahoo.com	215	10	0.92	32	1600
5002	Khalid Asad	Al Jubala	Basrah	078046738763	Khm76@hotmail.com	221	15	0.95	46	2300

Below the table, there are several control buttons: 'Start Monitoring', 'Connect', a dropdown menu, 'Refresh', 'Send email', 'Send SMS', and 'Preview Report'.

Figure 7: Power meter software at base station side.

System software has been designed to manage and monitor the electric power parameter and personal information of customers. For this reason, database has been designed by using Visual Basic Dot Net. For each customer there are (ID, Name, Address, City, Phone No., Email, Vrms, Irms, PF, KWh, and KWh Cost). The information of KWh and KWh cost has been updated during period time. Also the information of KWh cost will be sends to customers through email or mobile phone messages for cost payment.

V. Experiments results

Several experiments have been achieved in order to emulate the operation of wireless power system which the performance of this system depends on the comprehensive performance of all parts compounds the system. The prototype of practical wireless electrical power meter circuit is shown in Fig. 8.

The measurements starting through potential divider step which the AC voltage supply damping to low level voltage by using potential divider as shown in Fig. 4 which R1 and R2 has been selected as (210 K Ω and 750 Ω respectively) to attenuate (304 to 1.08 V) peak supply voltage. The load

current has been attenuated by CT of 100/5 transformation ratio which reduces (15 to 0.75 A) peak load current. The load current converted to voltage by using R6 as shown in Fig. 4 which selected as (1 Ω) to evaluate 0.75 V. Next step is modifying the instantaneous values of input voltage and load current by non-inverting Op-Amp amplifier which amplifier output has been converted to digital value by 8 bit - ADC. In microcontroller the consumed power has been evaluated which KWh counter will be increment when consumed power exceeds the value of D.

R3, R4, R7, and R8 have been selected as (647 Ω , 5 K Ω , 5 K Ω , and 3.33 K Ω respectively) while Fs have been selected as (400/50). The value of D has been evaluated as (115, 302) by using equations 4, 5 and 6. The comparison between practical and theoretical values is shown in Table 1. The server is connected to XBee Kit which is sets as Coordinator Device with ID=5000 and exchange data with base station through RS232. Also the electrical power meter of customers is connected to XBee Kits which set as END Device with ID=5001, 5002, etc. and exchange data with microcontroller through RS232.

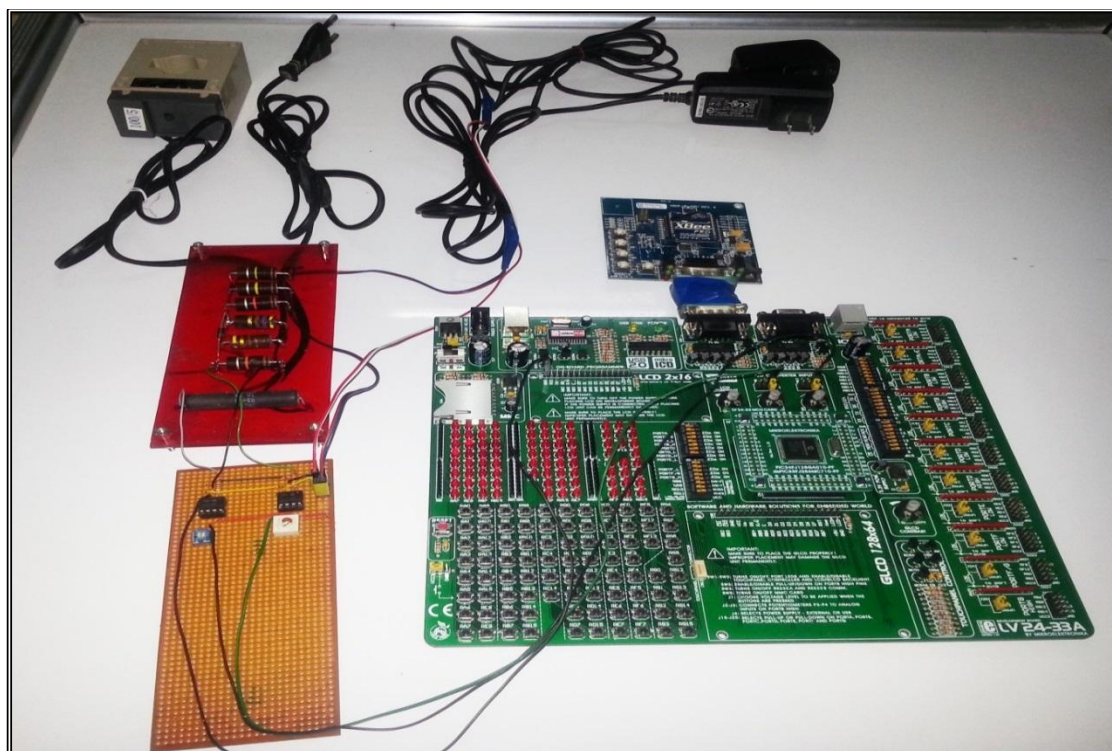


Figure 8: The prototype of practical wireless electrical power meter circuit.

Table 1: Comparison between practical and theoretical results.

	V_i (V)	I_i (A)	V_i/K_v (V)	I_i/K_i (A)	V_d	I_d	Consumed Power $\sum_{k=1}^N V_{dk} * I_{dk}$	KWh (1 hour)
Theoretical	304	15	1.22	1.25	134	136	$3.6 * 10^6$	31.5
Practical	304	15	1.2	1.26	136	137	$3.7 * 10^6$	32

At the base station, the information has been received and stored in database depending on ID of each customer. In this project the ID of customer has been selected same as XBee Kit ID which is represents the source address of XBee Kit.

The measurement information has been sent from END devices to coordinator by frames includes source address. The electric power measurement information has been analyzed and can be printed or sends to costumers as report through cell phone

SMS or email. The report of customer is shown in Fig. 9.

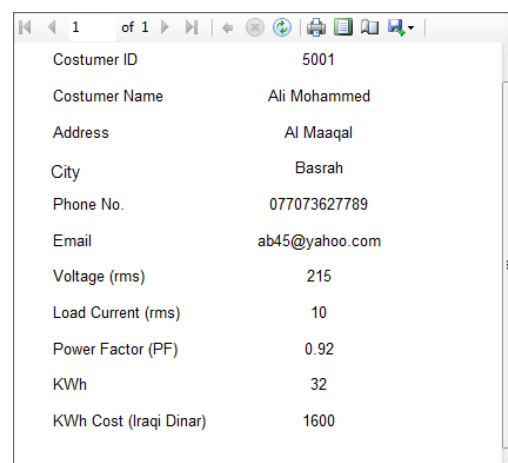


Figure 9: Email and SMS report of Customer.

VI. Conclusions

The design of the Wireless Smart Power Meter System described in this paper is based on the microcontroller and high performance, extremely low power consumption, high level of integration, and low price of ZigBee technology. Wireless Smart Electric Power Meter prototype has been implemented and successfully tested for demand of 304 V and 15 A (peak value). By using this system, the problem of the demand for electricity in Iraq can be reduced, where the cost of the electric power meter is a few compared to the cost of the device available in the market because it consists of a low-cost electronic items. Also this system reduces the cost of measurement which needs less measurement staff. The complete system setup and upgrade take a little time, requires low cost and the setup is very safe. Certainly rely on this system increases the accuracy of KWh, PF readings and monitor the amount of real demand for energy in addition to increasing security and not be manipulated by the customers and uncover abuses. The cost of the amount of power factor can be added if the customer doesn't improve the power factor conditions. As well as to increase the performance of programming operation of the electric power distribution system by controls the energy consumption of customers.

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