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Smart Energy Monitoring and Control System Based on Wireless Communication

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Abstract— This paper presents new design of a smart energy meter integrated with a monitoring and control system to monitor the quality of electrical power supplied to consumers and to protect them upon abnormal situations with the capability of storing all the events in real date and time as a history. This system provides several advantages for utility companies such as consumed energy, issuing the bills remotely and use multiple tariffs for billing electricity at different times during the day. Also the system offers a capability to disconnect/resume the supply for a client if the bill has not being paid after a specific time or other clients caught in electricity theft.

Index Terms — Energy Meter, PIC Microcontroller, Real Time & Calendar, Smart Meter, Serial Port Interfacing.

I. INTRODUCTION

Service improvements of the Local Monitoring and Maintenance Station (LMMS) can be achieved by designing and implementing a Consumer Smart Sensor Unit (CSSU) which includes smart sensors to sense the quality of the electric supply to the consumers and record all the abnormal situations after an action is undertaken if the electric supply status exceeds the permissible limits of supplying standard, and also to record the consumed energy [1, 2]. The CSSU works as a slave to communicate with a master computer in the LMMSusing wireless data acquisition techniques as shown in Fig. 1 below.

Figure 1. The connection between CSSU & LMMS block diagram.

The recorded history of the abnormal situations for each client will offer a statistical data for the LMMS to assist in improving the maintenance by locating and fixing problems in the distributed network.

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In Iraq, the usage of such this system will offer the capability of improving the Daily Load Curve by different ways, i.e., using multiple rate (Tariff) billing to reduce the load at time intervals corresponding to the highest consumption rate; these intervals present the peak load intervals in the daily load curve, or limiting the supplied energy at the peak load intervals in the daily load curve. CSSU also includes single-phase energy metering section based on energy metering IC (AD7755) connected to a digital counter.

The Microcontroller Unit employed in this system acts as a manager of all the functions of protection and controls of the electricity supply. In addition, the CSSU periodically performs self-calibration or remotely when there is a need to correct the errors that may happen by the voltage or current transducers.

II. RELATED WORK

A close scrutiny of the literature on smart metering system revealed that numerous researchers reported on the metering technology of the consumed energy with the objective of ensuring efficient metering process and build up the first stage of the smart grid which is the remote billing system of the energy metering. Sun Hao, et al. [3]developed hardware and software integrated design of three-phase digital watt-hour power meter based on Nios II which is a 32-bit embedded-processor architecture designed specifically for the Altera family of FPGAs. Nios II is applied in their system as the processor and an ADC is employed to sample electric signals. The software includes multi-parameter measurement, multi-rate calculation, and network communication. In the field of Tele-metering, Li Yujin, et al. [4] presented a wireless meter reading system based on GPRS technology, which facilitates online, high-speed and low power consumption. In hardware system, it mainly introduces a GPRS module's interface concentrator, whose core component is the TMS320F2812 chipset produced by the US's TI company. Their system had a promising market because of its simplicity, low operating cost, reliable performance, high automation, and quick investment return.

Anand Sunil Kulkarni, et al. [5] reviewed various products available in the market, which monitor electricity consumption and provide feedback for the energy usage and they categorize energy usage feedback systems into three groups: (i) socket monitoring systems, (ii) whole-house monitoring systems, and (iii) whole-house monitoring with breakdown to individual appliances. Arian, M. S., et al. [6]presented an advanced metering infrastructure, and analyzed the architecture expanded on by OPENmeter project, to improve the architecture [7, 8]. Through their system, a huge amount of data is flooded into utilities and these data help the utility to get a thorough understanding about the grid and subscribers.

The functions of the smart metering system which have been reviewed in the above related work are not applicable for the current demand of the Iraqi consumers and more importantly for the electric utility. From the standpoint of consumers, the power quality is the important issue and from the standpoint of utility, the balance of demand and generation is among the most important issues. Also the demand of energy not uniformly distributed along the day, and the peak value of the demand in energy may results in a problem especially in the utilities that have insufficient generation capacity like the current utility in Iraq, in which the energy demand is much more than the energy generated by utility in specific intervals in the day resulting in a programmable shutdown for some feeders in the occurring time of this problem and interchange the offline feeders with the others to achieve the balance between the available energy and the demand in the grid. This problem occurs only during the peak intervals of the daily load curve. As a result, the system proposed in this paper is designed to operate at the low-level (380V) distribution system, and consider the Iraqi national grid environments as a study case to improve and manage the daily load curve by investigating different methods of controlling the demand of the consumers using the proposed system. In addition, the proposed system also has the features of energy metering and power quality monitoring and protection.

III. CONSTRUCTION OF CONSUMER SMART SENSOR AND THEORETICAL ASPECTS

New electronic devices are more susceptible for low power quality events, like sags, swells, transients, flickers and harmonics distortion. These power quality problems can damage the electronic equipments in the end user [9, 10].

In this paper, we consider the voltage variation of the supply as the only power quality problem, and designing according to the permissible limits of about 10% of the nominal voltage as shown in Table I [11, 12].

TABLE I. PERMISSIBLE LIMITS OF THE VOLTAGE

Nominal Voltage	Permissible Limits	Minimum Voltage Limit	Maximum Voltage Limit
220 V	10%	200 V	240 V

CSSU is placed directly on the electric supply line through the voltage and current transducers, and it is constructed from:

1) Smart Sensor Main Unit (SSMU).
2) Energy Metering Unit (EMU).
3) Power Supply.
4) Wireless Module.

IV. CSSU METHODOLOGY

A. Smart Sensor Main Unit

The Smart Sensor Main Unit (SSMU) acts as manager of all functions of CSSU, and stores all important data such as CSSU ID, energy consumed by the consumer and history of the abnormal situations along with its time and date.This unit also monitors the quality of the electric supply through the voltage and current transducers.

When an abnormal situation occurs, the unit takes an action i.e. disconnecting the consumer’s load, providing local protection without demand of LMMS action, also sending the situation status to the LMMS after storing it.

The implementation of this unit is based on (PIC18F4620) microcontroller [13], and LCD screen to display the date/time, consumed energy, rate type and other service information, also it is connected to the wireless module using serial port communication (UART) and connected to the energy metering unit. Fig. 2 depicts the block diagram of SSMU.

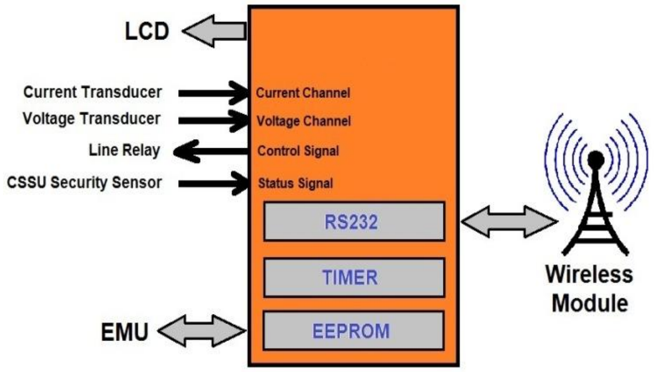

Figure 2. Smart sensor main unit block diagram.

The SSMU is responsible for recording and storing consumed energy day by day and sending it automatically or by request from LMMS; also it has the capability of saving the data even when losing supply. SSMU also monitor the security of the CSSU box, preventing any interrupt by consumer or electricity theft.If the security is penetrated, the unit will disconnect the electric supply and inform the LMMS.

B. Energy Metering Unit

The objective of the Energy Metering Unit (EMU) is to measure the energy consumed by the consumer.This can be done by using specific digital metering techniques.

In this paper, (AD7755) have been employed as energy metering IC to measure the energywhich is a highly accuracy electrical energy measurement IC. The only analog circuitry used in the AD7755 is the ADCs and reference circuit. All other signal processing is carried out in the digital domain. This approach provides superior stability and accuracy over time.

The AD7755 provides instantaneous, real-time power information on the high frequency (CF) logic output. This output is interfaced to a microcontroller.The frequency output CF is connected to pulses counter to count the number of pulses in a given integration time which is determined by a microcontroller internal timer [14, 15, 16].

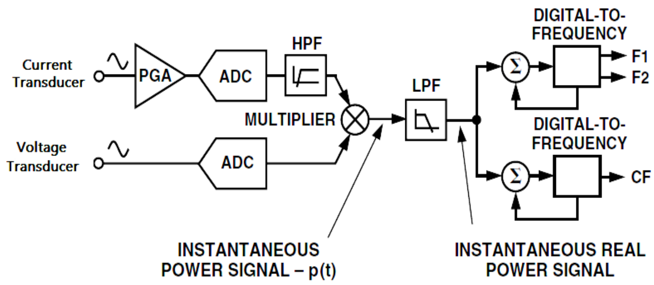

Figure3.AD7755 Signal Processing Block Diagram [14]

According to the definition of active power,

$$P = \frac{1}{T}\int_{0}^{T} vi\,.dt \quad (1)$$

The energy is obtained by integrating equation (1) for a specific time (T),

$$E = T * \left(\frac{1}{T} \int_0^T v\, i\, .dt \right)$$

$$E = \int_0^T v\, i\, .dt \; = \; \sum_0^N v_n i_n \quad (2)$$

Since the average power is proportional to the average frequency of the output pulses [14], hence

$$\text{Average Real Power} = \frac{\text{Counter}}{\text{Time}} \qquad (3)$$

According to equation (2), the energy consumed during an integration period is given by:

$$Energy = \; Average\ Real\ Power \; \times Time$$

$$Energy = \frac{Counter}{Time} \times Time = \text{Counter} \qquad (4)$$

As a result, the number counted by the microcontroller (PIC16F84A), present the consumed energy by the load. Fig. 4 explains the block diagram of the EMU.

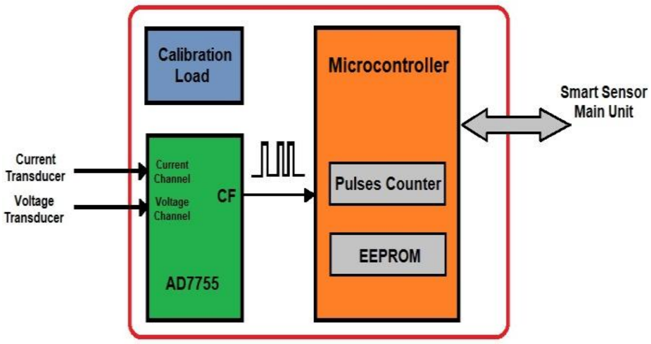

Figure 4. EMU block diagram, explain interfacing the AD7755 to the microcontroller.

C. Power Factor Considerations [14]

The method used to extract the real power information from the instantaneous power signal (i.e., by low-pass filtering) is still valid even when the voltage and current signals are not in phase as shown in Fig. 5.

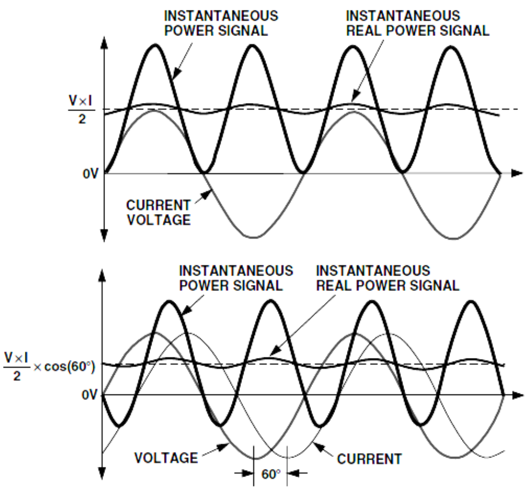

Figure 5. DC component of instantaneous power signal conveys real power information for PF = 1 and PF < 1 [14].

The final circuit diagram of the CSSU implemented including SSMU and EMU integrated with ZigBee Wireless module is shown in Fig.6.

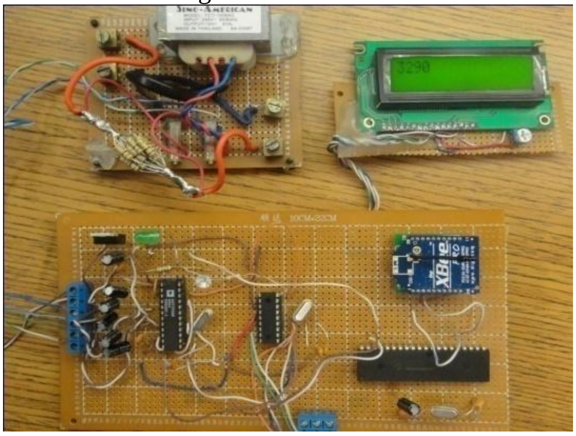

Figure 6.Hardware implementation of CSSU circuit

D. Self-Calibration

This is an important function which should be used in the proposed smart sensor. In a simple way, a standard load with known value is used for calibration,when there is a need for calibration.The EMU producesa control signal to change the flow of the power to the calibration load and the consumed power will be only the standard load, as shown in Fig. 7.
As a result, the measured value is compared against the standard value; if there is a deviation in the reading, suitable correction applied, and hence the EMU can be self-calibrated. This operation can be made periodically as needed.

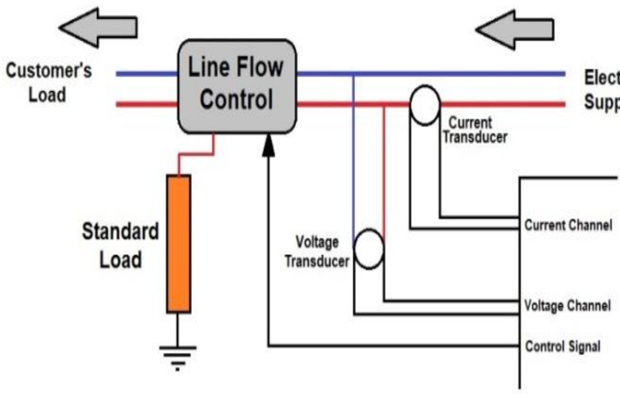

Figure 7. Standard load in calibration operation

E. Wirless Module

This part represents the tool that provides the communication method between the CSSU and LMMS. In this paper, we have used the ZigBee wireless communication scheme.

ZigBee network supports star, tree, and mesh topologies. In a star topology, the network is controlled by one single device called the ZigBee coordinator. The ZigBee coordinator is responsible for initiating and maintaining the devices on the network. All other devices, known as end devices, directly communicate with the ZigBee coordinator. In mesh and tree topologies, the ZigBee coordinator is responsible for starting the network and for choosing certain key network parameters. In tree networks, routers move data and control messages through the network using a hierarchical routing strategy [17]. ZigBee Interfaced with SSMU through UART and the data send automatically or manually to the coordinator, which is here the LMMS.

V. LOCAL MONITORING & MAINTENANCE STATION

The Local Monitoring & Maintenance Station (LMMS)is the final destination of data to be sent by CSSU. The functions of LMMS is monitoring, controlling, and storing database of each CSSU. Personal computer used here after interface it with ZigBee module that work as coordinator.

Monitoring and controlling is performed using Computer basedVisual Basic 0.6 GUI software, as shown in Fig. 8, in which each CSSU is defined by ID and storing data transferred from/to CSSU with the capability of sending commands to control any function in the CSSU. In LMMS, the bills issuedfor the consumed electricity after receiving a request from the CSSU.

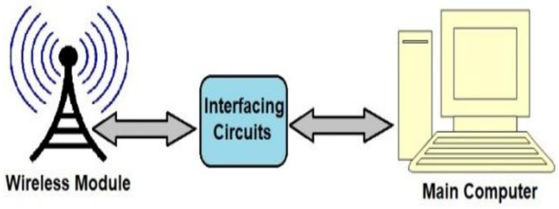

Figure 8. Block diagram of local monitoring & maintenance station.

VI. FIRMWARE DESGIN & IMPLEMENTATION

The firmware of the SSMU which is operated at clock speed of 19660,800 kHz has been implemented by using “PROTON IDE (Basic Pro)”. The real time and calendar was implemented by utilizing the interrupt of the internal timer (TIMER0) of the PIC18F4620. The main program is shown in Fig. 9 and the main loop sub programs shown in Fig. 10.

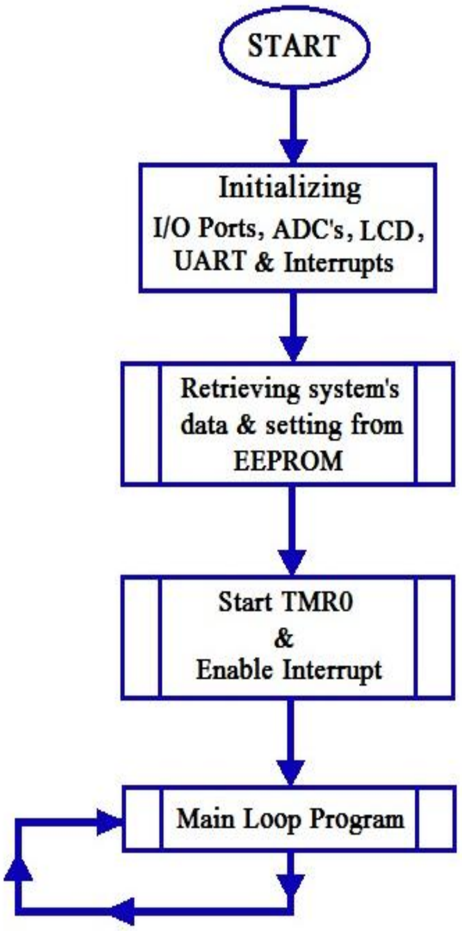

Figure 9. Flow chart he main program of smart sensor main unit.

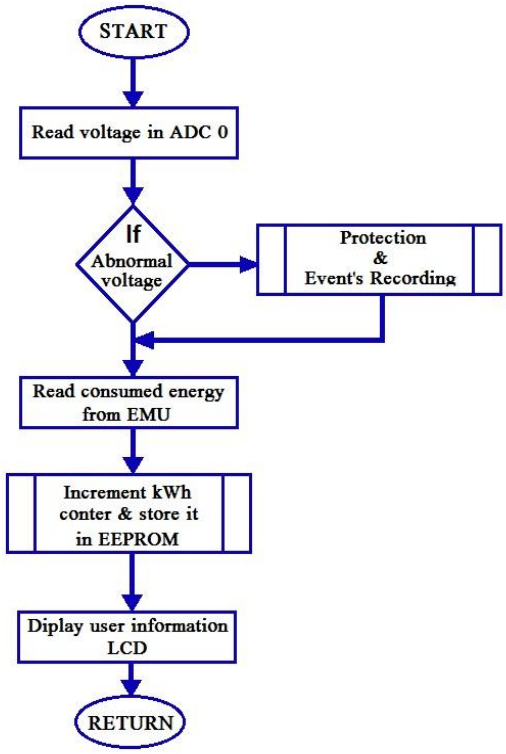

Figure10. Flow chart of the main loop sub program

The EEPROM of the main unit was divided into sections, including the locations of energy counters, device configuration, address, and the event history locations. Events history section has the capability of storing 600 bytes, which are divided into segments of time, date and event reason as shown in Fig. 11.

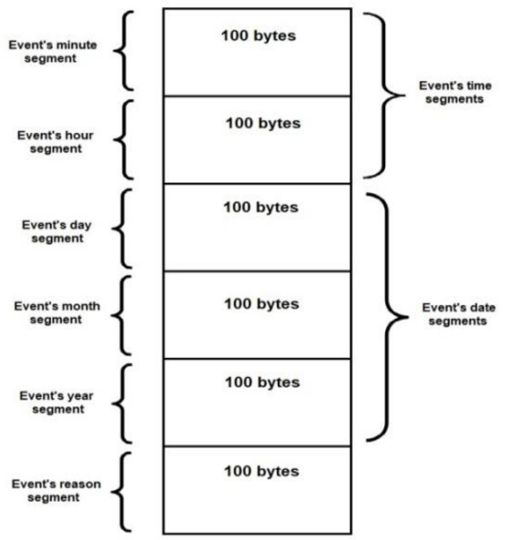

Figure 11.Memory map of (600 bytes) events history section.

VII. RESULTS & CONCLUSIONS

The energy meter unit was tested at the System Engineering Department of the University of Arkansas at Little Rock using different loads. Various abnormal conditions were applied to the system. The system acted and responded as intended in the design and the events of the bad situations were successfully recorded.

The recorded events resulting from applying the abnormal situations to the system are shown in Fig. 12 and tabulated in

Table II.

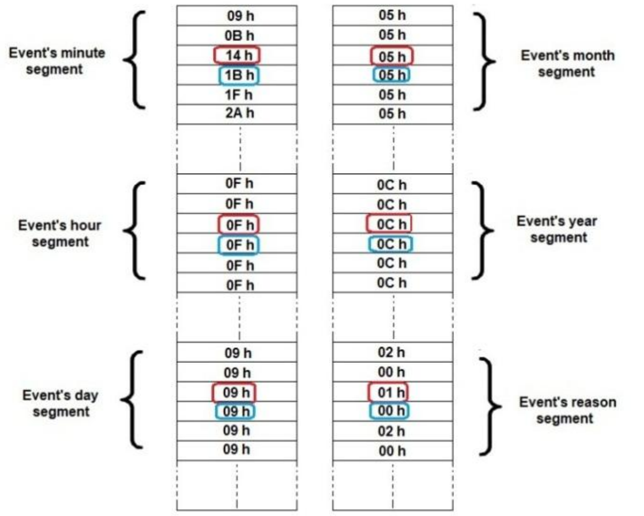

Figure 12. The results of the six recorded events in the EEPROM.

TABLE II. THE RESULTS OF TWO EVENTS OVER VOLTAGE CONDITION AND SERVICE ON (RETURN) AFTER 7 MINUTES

Event No.	Time (hh:mm)	Date (mm/dd/yy)	Reason
3	15:20	05/09/12	Over Voltage
4	15:27	05/09/12	Service ON

Moreover, the whole system works properly with high reliability, protection functions, abnormal situations history and multiple rates. Finally, the operation of the system summarized in Table 3.

TABLE III. SYSTEM OPERATION'S SUMMARY

Cases	CSSU Response	LMMS Response	Action Details
Under Voltage	Take an action	No action taken	Disconnect the service, Record the case in the history, Inform LMMS
Over Voltage	Take an action	No action taken	Disconnect service, Record the case in the history, Inform LMMS
Security Penetration	Take an action	No action taken	Disconnect service, Record the case in the history, Inform LMMS
Bill not paid	No action taken	Take an action remotely	Only disconnect the service

Table III provides a comparison between CSSU and the LMMS, as well as how the CSSU is smart enough to take many actions for many causes.

The EMU has been tested to measure different loads. The high frequency output CF pulses have been counted, and then the measured power has obtained as shown in Table IV. Graphical representation of the calculated and measured power is shown in Fig. 13.

TABLE IV. EMU PRACTICAL RESULTS FOR DIFFERENT LOADS

No.	Tested Load (W)	Measured Power (W)	High Frequency CF (Hz)		Absolute Percentage Error
			Calculated	Measured	
1	1386	1445	5.6574	5.9000	4.11 %
2	1936	1935	7.9024	7.9000	0.03 %
3	2464	2670	10.0576	10.9000	7.72 %
4	2772	2915	11.3148	11.9000	4.91 %
5	3873	3625	15.8089	14.8000	6.81 %
6	3960	3944	16.1640	16.1000	0.39 %
7	7920	7864	32.3280	32.1000	0.71 %
8	130.00	132.29	0.53063	0.54000	1.77 %
9	985.60	984.85	4.02304	4.02000	0.57 %
10	1391.52	1381.73	5.67993	5.64000	0.70 %
11	1620.60	1612.02	6.61499	6.58000	0.52 %
12	1768.00	1759.02	7.21665	7.18000	0.50 %
13	2013.31	2004.00	8.21796	8.18000	0.45 %
14	2847.00	2861.47	11.62093	11.68000	0.50 %

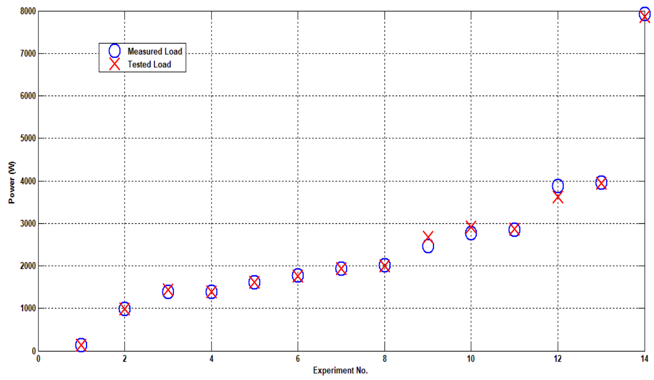

Figure 13.Comparison between the measured and the tested load.

Many related research presented wireless energy metering, while others developed systems to record a history of service outage. Multi-Tariff system has been also covered by many researchers but the system proposed in this paper has covered all of these functionalities as well as the protection upon the power quality issues. Since this paper presented a design and implementation of smart system for monitoring the consumption of energy and the abnormal situation that may occur in the service, and has the capability of controlling the service as well as the multi-Tariff for different time intervals, the following points can be concluded:

1. The proposed system has a fast response to alert the LMMS about the abnormal situations.
2. Exact method to locate the fault and unacceptable service at the individual consumer is supported by the proposed system.
3. The proposed system provides a worthy statistical data, the most frequent abnormal situations that may occur in the consumer side.
4. The statistical data providesexcellent resources to enhance the maintenance services in the L.V. distribution grid.
5. Employment of Multi-Tariff system for counting the consumed energy provides indirect method for controlling the load during different time intervals, which assists the utility to reduce the peak load at specific intervals by applying the highest Tariff.
6. The proposed system presents a local protection for the consumer upon two of the power quality problems (over and under voltage).

As mentioned above, the proposed system presents local protection upon over voltage and under voltage conditions which occur frequently in Iraq, these present only two cases of the whole power quality issues. The other issues of power quality can be included in the system as different events to protect the consumer, i.e. harmonics, frequency variation, etc. Many efforts are in progress to use the SMS service of GSM communication technology instead of using ZigBee protocol. Such developmentswill be included in the future work.

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