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Design of a Smart Meter for the Indian Energy Scenario

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ABSTRACT
Accurate metering, detection of energy theft and implementation of proper tariff as well as billing system are vital in wise energy management. These objectives can be achieved by using Smart Meters. This article introduces a microcontroller based Smart Meter using wireless communication and LabVIEW suitable for the Indian Energy Scenario. The Smart Meter and Time Of Day (TOD) tariff pricing make the consumers an active part of energy management, thereby energy deficit during peak hours can be alleviated indirectly.
Keywords - Energy Management, Energy Conservation, Demand Side Management, Smart Meters, Time Of Day Tariff, Zigbee, LabVIEW

I. INTRODUCTION

Due to rapid increase in human population and the human's dependency towards electrical energy, the demand of electricity has increased, causing deficit of electrical energy during peak hours. As per the report of CEA, India [1], the gap between the electrical energy supply and the energy demand in July-2014 is -3.9% (MW). Accurate metering, detection of illegal activities and implementation of proper tariff and billing system would manage the consumption of electrical energy. Collecting meter reading is one of the most difficult procedures in billing [2]. The traditional electrical energy meter data collection is such that a person from the utility provider visits the consumer sites periodically to note the meter reading. This procedure has lot of drawbacks such as, it is time consuming, tiresome and requires more human resource, human error and even corruption is probable [2-16]. The process may be interrupted due to bad weather conditions, also if the consumer is not available, the billing will be pending and human operator needs to revisit. India is facing energy deficit during peak hours. Low voltage during peak hours has been reported as a major power quality issue. Load shedding is a common power management practice followed by the utility providers [17]. Energy conservation has great significance in this scenario of increasing electrical energy demand. An Automatic Meter Reading (AMR) system equipped with advanced features like two-way communication, Time-Of-Day (TOD) tariff, etc. will address the problems of manual collection of meter data, energy deficit during peak hours and opens a channel for the consumers to participate in energy conservation.

With development in technologies in the fields of communication and information technology, a wide variety of AMR and smart meters has been developed. A smart meter is an AMR with two-way communication infrastructure. Smart meters has been designed for various features like remote monitoring of energy consumptions, remote turn ON/OFF power supply, remote detection of energy theft, with time varying pricing system, remote fault detection, capable of monitoring power quality etc. [17]. Developments in information management and remote monitoring technology can play a vital role in energy management [18-19]. Smart meter reading co-operate both utilities and consumers in power management, giving them detailed information about power consumption [7]. Although the implementation cost of Smart meters systems are high [20], their implementation will increase the revenue of the utility provider because of the following reasons, the working status of the consumer end meters can be identified remotely [3], eliminate the corruption by the human operator or the consumer [3], [12] and [21], labour of meter reading is eliminated [22], integration of an apt tariff system with the smart meter reading data reduces the consumption of electricity during peak hours [19] and [23], etc. Smart meters perceived to be a necessity rather than luxury in India [20].

This article proposes the design of a smart meter which can address issues in the power distribution. The rest of the paper is organized as follows. Section two discusses the architecture of demand based smart metering system. Software design of the system has been presented in section three. This includes mathematical formulation of billing, software incorporation of functionalities and GUI design.

Section four describes the hardware design. The procedure for cost-benefit analysis of smart meter implementation and TOD tariff is described in section five.

II. DEMAND BASED SMART METERING SYSTEM ARCHITECTURE

'Demand based Smart Metering' is designed to measure the energy consumption during peak and normal hours separately and to send these consumption data periodically to the utility provider through wireless communication. These data are acquired at utility provider server and further used for billing. The smart metering is capable to alert the utility provider if theft is detected and automatically can disconnect the supply to such consumers. Designed system has the feature of remote turn on/off the supply. In India, the time slots from 12:00 AM to 06:00 AM, 09:00 AM to 06:00 PM and 09:00 PM to 12:00 AM can be considered as normal hours and time slots from 06:00 AM to 09:00 AM and 06:00 PM to 09:00 PM can be considered as peak hours [24]. The time slots can be defined as normal hour I, normal hour II, normal hour III, and peak hour I and peak hour II. Separate monitoring of energy consumption during these normal and peak hours and applying higher tariff for peak hours would reduce the consumption during peak hours. The system is designed to monitor the energy consumption separately for the normal hours and for two of the peak periods. A limit for the energy consumption during peak hours can be set and load shedding can be imposed for those consumers who cross the limit. This feature force consumers to reduce the energy consumption during peak hours thereby Demand Side Management (DSM) can be achieved, with indirect involvement.

The demand based smart metering system comprises two separate modules, a Smart Meter at the consumer end and a server computer at the utility provider side. Fig. 1 shows the block diagram of the system architecture.

Every Smart Meter installed at the consumer end has a unique meter ID. In India, developing a low cost basic Smart Meters by upgrading the existing one is more acceptable [20]. That is the system has to be cost-effective such that reduced implementation cost, maintenance free while providing robust and reliable performance [25]. In the proposed design of smart meter a properly designed optical pick-up circuit is used to generate pulses in accordance with the LED blink / dark marking of the rotating disk of the existing energy meter [13]. AT89S52 microcontroller is used to count the pulses. DS1307 Real Time Clock (RTC) is used along with the microcontroller to count the pulses separately for the peak and normal hour slots. The supply to the consumer is through a single pole double through relay. Features like remote turn ON/OFF the supply, automatic cut OFF on theft detection and crossing the peak time energy consumption limit are governed through this relay. The consumption data is displayed on the LCD screen of the smart meter and the same is sent to the server every day at the end of the normal hour III through Zigbee [26] module. However, protocols like WiFi [7], WiMax [7] and [13], Global System for Mobile (GSM) [11], [16], [19], [21], [25] and [27] etc. can also be used [23]. A server computer with Graphical User Interface (GUI) or front end, designed using LabVIEW, receives this data and store in a database according to the meter ID. At the end of every month, electricity bill is generated automatically and maintained in the secondary memory of the server. Display of amount of the last bill, bill due dates, alert for theft detect, push switches for remote turn ON/ OFF are available at the GUI.

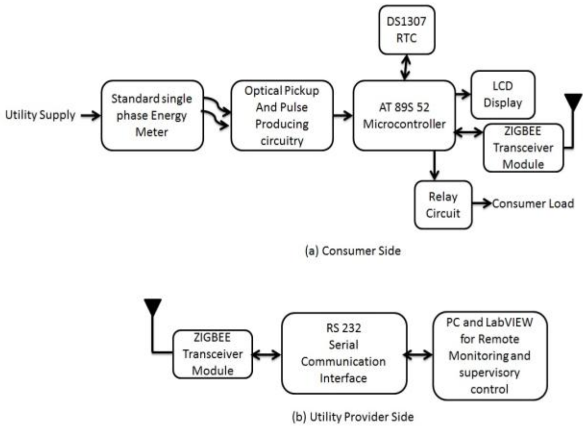

Fig. 1: Architecture of Demand Based Smart Metering System

III. SOFTWARE DESIGN

The designed software incorporates the functionalities necessary at consumer end and utility end. At the consumer end microcontroller program is embedded in the flash memory of AT89S52 microcontroller and at the utility end, a GUI is designed with LabVIEW.

3.1 DESIGN OF EMBEDDED FUNCTIONALITIES

The functioning of the smart meter is based on the program embedded in the microcontroller and is written on 'Keil μvision' platform. The program is designed in accordance with the hardware connections of the Smart Meter. An ISR [28-29] is written to count the pulses. Counting is done separately for normal hours and peak hour I and peak hour II. The electronic energy meter, which produces pulses in accordance with energy consumption is calibrated such that one unit is equal to 3200 pulses. For experimental demonstration, it is assumed that one unit is equal to 10 pulses. A maximum limit for the peak hour I and peak hour II is set to 2 units and this limit is programmable. Through relay, supply will be disconnected when the limit is crossed and connection will be re-established at the beginning of the next slot of normal hours. A separate ISR is written for the theft detection. When the theft detect switch is activated, supply will be disconnected through relay, and a theft alert message will be sent to the server. The power supply will reconnect only after a power ON switch corresponds to that particular meter ID at the utility server is activated. At the end of every eight minutes, separate reading for normal hours, peak hour I and peak hour II are sent to the server. Algorithm of the program embedded is illustrated in the flow chart shown in Fig. 2.

3.2 Graphical User Interface (GUI)

The energy consumption data is communicated to the server by the Smart Meter through Zigbee. Zigbee module has serial communication interface with the server. The server comprises GUI and software for billing, both designed with LabVIEW. The LabVIEW based GUI is shown in Fig. 3. The GUI displays meter ID, date and time, units consumed per day during normal hours and during different slots of peak hours, i.e. first Peak slot as well as second peak slot, separately, consolidated consumption details for normal and peak hour I and peak hour II, a visual indication alert for the energy theft, total bill amount and due date if last bill payment remains pending. A provision to determine the tariff from utility side is also incorporated in the GUI. Remote control over the consumer end is possible with turn ON/OFF push switches at the GUI and the utility provider can make use of the same in case of pending bills or energy theft. A database is maintained for each consumer marked by their meter id. This is made possible with a provision of one time the registration provided in the GUI and the same is expandable. A bill corresponding to the meter ID will be generated at the end of the fifth day and is saved in a spread sheet. The format and information content of the bill is shown in Fig. 4.

3.3 Billing

The smart meter communicates with the server through ZigBee and transfer a 26 character serial data of format D={D_{25}, D_{24},… … ,D_0}, where the Least Significant Digit (LSD), 'D_0' is '&' which represents the start bit of data, 'D_1-D_2' indicate the string, 'Meter ID' ('MI'), 'D_3-D_6' stands for the four digit meter ID, 'D_7-D_9' indicate the string, the energy consumption during normal hours, ('NCa'), D_{10}-D_{12} stands for the three digit number which indicate units consumed during normal hours, 'D_{13}-D_{15}' depicts the string, the energy consumption during peak hour I, ('XCa'), 'D_{16}-D_{18}' defines the total units consumed during peak hour I and 'D_{19}-D_{21}' depicts the string, the energy consumption during peak hour II, ('XCa'), 'D_{22}-D_{24}' defines the total number of units consumed during the period of peak hour II and finally, the Most Significant Digit (MSD) is '$', which represents end of the data.

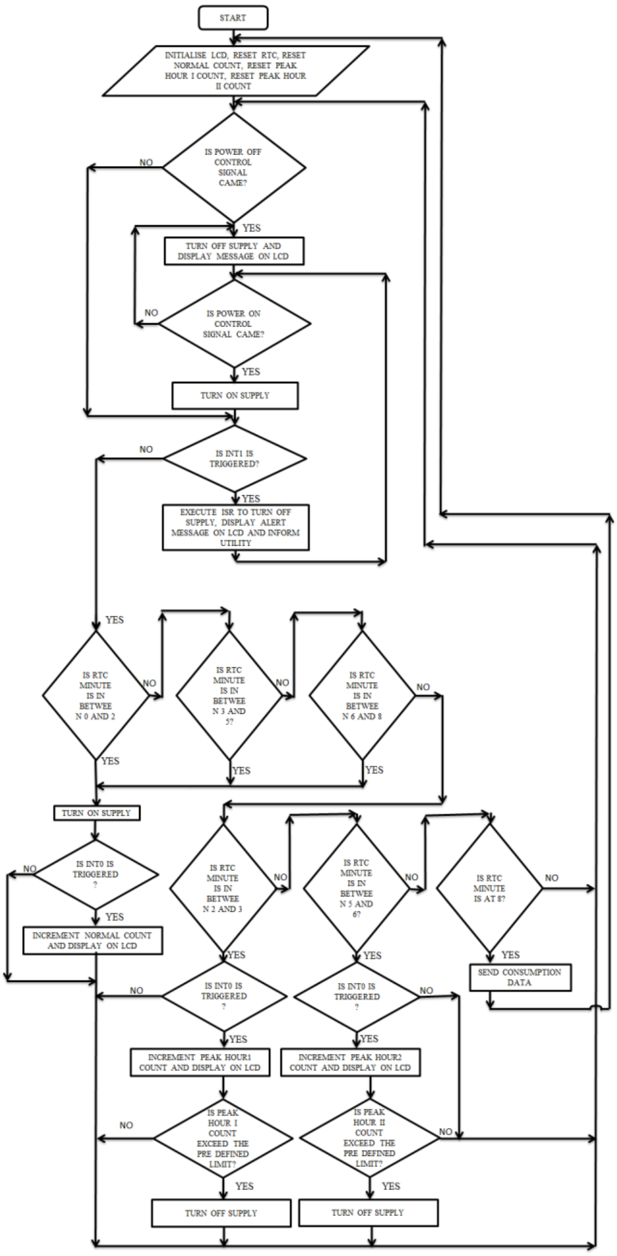

Fig. 2: Flow Chart of Smart Meter Program

The serial data is acquired using VISA functions in LabVIEW [30]. The meter ID, the total number of units during normal hour, the peak hour I and peak hour II are extracted from the 26 character data using the function scan from string. The energy calculation for the corresponding meter ID is selected using a case structure. Energy consumption during normal hour, peak hour I and peak hour II are stored to separate global variables for every day using another case structure. These global variables are later used for total energy calculation for normal hour, peak hour I and peak hour II. This is done using the compound arithmetic tool and the total bill amount is calculated using equation (1),

$$C_T = C_n \sum_{i=1}^{N} X_i + C_{p1} \sum_{i=1}^{N} Y_i + C_{p2} \sum_{i=1}^{N} Z_i \quad (1)$$

where, C_T is the total bill amount as per TOD Tariff, X is the total units consumed during normal hours, C_n is the cost per unit during normal hours, Y is the total units consumed during peak hour I, C_{p1} is the cost per unit during peak hour I, Z is the total units consumed during peak hour II, C_{p2} is the cost per unit during peak hour II and N is the number of days in the billing periods. Fig. 5 depicts the LabVIEW analogy of bill estimation.

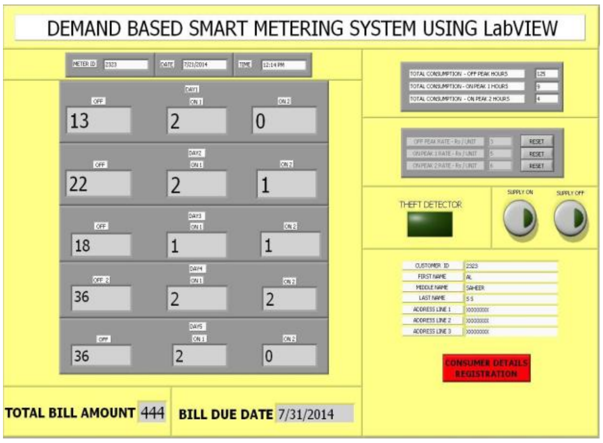

Fig. 3: GUI at Server End

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DEMAND BASED SMART METERING SYSTEM USING LabVIEW

CUSTOMER ID : 2323

PERSONAL DETAILS

NAME OF THE CUSTOMER : AL SAHEER S S

ADDRESS OF THE CUSTOMER :
XXXXXXXX
XXXXXXXX
XXXXXXXX

ENERGY UTILIZATION AND COST DETAILS

PRICE PER OFF PEAK UNIT IS Rs 3
PRICE PER ON PEAK 1 UNIT IS Rs 5
PRICE PER ON PEAK 2 UNIT IS Rs 6

TOTAL CONSUMPTION FOR OFF-PEAK HOURS IS 125UNITS
TOTAL CONSUMPTION FOR ON-PEAK 1 HOURS IS 9UNITS
TOTAL CONSUMPTION FOR ON-PEAK 2 HOURS IS 4UNITS

TOTAL ENERGY UTILIZATION BILL : Rs   444

THE BILLING WAS DONE ON 7/21/2014 AT 12:14 PM

                DEVELOPED BY AL-SAHEER S. S.

BILL REFERENCE NUMBER IS 7/21/2014/2
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Fig. 4: Bill Format

IV. HARDWARE DESIGN

A Smart Meter at consumer end and a data acquisition system at the utility end have been designed. For the experimental demonstration, the pulse corresponding to the energy consumption at the consumer end is obtained by connecting wires parallel to the pulse LED of an electronic energy meter. This pulse is connected to the INT0 hardware interrupt pin (Port 3.2) of the AT89S52 microcontroller. For ease of analysis and demonstration eight minutes are considered as a full day and first two minutes are considered as normal hour I, third minute as peak hour I, fourth and fifth minutes as normal hour II, sixth minute as peak hour II and seventh and eighth minutes as normal hour III. Theft detect switch is connected to the INT1 hardware interrupt pin (Port 3.3) of the microcontroller. Port 0 pins of the microcontroller are used as data lines for the 16x2 LCD display. Control signals E, RW and RS of LCD display are connected to the Port 1.0, Port 1.1 and Port 1.2 pins of the microcontroller, respectively. RTC is connected to the Port 3.4 and Port 3.5 pins of the microcontroller. Relay is connected to the Port 1.5 of the microcontroller through ULN2003 relay driving IC. RxD and TxD serial data pins of the microcontroller (Port 3.0 and Port 3.1 respectively) are connected to the ZigBee module to achieve two way communications between the smart meter and the utility server. The prototype of a practically implemented demand based smart meter is depicted in Fig. 6.

The data from the smart meter is acquired by the server through Zigbee module connected to the RS232 serial port. GUI designed using LabVIEW acquire this data using the VISA functions and displays on the monitor of the server. The complete working prototype of the designed system is shown in Fig. 7.

V. EXPERIMENTAL AND COST-BENEFIT ANALYSIS

An experiment is conducted to evaluate the influence of percentage of load shifted from peak to normal hours on percentage change in total cost, on implementation of TOD tariff and Smart Meter. A 1kW load comprising 10x100W bulbs, L_0, L_1, …., L_9, each connected in parallel through switches is fed through the designed metering system. The test conditions varies from the condition, where the entre 1kW load drawn during peak hours to the entre 1kW load shifted to normal hours by successive shifting of 10% load as illustrated in table 1, in which '1' indicates ON state of the load and '0' stands for OFF.

In table 2, numerical values of total units consumed during normal hours 'X', the total units consumed during peak hours 'Y+Z', total units consumed in a day ‘T_C’, the percentage of energy consumed in normal hours with respect to the total energy consumed (X/ T_C)%, the percentage of energy consumed in peak hours with respect to the total energy consumed [(Y+Z)/ T_C]%, the total cost as per flat tariff ‘C_F’, the total cost as per TOD tariff ‘C_T’, the value of C_T in the Test condition in which 100% of the total energy consumption was during peak hour time ‘C_{TMAX}’, the percentage reduction in C_T on load shifting from ‘Test 1’ condition, $\alpha = [(C_{TMAX} - C_T)/C_{TMAX}]\%$, and the percentage change in C_T with respect to C_F, $\beta = [(C_T - C_F)/ C_F]\%$.

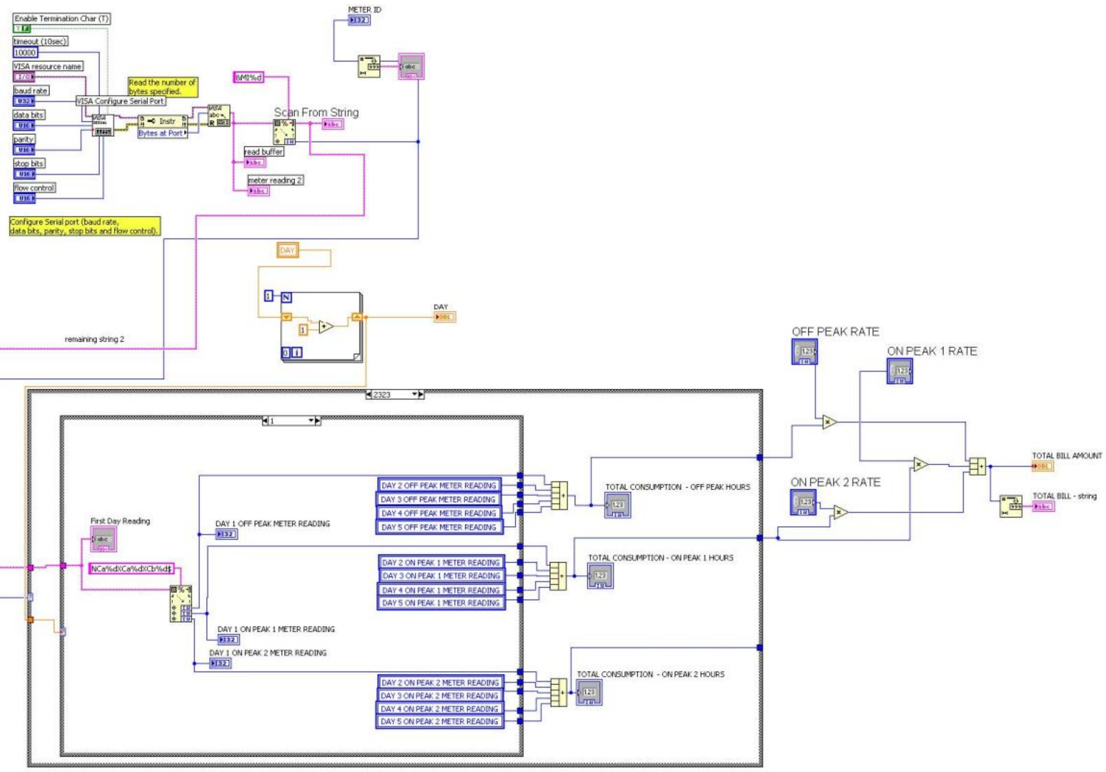

Fig. 5: VI for Bill Computation

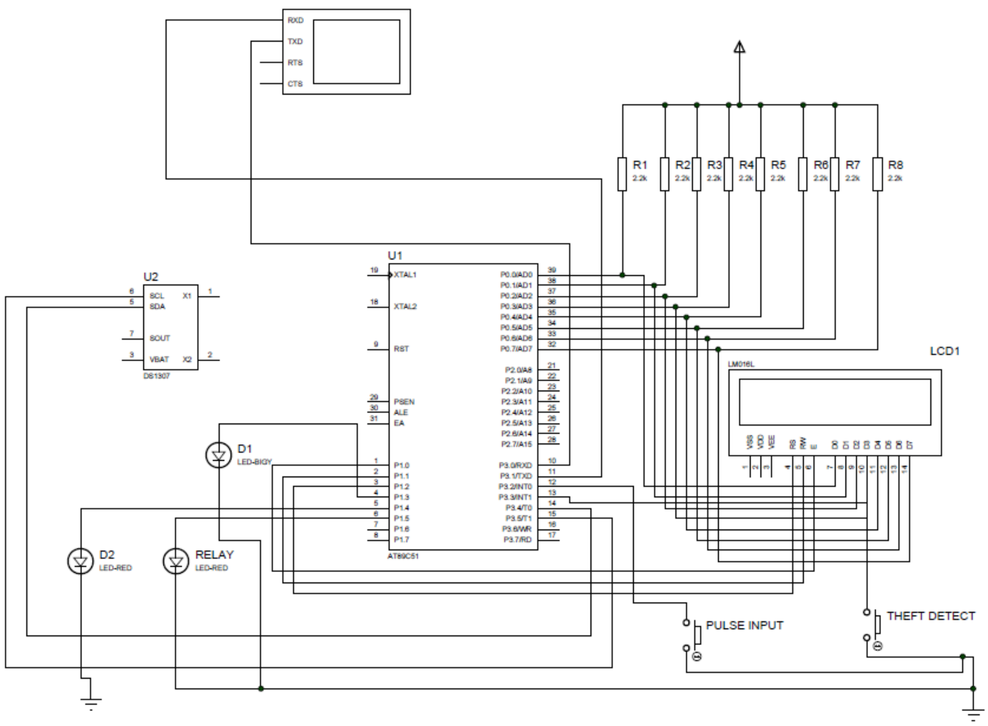

Fig. 6: Circuit Schematic of Smart Meter

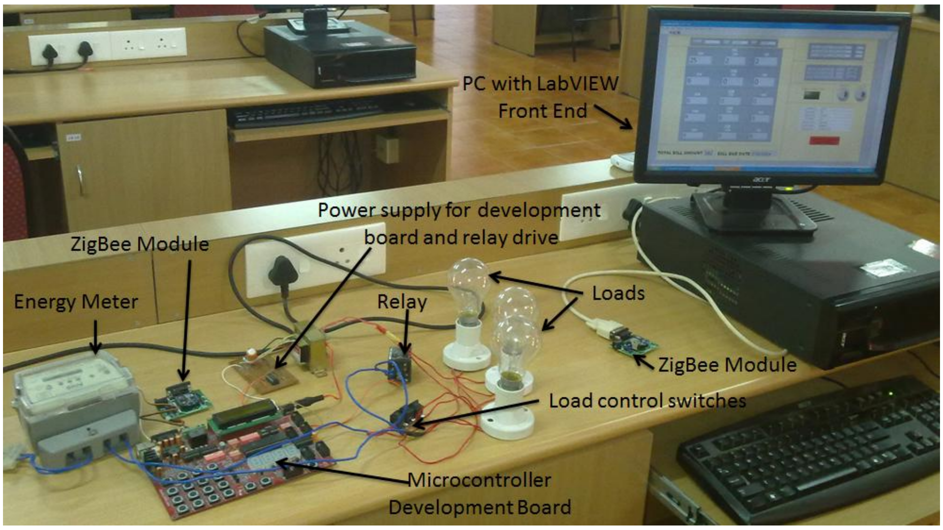

Fig. 7: Prototype of Designed System

Table 1: Test Conditions

	Normal Hour Slot 1 (2 Minutes Duration)									
	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9
Test 1	0	0	0	0	0	0	0	0	0	1
Test 2	0	0	0	0	0	0	0	0	1	1
Test 3	0	0	0	0	0	0	0	1	1	1
Test 4	0	0	0	0	0	0	1	1	1	1
Test 5	0	0	0	0	0	1	1	1	1	1
Test 6	0	0	0	0	1	1	1	1	1	1
Test 7	0	0	0	1	1	1	1	1	1	1
Test 8	0	0	1	1	1	1	1	1	1	1
Test 9	0	1	1	1	1	1	1	1	1	1
Test 10	1	1	1	1	1	1	1	1	1	1

	Normal Hour Slot 2 (2 Minutes Duration)									
	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9
Test 1	0	0	0	0	0	0	0	0	0	0
Test 2	0	0	0	0	0	0	0	0	0	0
Test 3	0	0	0	0	0	0	0	0	0	0
Test 4	0	0	0	0	0	0	0	0	0	0
Test 5	0	0	0	0	0	0	0	0	0	0
Test 6	0	0	0	0	0	0	0	0	0	0
Test 7	0	0	0	0	0	0	0	0	0	0
Test 8	0	0	0	0	0	0	0	0	0	0
Test 9	0	0	0	0	0	0	0	0	0	0
Test 10	0	0	0	0	0	0	0	0	0	0

	Normal Hour Slot 3 (2 Minutes Duration)									
	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9
Test 1	0	0	0	0	0	0	0	0	0	0
Test 2	0	0	0	0	0	0	0	0	0	0
Test 3	0	0	0	0	0	0	0	0	0	0
Test 4	0	0	0	0	0	0	0	0	0	0
Test 5	0	0	0	0	0	0	0	0	0	0
Test 6	0	0	0	0	0	0	0	0	0	0
Test 7	0	0	0	0	0	0	0	0	0	0
Test 8	0	0	0	0	0	0	0	0	0	0
Test 9	0	0	0	0	0	0	0	0	0	0
Test 10	0	0	0	0	0	0	0	0	0	0

	Peak Hour Slot 1 (1 Minute Duration)									
	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9
Test 1	1	1	1	1	1	1	1	1	1	1
Test 2	0	1	1	1	1	1	1	1	1	1
Test 3	0	0	1	1	1	1	1	1	1	1
Test 4	0	0	0	1	1	1	1	1	1	1
Test 5	0	0	0	0	1	1	1	1	1	1
Test 6	0	0	0	0	0	1	1	1	1	1
Test 7	0	0	0	0	0	0	1	1	1	1
Test 8	0	0	0	0	0	0	0	1	1	1
Test 9	0	0	0	0	0	0	0	0	1	1
Test 10	0	0	0	0	0	0	0	0	0	1

	Peak Hour Slot 2 (1 Minute Duration)									
	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9
Test 1	1	1	1	1	1	1	1	1	1	1
Test 2	0	1	1	1	1	1	1	1	1	1
Test 3	0	0	1	1	1	1	1	1	1	1
Test 4	0	0	0	1	1	1	1	1	1	1
Test 5	0	0	0	0	1	1	1	1	1	1
Test 6	0	0	0	0	0	1	1	1	1	1
Test 7	0	0	0	0	0	0	1	1	1	1
Test 8	0	0	0	0	0	0	0	1	1	1
Test 9	0	0	0	0	0	0	0	0	1	1
Test 10	0	0	0	0	0	0	0	0	0	1

Table 2: Test Run Data

No.	X	Y+Z	Tc	(X/Tc)%	[(Y+Z)/Tc]%	CF	CT	α	β
Test 1	0	12	12	0	100	36	48	0	33.33
Test 2	1.2	10.8	12	10	90	36	45.6	5	26.67
Test 3	2.4	9.6	12	20	80	36	43.2	10	20
Test 4	3.6	8.4	12	30	70	36	40.8	15	13.33
Test 5	4.8	7.2	12	40	60	36	38.4	20	6.67
Test 6	6	6	12	50	50	36	36	25	0
Test 7	7.2	4.8	12	60	40	36	33.6	30	-6.67
Test 8	8.4	3.6	12	70	30	36	31.2	35	-13.3
Test 9	9.6	2.4	12	80	20	36	28.8	40	-20
Test 10	10.8	1.2	12	90	10	36	26.4	45	-26.7
Test 11	12	0	12	100	0	36	24	50	-33.3

For the cost calculation, in the TOD tariff it is assumed that, $C_{p1} = C_{p2} = 2C_n$, and in flat tariff, the cost per unit, 'C_f' is the average of rates in normal and peak hours, $C_f = (C_n + C_{p1} + C_{p2})/3$. The values C_T and C_F in Table 2 are calculated by assuming C_n = Rs. 2/-.

From the graph in Fig. 8, it is apparent that the TOD tariff equals flat tariff, if the load is equally distributed between normal and peak hours. If the amount of load shifted to normal hours is more than 50% of the total consumption hours, the TOD tariff causes a reduction with a maximum of 50% in the total cost. It may be felt that the revenue of the utility provider is reduced as a consequence. However, 'peaker plants are operated to meet the demand in some extend during peak hours, and majority of the peaker plants are thermal, hence the production cost during these hours are much higher than the normal hour production. Since the consumption during peak hours are lesser here, peak demand will go down and hence power generation during peak hour can be reduced, this brings the production cost down. Since, the consumers get benefited for limiting the consumption during peak hours, they become vigilant in managing electricity consumption. Hence the designed Smart Metering System is useful to both utility provider and consumers.

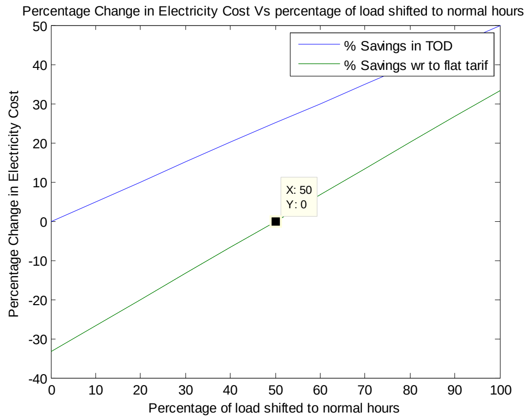

Fig. 8: Percentage Cost Savings verses Percentage Load Shifting

VI. CONCLUSION

A demand based smart metering system using LabVIEW and ZigBee has been designed, which is capable of monitoring energy consumption during peak hours and normal hours separately, alerting the utility provider on energy theft, remote turn ON/OFF the supply of individual consumers and capable of incorporated TOD tariff. The proposed design modify the consumption of the consumers, thereby reduces the energy consumption. The system is useful to both consumers and utility providers. An intelligent circuit which detects theft and generate a switching pulse on detection of theft can be designed and integrated with the system. Each smart meter can be considered as a wireless sensor, and since the consumer's number is high, the overall system may be considered as a wireless sensor network. The approach of a wireless sensor network would help in optimum handling of smart meters. A detailed investigation, scientific analysis and statistical evaluation for a best tariff system, suitable for Indian energy scenario would be helpful in applying an apt tariff system. An apt tariff system and theft detection circuitry can be integrated with the proposed smart meter design.

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