Development of Smart Energy Meter for Energy Cost Analysis of Conventional Grid and Solar Energy

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***Abstract*— This paper focuses on the development of a smart energy meter that can monitor the energy usage of different appliances. A smart energy meter is a digital electric meter that measures the electricity generation, consumption and provides other additional features such as advanced billing system and high accuracy which makes it more advantageous than the traditional energy meter. The proposed smart meter model is verified by designing an appropriate circuit and associated hardware. The hardware is designed using a microcontroller PIC16F877, current and voltage transformer, voltage regulator 7805, solar panel, solar charge controller and inverter. The developed energy meter can control the energy supply and usage of the consumers accurately based on load requirement. In addition, the meter can calculate the cost of power consumption of convection grid and solar energy. Thus, the consumer will get a clear idea about the costs of their usage. Hence, the proposed metering system is more advantageous than the traditional metering system which will reduce the manpower, cost and time.**

Keywords*— *Conventional grid, Energy cost, energy meter, electricity consumption, solar energy.

I. INTRODUCTION

Affordable and efficient use of electricity is a major concern for a densely populated developing country like ours. Many people in our country do not have access to reliable, uninterrupted and cost-effective electricity supply [1], [2]. The demand for electricity is rising day by day. The conventional grid supply cannot meet the basic demand of the people. Therefore, there are no other solutions but to use solar power or wind turbine to generate electricity [3], [4]. Previously, the solar home system (SHS) was implemented remotely regardless of the connection to the utility grid [5]. After this, the grid-connected solar system has gained the popularity due to the energy savings and cost-effectiveness of the total network [6]. Therefore, the total number of SHS is increasing rapidly. Through this system, owners of the houses can choose to get the electricity supply partly from the grid or the rest from the solar depending on the availability of power and cost. As the initial cost of solar system installation is very high, many of these consumers initially install SHS that meet about one quarter to one-half of their energy usage [7].

With the rising trend of electricity consumption by different types of consumers (residential, commercial, and industrial) around the world, it has become necessary to develop better, non-intrusive, environment-friendly techniques of energy consumption to get the accurate calculation of billing system. Therefore, the main aim of smart grid and smart meter is to provide efficient energy utilization throughout the entire electricity network [8]. Traditional energy meter which was being used previously has many limitations. Its accessibility is limited, and it needs more human involvement. Moreover, customers cannot get any information about the billing without the help of the meter reader [9], [10]. Therefore, the use of traditional meter is decreasing rapidly with the advancement of smart meter applications.

"Net metering" or "net billing" system is generally used to process the electricity billing in a grid connected system. In this system, if there is any surplus energy from the solar power after meeting the demand of load, then this power can be sent to the utility grid [11]. On the other hand, if the power produced from the solar system is less than the required amount, the rest of the power can be accessed from the grid. The major problem arises when consumers are unaware of their daily behavior. Monthly feedback given to the consumers is not sufficient as the consumers will not have knowledge on how much energy each appliance consumes individually.

To address the above challenges, this paper aims to fulfil the following two objectives; (i) To develop an improved model designing a smart energy meter for household appliances in order to control the consumption economically and (ii) To analyse the energy cost of electricity produced from conventional grid and solar energy in order to choose a reliable and cost-effective power supplier.

II. SMART ENERGY METER MODEL

The proposed model for designing an energy meter is divided into various parts. They are classified below; (i) Utility connection, (ii) solar power generation and meter input for the generated electricity connection, (iii) current sensing unit, (iv) voltage regulator, and (v) microcontroller unit. An AC main power is used which is then rectified by a bridge rectifier. Then, the output of the rectifier is converted to DC. Later, a voltage regulator is used to step down the voltage to the level of microcontroller input. The load is connected to the microcontroller through the current sensor. For solar power generation, a solar panel is used. Solar panel stores maximum amount of energy into battery cells using a charge controller. Then the conversion of the DC output voltage of the battery to AC voltage takes place using an inverter. Two voltage transformer and current transformers are used for measurement of the solar generation. Fig. 1 shows the block diagram of the proposed metering system. The factors related to the development of

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smart energy meter are discussed in the following subsections.

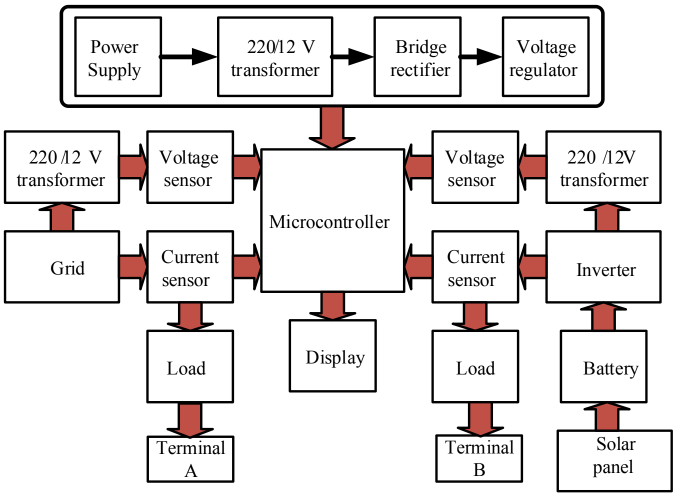

Fig. 1: Block diagram of the proposed system

A. *Utility network*

A power system network comprises of the transmission lines, distribution lines, distributed generators and loads. All these appliances are connected to a common point which is called the bus system. In this study, the connection from 220V AC is marked as terminal A of the meter.

B. *Solar system*

Solar energy generated from the panel can be stored in a DC storage device. In this paper, a 12V DC storage device is used for this purpose. This 12V DC can be connected to AC with an inverter which is named as terminal B.

C. *Current sensor*

The choice of choosing the correct method of current sensing is a difficult task as there are many harmonic contents in the current. Therefore, a current sensor is required to handle the much wider frequency range. In this study, the Hall Effect sensor is used for sensing the current for the application in a smart energy meter.

D. *Voltage control*

Another important factor of modeling the smart meter is voltage control which can be done using a potential divider method or with a step down potential transformer. Selection of the appropriate method depends on the users. Potential divider method is a widely used method for measuring the voltage.

E. *Microcontroller Unit*

The microcontroller is used for computing the voltage, current and power and cost, thus giving the command of displaying the output. A microcontroller with 10 MHz crystal oscillator is used for this purpose. It calculates both the power generations from the grid and solar. Then, it also determines the cost difference between the two systems and shows the value to the display.

III. Model Operation

The operational flowchart of the proposed system is shown in Fig. 2. The procedures are described in the following steps.

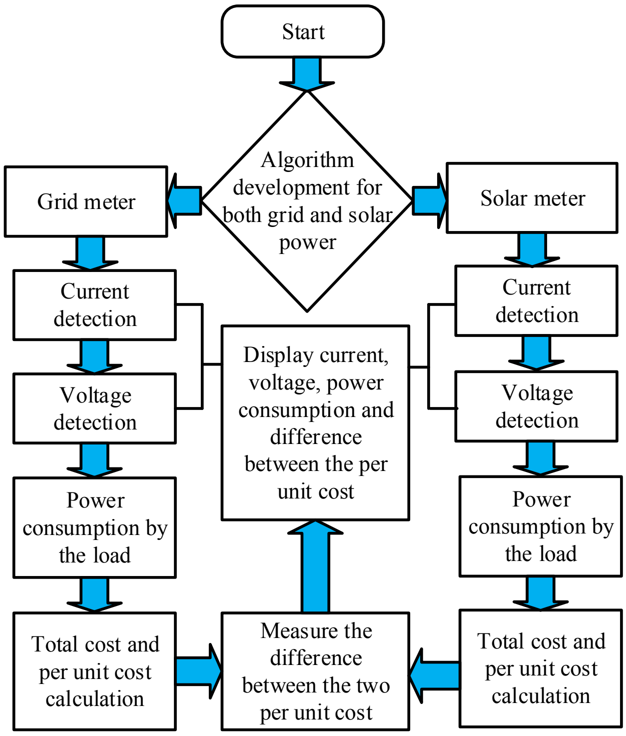

Fig. 2: Energy meter operational flow chart

Step 1 At first, the energy meter measures the reading of grid supply, solar energy supply, and load.

Step 2 The measured data is used for the specific functioning of the microcontroller through the current and potential sensor. This circuit has two current transformers. The current values from these transformers are sent to the respective Analog-Digital converter (ADC) of the microcontroller, and then the ADC converts these values to digital values, and thus the microcontroller does the necessary calculations to find the energy consumption.

Step 3 The microcontroller is programmed in such a way that the voltage and current values from the ADC are multiplied and integrated over a specified time period, and then correspondingly drive the counter mechanism that displays the number of units consumed (kW) over a time period.

Step 4 The cost of both the grid and the solar power supply is calculated assuming the grid energy (PDB) supply as terminal A and solar energy supply as terminal B.

The mathematical expression for calculating energy cost can be expressed by the following equations,

$$\text{Cost of Energy} = EC \times UCE \qquad (1)$$

Where EC is the energy consumption in kWh, UCE represents the unit cost of electricity in BDT.

IV. Model Implementation and Interfacing

Implementation and interfacing of the system with the central processing unit and power system is the main challenging part of this research. Circuit diagram of the proposed energy meter model is shown in Fig. 3. This circuit contains the PIC microcontroller, LCD unit, voltage comparator and resistor divider networks. Details of the model are discussed in the following subsections below.

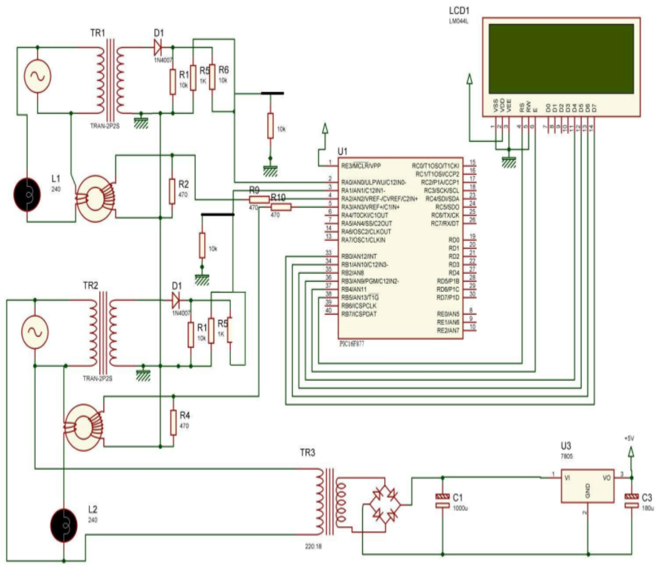

Fig. 3: Circuit diagram of the proposed model

Current Transformer or Hall Effect Sensors are the elements that can be used for current sensing whereas Voltage Transformer and a Resistive Voltage Divider circuit are utilized for voltage sensing. This system is designed based on a PIC microcontroller. Microcontroller acts as a data acquisition processing and transmission system. A current and a voltage signal are connected to its analog inputs and converted into digital form. Current sensors are connected to the pin no 4 and 5 of the microcontroller. Voltage sensors are connected to the pin no 2 and 3 of the microcontroller. Display pins are connected to the pin no 33, 34, 35, 36, 37, 38 of microcontrollers. A voltage regulator 7805 is used with coupling capacitors. For potential divider resistors with 10 kΩ and 1kΩ values are used.

A. Solar generation System

The solar system consists of following components; (i) Solar Panel (20 Watt), (ii) Solar Charger Controller, (iii) 12-volt DC battery, and (iv) 100 Watt Inverter. The solar panel is connected to the solar charger controller. Solar charger controller is able to generate a regulated voltage. It regulates the voltage to charge the DC battery. DC battery stores DC charges. But for home usage, it requires AC. Therefore, an inverter is used to convert the DC into AC.

B. Power units

The power unit of the energy meter consists of the following parts; (i) Step Down transformer (220 V/12 V (ii) Diode Bridge, and (iii) 5V Voltage regulator. Here, the input 220V AC voltage is first stepped down with the transformer and then passed through the bridge rectifier to convert it into DC. The output of the rectifier is then step down to 5V DC using a voltage regulator to maintain the level of microcontroller input. The diode bridge is an arrangement of four diodes that provides the same polarity of output for either polarity of the input. In this research, a 7805 IC is used as a voltage regulator to reach the pure 5 V.

C. Sensing units

To develop the sensing units, current transformer and voltage transformer are used. The AC input of both grid and solar systems are transferred to the microcontroller through the sensors. The sensing units consist of both transformer and ADC. That means that it feeds a reduced voltage of 5V to the ADC (AN0) of the microcontroller. The electrolytic capacitors in the network decouple the signal before feeding the signal to the ADC thereby allowing only AC properties into the controller. The mains voltage (the one across the load) is divided by a factor 220 and shifted to a DC level of 5 V. This voltage is then fed to an ADC of the PIC microcontroller. The level shifting enables the measurement of positive and negative voltages.

D. Interfacing with microcontroller

Microcontroller acts as a data acquisition and transmission system in the network. Current and voltage signal are connected to its analog inputs and converted into digital form. Current sensors are connected to the pin no 4 and 5 of the microcontroller. Voltage sensors are connected to the pin no 2 and 3 of the microcontroller. Display pins are connected to the pin no 33, 34, 35, 36, 37, 38 of microcontrollers. The microcontroller takes the voltage from 0-Vdd and converts in digital form between 0 and 255 (for 8-bit conversion) or 0-1023 (for 10-bit conversion). A crystal oscillator connected with a ceramic capacitor (22pf to 33pf) is used to make the controller ready for action.

V. Prototype Development

The following equipment are used for the prototype development, (i) Microcontroller PIC16F877, (ii) 20x4 Liquid Crystal Display (LCD) Display, (iii) Current Transformer, (iv) Voltage Transformer, (v) Voltage Regulator 7805, (vi) Resistors, (vii) Solar Panel, (viii) Solar charge controller, (ix) Inverter, (x) DC Source, (xi) AC source, (xii) Diode, (xiii) LED, (xiv) Wires and Jumpers, and (xv) Circuit Breaker. The description of the main equipment of the prototype is presented in the following subsections.

A. Microcontroller

PIC16F877 Controller is used in this research as it has several advantages such as small size associated with flexible control systems in real-time monitoring applications. PIC16F877 includes 8kb of internal flash Program Memory, along with large RAM and an internal EEPROM. Moreover, it has some additional features of having (i) operating speed at 10MHz, (ii) 28 I/O points (iii) RS232 Connection with MAX232, (iv) 8 Channel 10-bit A/D Converter, (v) One 16-bit Timer with Two 8-bit Timers.

B. 20 x 4 LCD Module

This unit displays the information in a readable format for future use of the consumer or supplier. A 20 × 4 display unit is used in this research as it is economical; easily programmable; have the opportunity of displaying special and custom characters, animations and so on. A 20x4 LCD displays 20 characters per line and it contains four such lines. This LCD has two registers named as Command and Data. With the command instruction, information for initializing, clearing or controlling the display is given while the data register serves to store the data for display.

C. Solar Panel

Solar panel absorbs the sunlight as the source of energy for generating electricity. Rating of the solar panel (SLPV-10P) is presented in Table I.

TABLE I
SPECIFICATION OF SOLAR PANEL

Particular	Value
P_m	20 W
V_{mp}	19.35 V
I_{mp}	0.58 A
V_{oc}	21.16 V
I_{sc}	0.69 A
Max system voltage	1000 V
Max series fuse rating	10A
Dimension	290×360×23mm
Frame	Aluminum
Output Tolerance	0~+3%
St. Test condition	1000W/m^2
Operating temperature	-40^0 C to +85^0 C

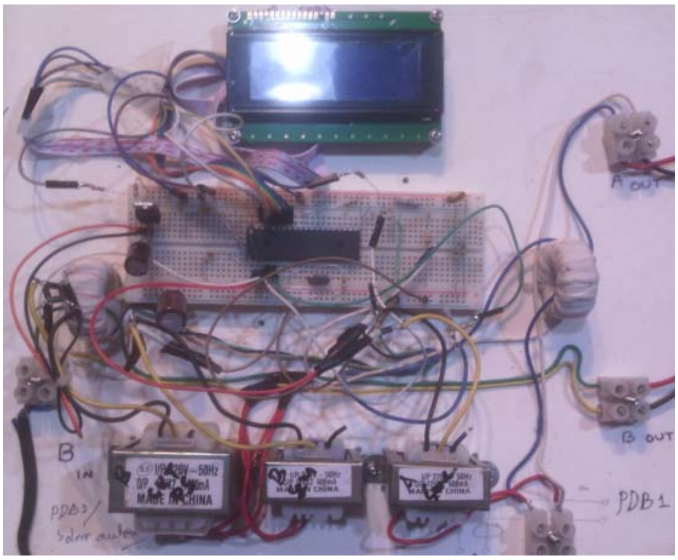

Fig. 4. A prototype of the proposed smart energy meter

D. Voltage regulator

A voltage regulator is designed to automatically maintain a constant voltage level. In this research, 5-volt voltage regulator LM 7805 which is a fixed-voltage integrated-circuit voltage the regulator has been employed. This type of voltage regulator can overcome the noise and distribution problems associated with single point regulation. Each of these regulators can deliver up to 1.5 A of output current. LM 7805 has some attractive features including internal current limiting and thermal shutdown. Furthermore, LM 7805 can also be used with external components to achieve adjustable output voltages and currents. The overall prototype diagram is shown in Fig. 4.

VI. RESULTS & DISCUSSION

The main aim of this research is to develop the smart energy meter which can evaluate the load and energy cost of the conventional grid and solar energy. In order to achieve the target, a rural house was selected randomly to measure the total power by the appliances of a particular day. Since the consumer of that particular house does not have a continuous electricity supply, hence, the solar panel is used as a backup source. The developed meter sensed the load of the house and calculated the power consumed by the load. Fig. 5 shows the output load curve of that particular house. The figure shows that the power demand varies from 30 W to 100 W where the load is the maximum during the night time.

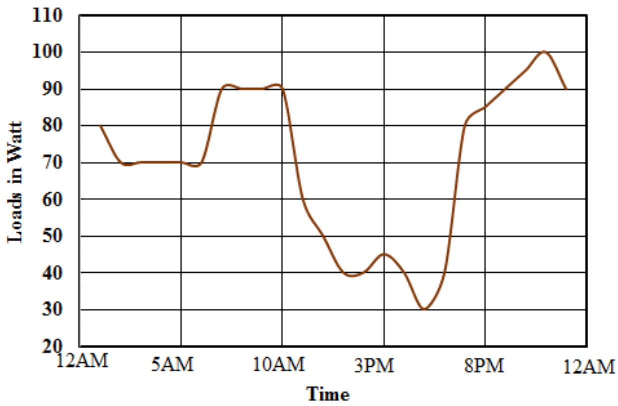

Fig. 5: Load curve of a particular house in a day

A total of 7 solar panels with 20 W capacity is used for running a load of the house during the specific hours in a day. The solar power output starts increasing in the morning and reaching its peak at noon time. The output power of solar energy varies according to the presence of solar radiation and temperature. In a sunny day, the power generation is high while in the cloudy day power generation is low. Hence, solar power output may not be sufficient to meet the load. Fig. 6 illustrates the curve for the solar power output of the solar panel at different times of the day, developed by a smart energy meter.

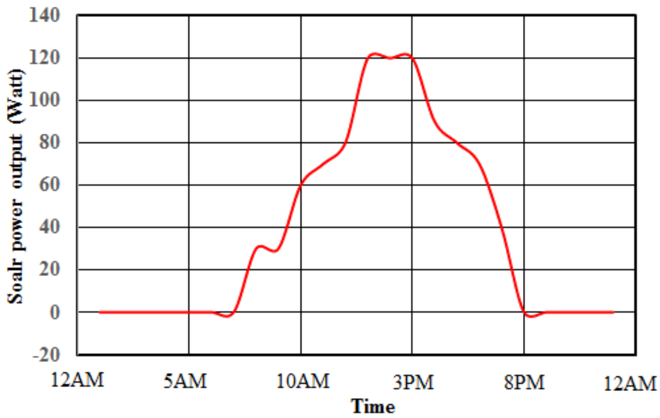

Fig. 6. The curve for the output of the solar power of the solar panel

Since the solar power is intermittent and the grid power not available all the time, a mixed power supply from both grid and solar energy will give the cost-effective solution for the consumer. The developed meter has the ability to show both the reading of solar energy and grid. By using a smart energy meter, the consumers can choose the best power supply for the appliances. In addition to power reading, smart meter calculates the costs for both grid and solar systems. The per unit rate of electricity for solar is 13.6 BDT per kWh [12] while for the grid is 5.01 BDT per kWh [13]. Table II shows the cost analysis results.

TABLE II
COST ANALYSIS OF GRID AND SOLAR ENERGY

Time	Grid Supply	Solar energy supply	Grid energy cost (BDT)	Solar energy cost (BDT)
12 AM – 6 AM	OFF	ON	-	7.07
6 AM – 6 PM	ON	OFF	3.48	
6 PM – 12 AM	OFF	ON	-	6.26
Total energy cost/day (BDT)			16.81	
Total energy cost/month (BDT)			504.3	

It is evident from the above table that the consumer takes energy from the grid during the daytime from 6 AM to 6 PM. Solar energy is used to run the load during the night time from 6 PM to 6 AM. The reason is that the maximum amount of sunshine is available during the daytime and as a result, maximum energy is stored in battery cells which are used later during the night time. Furthermore, the consumer will be benefited if solar panel can be employed during the night since grid power outage occurs frequently at night time in rural areas. The results show that the monthly energy cost for a rural house that receives energy from both grid and solar is estimated to be 504.3 BDT. If the total load is supplied from the solar energy, the total energy cost is 683.4 BDT. So, the additional amount required is only 179.1 BDT. However, with the advancement of solar technology, per unit cost of solar electricity will be decreased in near future.

VII. CONCLUSION

An improved smart energy meter model is proposed for the accurate meter reading and cost analysis. The energy meter model algorithm, operation, and implementation are discussed in detail. In addition, the circuit diagram and the associated prototype are developed to evaluate the accuracy of the proposed model. The experimental results prove that the proposed energy meter can estimate the load curves accurately for households, grid-connected system, and solar system. By constructing an enhanced energy meter model, a substantial energy can be saved during the peak hours. The proposed meter would certainly help to decrease the energy cost and improve the efficient use of time for appliances. The developed smart energy meter offers some benefits such as it is reliable, cost-effective and has an easy process. Future works may include the design of automatic switching of the load from solar to grid and vise versa to save energy and cost. Also, the development of the sensors to replace the present potential divider and current transformer for achieving more accurate readings of the power meter. Moreover, wireless meter reading can be developed for distant power measurement reading instead of reading power from operating places. Furthermore, investigation of the circuit design can be conducted to develop a more static and dynamic circuit design.

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