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Design and Development of Net Metering-Based Energy Meter †

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Abstract: Solar energy is a green and sustainable source of energy which can be converted to electrical power through photovoltaic (PV) panels. In an electrical network system, electrical energy is supplied to end consumers through utility networks. Smart Grids allow consumers to generate electrical energy locally and surplus energy at the user's end can be supplied to the national grid. Bidirectional energy meters keep the record of the imported and exported units to the grid and vice versa. Photovoltaic panels cannot generate power at night, so users have to import power from electric grid. The utility charges the consumer monthly as per net balance of the energy meter depending on the energy trade balance. This IoT-based meter allows real-time monitoring of power ratings via the Android application.

Keywords: Android application; Internet of Things (IoT); net metering; photovoltaic

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1. Introduction

Conventional electric power systems consist of power plants and generation stations located at remote locations far away from the consumer load [1]. These distributors are 11 kV lines with at least one distribution transformer at the end which steps down the voltage from 11 kV to 440 V and supplies electrical power to the energy meters of the consumer's service mains. The total energy demand of Pakistan was 112,070 GWh in 2020 and technical and commercial losses are about 29.7% of the total generation [2,3]. Smart grid is a new concept in the engineering field and engineers. Line losses need to be addressed to meet the energy demand. One of the major causes of line losses is the old structure of transmission systems [4]. Smart Grid technology proposes another solution to overcome line losses and this method is called power sectionalizing [5,6]. Through this method, the overall power demand will decrease significantly as most of the load on the grid system is based on household type and the power demand never remains constant, it increases and decreases over time [7]. A smart grid tied inverter is used which supplies surplus energy to the mains [8,9]. The supplied energy is calculated through an energy meter and supplied to the secondary side of the distribution transformer. This is where sectionalizing works, as other loads are also connected to the secondary side, the supplied surplus energy is then consumed by other connected loads when needed and will eventually reduce the energy demand from the grid.

2. Methodology

The meter is divided into two sections. One measures the AC values while the other measures DC values; they have separate microcontrollers acting as a master and slave. The design and implementation procedure of each section of the project is explained in the following.

2.1. Voltage Measurement

In the AC circuit, a potential transformer is used for high AC voltages and connected with the ESP32. Before connecting to the microcontroller, the output of the PT should be reduced to the level of the microcontroller. The output of the PT is in sinusoidal waveform, so to read the sinusoidal signal using digital microcontroller we need to condition the output signal of PT. A passive signal conditioning circuit is connected to output terminals of the PT which is a combination of resistors and capacitors. The function of the circuit is to compare the signal amplitude value to the AREF value of the microcontroller.

The energy meter is designed with the internal solar charge controller. Solar array can be directly connected to the designed energy meter. To measure the solar voltages, an Arduino UNO microcontroller is used, measuring the voltages of solar and battery for the Battery Management System (BMS). The Arduino communicates with the ESP32 microcontroller acting as a slave microcontroller. For the DC voltage measurement, a resistor-based voltage divider circuit is used. The measured values of the resistors are entered into the Arduino. As we know, the microcontroller reads the analog signal in the form of bits. So, the measured bits value converts into the offset value using following formula:

$$\text{offset value} = (\text{Analog pin value} \times 5.0)/1024.0 \tag{1}$$

The calculated offset value is then used to measure the input DC voltages of the solar and battery using the following formula:

$$\text{input voltage}= (R\_1 + R\_2)/R\_2 \times \text{offset value} \tag{2}$$

2.2. Current Measurement

In this meter, a donut type current transformer is used for the measurement of the AC load current. A wire passing through the hole of the CT acts as the primary of the CT. The secondary of the current transformer is then connected to the passive signal conditioning circuit in the same way as we connected it for the voltage measurement. When the load is turned on, it draws some current from the source which produces a potential difference in the secondary too. The potential difference produced in the secondary of the current transformer is directly proportional to the current drawn by the load. The produced secondary voltage then feeds to the passive circuit to measure the duration of the rising signal by comparing it to the AREF voltages of the microcontroller. Similar to the voltage section, the A pin of the ESP-32 microcontroller is directly connected to the output of the passive filter to measure the CT developed voltage level. That measured voltage represents the current flowing through the load. The burden resistor value is 33 Ω and the rating of the CT is 1/1000 turn ratio. This energy meter uses three DC Hall Effect current sensors that are connected to the Arduino UNO to calculate currents like solar, battery, and grid currents. It also checks the grid current's polarity in order to record both the imported and exported energy. Surplus solar energy causes the polarity to change to negative which indicates exported energy, while a positive polarity shows imported energy. The battery current sensor monitors charging or discharging.

2.3. Power Factor Measurement

The power factor is the cosine of the angle between the voltage and current. To measure it with digital devices like microcontrollers, the signal should be converted into pulses. An operational amplifier is used for this purpose in comparator mode. The inverting pin of the operational amplifier is grounded while the sinusoidal signal is connected to the non-inverting pin of the operational amplifier with a resistor in series. When the signal is high during the positive half cycle, it will generate a constant high signal until the negative half cycle starts, at which point the output will be zero. Then, the sinusoidal signal is converted into pulsating signal. Both voltage and current signals are required to be converted into pulsating signals to further compare them.

Both converted signals of voltage and current are then connected to an XOR gate to compare them. When the output of the XOR is high, it starts a timer and counts the time until the signal reaches low. That measured time is then converted into degrees to measure the phase angle. Since the power factor is the cosine of the phase angle, the cosine is taken of that calculated phase angle to calculate power factor.

2.4. Export and Import Energy

Almost all supply companies are using digital energy meters for billing. There are many problems associated with such conventional energy meters. The use of smart energy meters is the only solution to overcome power theft and other issues regarding DISCOs. In this project, we proposed a cost-effective solution for smart energy meters. This smart energy meter is like a smart IOT-based controller kit that can be communicated to any conventional energy meter. The blink signal of the conventional energy meter is used to measure consumed or exported energy. The meter is calibrated to 32 pulses per kWh. An Arduino microcontroller is employed to handle all solar charge controller applications. The Arduino microcontroller reads the data from the connected sensors and transmits it to the master controller through I2C communication. The master controller (ESP32) communicates it to the conventional energy meter by counting the pulse signal. Bidirectional energy meters are designed to deal with two types of energy: imported energy and exported energy. During the daytime when solar energy is sufficient to meet the load demand; excessive energy is supplied to the main grid. Similarly, when solar energy is not sufficient to meet the load demand, the extra energy will be supplied through the main grid. The amount of energy being imported from the mains is calculated by checking the polarity of the grid current sensor as explained in export energy. In this meter, our main objective is to design a smart bidirectional energy meter with a secure home automation channel and secure data monitoring application. No billing method is proposed in this project yet but can be easily modified through an Android application update as the energy meter communicates through the online database.

2.5. Home Automation

This bidirectional energy meter is designed with the additional feature of home automation. The energy meter measures the load and charge controller data and uploads this to the database. The Android application reads the data from the database and displays them on the application screen. The application also checks the status of the load switches through the database. Blovk diagram of home automation is shown in Figure 1.

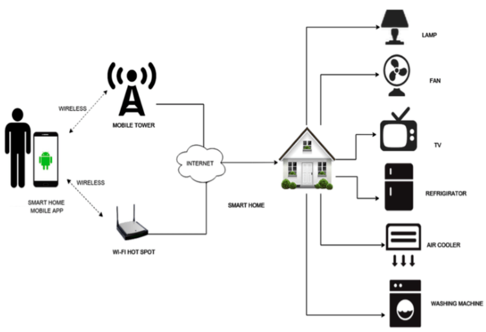

Figure 1. Home automation block diagram using Android.

2.6. Android Application Development

The Android app development is a method to design and develop new apps for Android devices. The official way to distribute an Android app to end-users is Google Play. Google is the main developer of the Android operating system, the used for design and development of the Android app are Native Development Kit (NDK) and Software Development Kit (SDK).

2.7. Circuit Diagram

The high voltage circuit of the energy meter consists of a current transformer and a potential transformer to measure the load current and line voltages, respectively. The five relays are used for switching of load through home automation. An ESP32 is used as a main, receiving data from CT, PT, and the connected slave microcontroller. The internal Wi-Fi connectivity of the ESP32 allows communication with the Android application and database. The ESP32 works on 3.3 V while Arduino and other connected sensors and relays operate at 5 V. Some other sensors and MPPT controllers require a 12 V supply. Arduino UNO is used as a slave microcontroller, reading data from all current sensors and voltage sensors. The Arduino UNO also generates a PWM signal for the solar buck boost converter to obtain the maximum power from the solar array. The PWM duty cycle is determined by the principle of the Fill Factor. It modifies the duty cycle by comparing the power value. The Arduino UNO also communicates with the conventional energy meter to read the pulse signal from it. An isolated optocoupler is also used to keep the designed circuit away from the high voltage circuit. The relays are used for protection and self-calibration as shown in Figure 2.

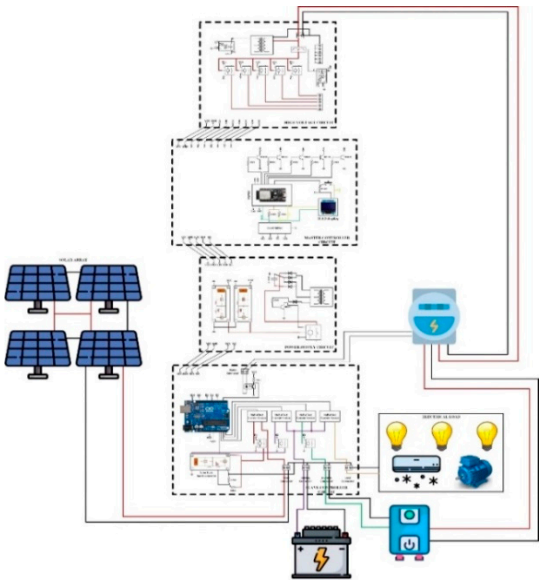

Figure 2. Circuit diagram of the bidirectional meter.

3. Results and Discussion

Small-scale solar systems are better than greater investments. For this purpose, bidirectional energy meters are installed at the users' end in order to measure energy flows. This smart bidirectional meter addresses supplier companies' apprehensions like theft, billing, and data monitoring and also offering features like home automation. The meter has both an AC and DC section. In the AC section, there is ESP32 that measures parameters like load current and line voltages; it also calculates both imported and exported energy. Another feature is the real-time monitoring of power. Into the bargain, it confirms agreement with power quality standards. This model is calibrated to 32 pulses per kWh that brings into line with IEC standards. DC section concerns solar power, pulse reading, and battery systems. Arduino UNO is used to read data from sensors and controls the solar module output. The whole system is programmed to be compatible with power inverters that are available in the market and achieves an efficiency of 85% at 30V_DC. Higher DC voltages can result in even greater efficiency. This meter is an IoT-based meter that connects to the internet for data transmission. This feature makes tampering impossible as the energy meter continually cross-checks data with the secure database. An Android application allows users to access real-time data and control the home automation functions. The data refresh rate on the Android application depends on the speed of the internet connection.

4. Conclusions

Smart net metering-based energy meters based on the principle of Internet of Things (IOT) for real-time monitoring and control by the Android application was designed and implemented. ESP32 is used as a main microcontroller to perform power factor measurements, AC power calculations, line voltages, and home automation. The built-in solar charge controller and battery management system was designed using an Arduino microcontroller. The overall efficiency of the charge controller at low DC voltages was 85% and this paper proposed a tempering free meter solution using the cloud storage method and blockchain. This smart energy meter can reduce the heavy loads of UPS batteries when no blackouts occur in areas as light load will keep servicing during peak times. Home automation can help users to monitor and control the connected load remotely.

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