Development of an Internet of Things Smart Electricity Meter Using MQTT Protocol

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ORIGINAL RESEARCH

Abstract— This research presents the development of an Internet of Things based Smart Meter with the ability to measure and report over the Internet not only voltage, current and power, but also power factor of connected load on two electric buses and it keeps historical data for future use. The historical data of power usage is accessible to the Power Supply Company and the Consumer. The smart meter has an LCD display and reports measurements using the Message Queuing Telemetry Transport protocol over a secured wireless internet connection. Home Assistant provides the necessary cloud-based user interface which displays real-time readings updated every few seconds from the meter as well as stores measurements over a period. The smart meter employs the ESP32 microcontroller with voltage and current sensors connected to its Analog to Digital Converter pins. Two methods, namely the peak method and root mean square (RMS) method were investigated for the measurement of the voltage and current on the busses. Other parameters like frequency, power and power factor were calculated in software routines implemented by the microcontroller. The meter was calibrated using a Fluke digital Multimeter. The smart meter performed reliably with an accuracy of +/- 3% when using the peak method of measurement. This was further improved to +/- 1% when the RMS method of measurement was employed

Keywords— Internet of Things, Smart Meter, Advanced Metering Infrastructure (AMI), Root Mean Square (RMS), Message Queuing Telemetry Transport (MQTT).

1 INTRODUCTION

Advanced Metering Infrastructure (AMI) consisting of Smart Meters (SM), intelligent terminals, communication technologies, Meter Data Collection System (MDCS) and Meter Data Management System (MDMS), is an integral component of any smart grid deployment (Sreedevi *et.al.*, 2020). AMI replaced Automated Meter Reading (AMR), the replacement occurred due to the advantages which two-way interactions between the utility companies and the consumers as provided by AMI superseded the one-way information flow of AMR (Desai *et. al.*, 2019). A smart meter measures the electrical parameters such as voltage, current, power, frequency, and power factor on the electric bus to which it is connected.

The smart meter developed in this work consists of four (4) modules namely the power supply module, measurement module, processing and control module, and finally the communication interface module.

The communication protocol required for communication between IoT devices is key to achieving reliability of the measurement reports. Message Queue Telemetry Transport (MQTT) Protocol was presented in Khan *et al.*, (2020) as an efficient and generally accepted protocol for IoT device management because of reduced transmission overhead and increased speed. In Khan *et. al.*, (2020) an IoT based power monitoring system was developed using microcontrollers and Wi-Fi technology. ThingSpeak - an open-source IoT platform was used to implement the cloud platform. The project was limited to the monitoring and reporting of voltage and current of respective appliances and did not measure the power, frequency, or power factor.

The researchers in Irfan *et. al.*, (2019) implemented an Arduino SM with two-way communication, voltage variation protection, net metering capabilities with theft and overuse detection. The designed SM had added switch gear to enable it to interrupt the line when conditions are unfavourable. The SM reported its readings to a web server via a Wi-Fi shield to which

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Section B- ELECTRICAL/COMPUTER ENGINEERING & RELATED SCIENCES

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an ESP8266 is connected. GET and PUT requests were used to exchange data with a web server using the Wi-Fi module. Although this method is less resource intensive it is rather insecure.
The reviewed literatures showed that IoT is an indispensable requirement for the modern smart grid (Cruz *et. al.*, 2018; Orlando *et. al.*, 2022). They also showed that so many IoT protocols abound for use in the advanced metering infrastructure ranging from Bluetooth, Wi-Fi, Zigbee and a host of protocols (Amankhan *et. al.*, 2019; Avancini *et.al.*, 2019; Luambano *et. al.*, 2020). There is yet to be established any single solution that fits all scenarios, thus the need to carefully select the communication protocol employed based on the availability of power and necessary communication infrastructure.

The works reviewed do not keep a historical record of the measured parameters for future reference, also they do not report frequency and power factor which serve as gaps filled by this work. The historical data of power usage is accessible to the Power Supply Company and the Consumer. This work presents the development of an IoT based wireless smart meter which measures instantaneous voltages and currents on two connected buses and calculates the power consumed by the connected load, power factor and frequency of the signal. The smart meter connects wirelessly to an MQTT broker embedded in a Home Assistant virtual machine on the Local Area Network. The readings from the smart meter are updated every few seconds. The developed SM supports novel services such as friendly presentation of readings using Graphical User Interface. It also provides for disconnection of a line over the internet.

2 MATERIALS AND METHODS

2.1 SMART METER DESIGN

Figure 1 depicts the block diagram of the IoT smart meter. At the heart of the design is the ESP32 microcontroller which embeds the Wi-Fi communication module, multiple SPI buses of which one is used for communication with an SPI LCD display and finally several Analog to Digital Converter (ADC) input pins of which some are dedicated to current and voltage sensors.

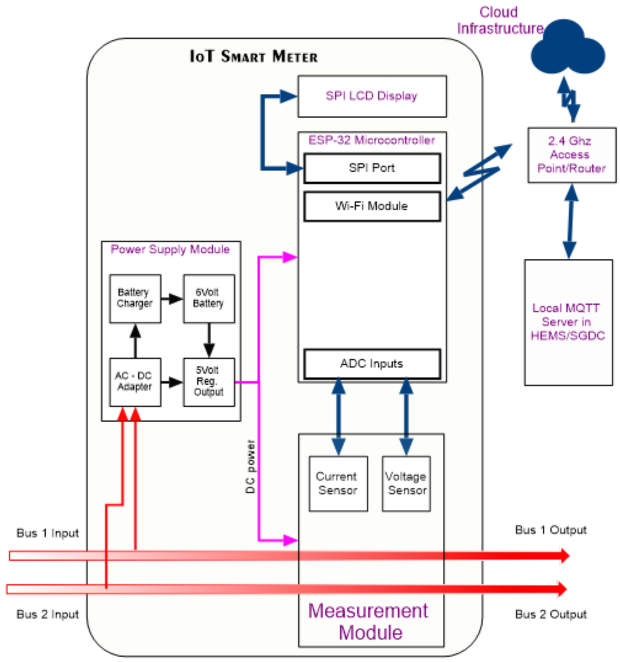

Figure 1 Block Diagram of the Smart Meter

The circuit diagrams of the smart meter showing the display and measurement interface and the power supply module are shown in Figure 2.

2.2 MEASUREMENT PRINCIPLE: the developed smart meter measures instantaneous values of voltages and current. It carries out scores of measurements within a period of the signal and stores these measurements in an array in the microcontroller's memory. The stored measurements can then be processed to determine the peak voltage, RMS voltage, period of the signal etc. The average power and Apparent Power are calculated by getting the average of the instantaneous products of the voltage and the product of the RMS values of voltage and current respectively. Two methods are implemented for the evaluation of the RMS values of voltage and current. They are peak voltage method and direct calculation of RMS voltages from equally spaced data samples within a period of the signal.

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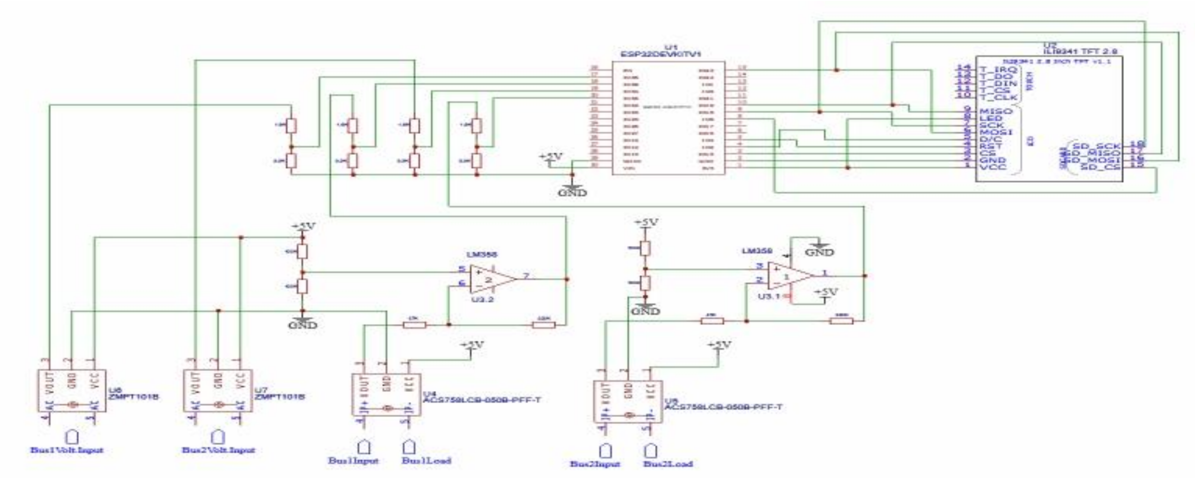

Figure 2. Smart Meter Circuit Diagram

The respective equations employed for the peak method are outlined in equations (1) and (2).

$$V_{rms} = (V_{ptp} \times 0.5 \ \times vratio) \times \frac{1}{\sqrt{2}} \qquad 1)$$

$$I_{rms} = (I_{ptp} \times 0.5 \ \times iratio) \times \frac{1}{\sqrt{2}} \qquad 2)$$

where V_{rms} is the rms voltage, V_{ptp} is the peak-to-peak voltage, I_{rms} is the rms current, I_{ptp} is the peak-to-peak current, vratio and iratio are the ADC calibration constants.

For the RMS method the instantaneous values are used as presented in equation (3) and (3).

$$V_{rms} = \sqrt{\frac{{V_1}^2 + {V_2}^2 + {V_3}^2 + {V_4}^2 .. + {V_n}^2}{n}} \qquad 3)$$

$$I_{rms} = \sqrt{\frac{{i_1}^2 + {i_2}^2 + {i_3}^2 + {i_4}^2 .. + {i_n}^2}{n}} \qquad 4)$$

where V_1 to V_n, i_1 to i_n are the instantaneous voltage and current samples measured, n is the number of samples.

The average and apparent power are calculated using equations (5) and (6).

$$P_{avg} = \frac{V_1 i_1 + V_2 i_2 + V_3 i_3 + \cdots . + V_n i_n}{n} \qquad 5)$$

$$P_{apparent} = V_{rms} \times I_{rms} \qquad 6)$$

The pf is then calculated using equation (7).

$$pf = \frac{P_{avg}}{P_{apparent}} \qquad 7)$$

To calculate the frequency of the signal an algorithm was developed which counts the number of positive and negative half cycles recorded within a sample time S and applying them in equation (8)

$$v_{freq} = \frac{(p_{count} + n_{count})}{2} \times \frac{1}{S} \qquad 8)$$

2.3 Power Supply Module

The SM power supply module (PSM) featured a dual source power supply module, a 12-volt mini uninterruptible Power Supply (UPS) powered with Lithium backup batteries and finally a 12volt to 5Volt Buck Converter circuitry to ensure compatibly with the 5Volt power requirement of the ESP32 devkit 1.0 microcontroller board. The diodes D1 and D2 ensure that DC voltage is not back fed to either of the PSMs. The PSM with its 4000mah battery provided about 8 hours of runtime for the SM even when none of the buses were energized.

2.4 Processing and Communications Module

The ESP 32 Devkit 1 microcontroller provides the core functionality of controlling the operations of the smart meter and communicating the readings of the smart meter via MQTT protocol over Wi-Fi and through its SPI communications port to an LCD display. The microcontroller was loaded with Mongoose OS – an open-source operating system for the Internet of things. The code for communication and display interface were written in JavaScript while the code for the acquisition of ADC readings from the ADC pins were done in C code for faster execution. Interrupt timers were utilized in the code to ensure that the display and MQTT readings were updated at regular intervals of 2.5 Seconds apart. A flowchart for the developed software program is presented in Figure 3.

2.5 Measurement Module

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The ESP32 has a 12-bit Analog to Digital Converter. This means that an analog input between zero and 3.33 volts would be converted to its digital equivalent between 0 and 4095

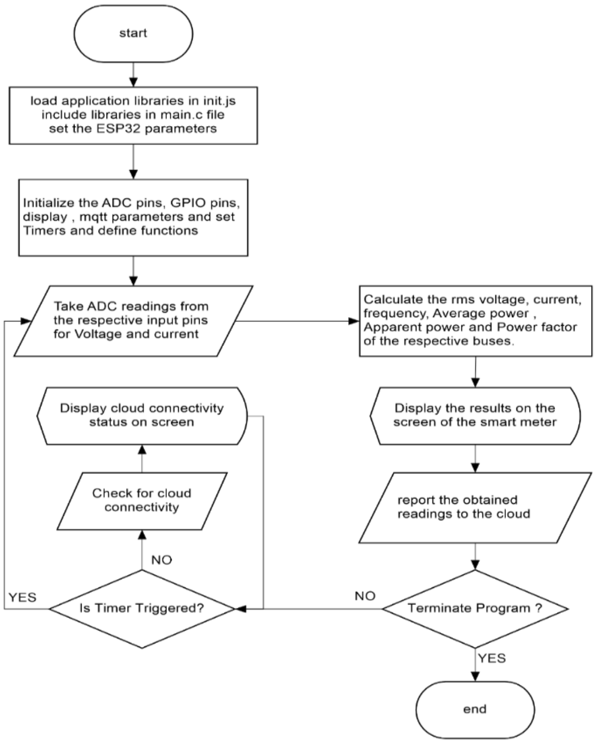

Figure 3 SM software flowchart

The measurement module consists of voltage and current sensors which perform the actual sensing of the parameter and produce an analog signal with voltage between 0 and 3.3 Volts to the connected ADC pins of the microcontroller. The ZMPT101B voltage sensor and ACS758 current sensor were used in this work.

VOLTAGE MEASUREMENTS:

The AC voltage terminals of ZMPT101B voltage sensor were connected across the BUS to be measured. While its signal out pin was connected to the microcontroller ADC pin via a 5V to 3.3V resistor level shifter. The reason was that the ZMPT101B had a 5V logic level while the microcontroller had a 3.3V logic level.

CURRENT MEASUREMENTS:

THE ACS758 Hall Effect-Based Linear Current Sensor IC was employed for current measurements in Figure 2. Its output was connected to the ADC pin via an LM358 differential Amplifier stage which had a gain of 4.68 and a 5V to 3.3V level shifter. The equation governing the output is presented:

$$V_{out} = 5\left(\frac{R_{10}}{R_9 + R_{10}}\right)\left(1 + \frac{R_{14}}{R_{13}}\right) - V_{cs}\left(\frac{R_{14}}{R_{13}}\right) \quad (9)$$

Where V_{out} is the output of the LM358 pin 7 and V_{cs} is the voltage output of the current sensor. Substituting all values into the equation reduces it to equation (10)

$$V_{out} = 2.5 - \frac{220}{47}(2.5 - V_{cs}) \quad (10)$$

The ratio 220/47 representing R14/R13 is the differential gain of the amplifier. The values were chosen so the LM358 did not go into saturation when the intended maximum current was flowing in the bus being measured.

Power Calculations:

The power and power factor were calculated from the instantaneous voltages and currents using equations (3) to (7).

Smart Meter Calibration

To initially calibrate the smart meter, it was necessary to obtain the constants vratio and iratio which were presented in equations (1) and (2). This was done by using a Fluke digital multimeter to measure the same voltage and current being measured by the IoT smart meter and comparing it with the output of the ADC. Fifty measurements were carried out and the values of vratio and iratio were determined. The voltages and current were once again varied, and the procedure carried out again and the values of vratio and iratio were once again revaluated. After Calibration the results showed that the accuracy of the IoT smart meter developed was +/- 3% while using the peak method and +/- 1% while using the RMS method. The reported energy consumption data was validated by use of a Legrand MDX energy meter which also showed the same results for accuracy.

3 RESULTS AND DISCUSSIONS

The designed smart meter prototype at different stages is presented in Figures 4 and 5.

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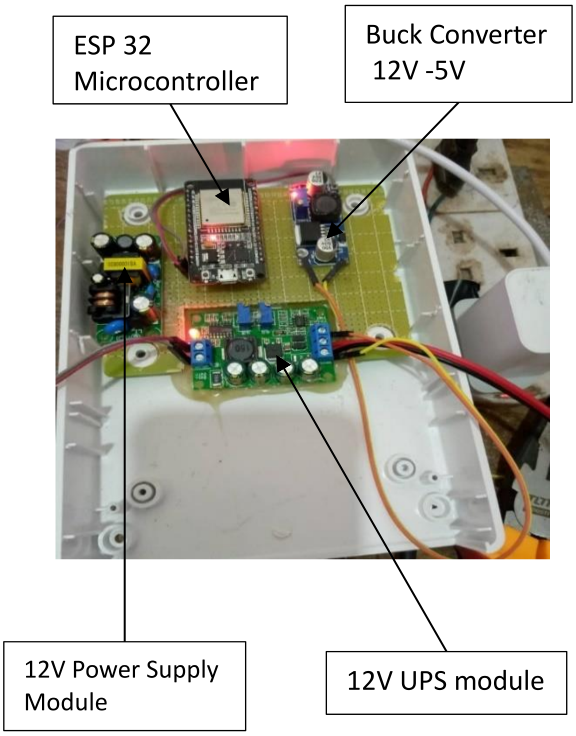

Figure 4 Smart Meter Prototype Base Board

Figure 5 Prototype IoT Smart Meter

The SM was mounted to monitor a home supplied by two buses. A utility supply on bus1 and a Solar powered Inverter system on bus 2. The energy readings recorded in the month of December 2022 are shown in Figure 6.

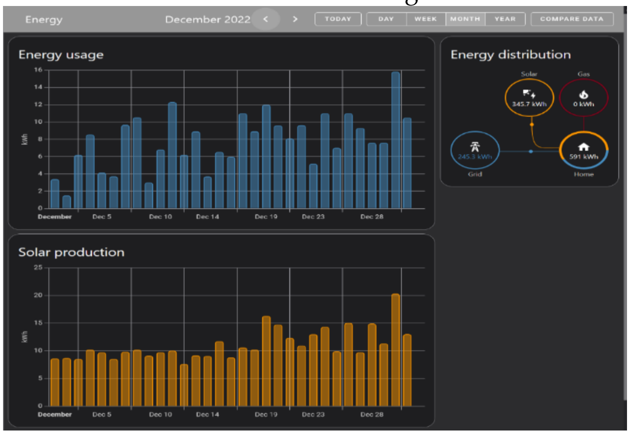

Figure 6 Energy Consumption Data

The power monitoring dashboard which is available to both the consumer and service provider is presented in Figure 7. The dashboard shows measurements for all five parameters being measured by the smart meter. The Home Assistant Platform implements SQLite database by default for the storage of history and events. A sample history of voltage measurements on bus1 in a particular month is presented in Figure 8. Similar history graphs are producible for all parameters measured on the dashboard.

Figure 7 Power Monitoring Dashboard

Figure 8 Voltage Measurement History for Bus 1 in December 2022

4 CONCLUSION

The paper developed a Smart Meter suited for integration into a smart micro grid for the measurement and reporting of voltages, current, power, power factor and frequency on two distinct buses. The method used integrated Home Assistant which enables the storing of measurements and reporting of the load profile and characteristics of the measured bus. The ADC used enable higher accuracy in converting the analog to digital signals. RMS method proved to be more accurate than the peak method used in reviewed literature as it inherently compensated for spikes at the ADC pins due to transients and power supply surges. Also, when compared with the work in Khan *et.al.*, (2020), the work has more functionalities with ability to measure the power, frequency, and power factor.

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