IoT Enabled Real-time Energy Monitoring and Control System

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***Abstract*—Electric energy metering infrastructure in many developing countries is limited in terms of its connectivity to the central station and real-time monitoring. To address the problem, there is a need to investigate more advanced means of measuring and distributing electrical energy. In this paper, we propose a real-time load monitoring and control system based on LoRa, that can measure both the quantity (in terms of voltage, current, and power) and quality (in terms of power factor and harmonics) of electricity in real-time, and also provide remote ON/OFF control functionality via an online SCADA server. The solution comprised of a Data Acquisition (DAQ) system based around a microcontroller, a Data Communication Network (DCN) using LoRa Radios, an Online Gateway using a Raspberry Pi, and a Remote IoT SCADA Server to collect and display data. The system is powered by a power line (also being measured) and is back-up by a battery supply to avoid loss of data. The proposed system was validated through simulations on Proteus and MATLAB and was followed by hardware realization. Results are presented for both hardware and software implementations and compared with standard lab equipment. The results show that the system is energy efficient due to LoRa technology and can accurately measure the power consumption parameters for different loads in real-time.**

Keywords*—Pakistan, Smart Electricity Metering, Data Acquisition System, IoT, AMI, Real-Time monitoring, microcontroller, LoRa, SCADA Server, Proteus, MATLAB, simulations

I. INTRODUCTION

In the 21st century, many developing countries are still unable to meet their growing electricity requirements due to shortcomings in their power distribution systems, and ongoing issues like theft, wastage, and poor efficiency. One such country is Pakistan, where resulting outages due to load shedding and breakdowns disrupt the activities of people and cause financial losses as industries and factories are shut down. In 2012, outages occurred around 5 times a day, and households did not have electricity for an average of 1453 hours [1]. Challenges like theft and meter tampering result in huge losses for the utility companies and shift the costs to other people. During 2017-2018, the number of electricity nonpayers in Pakistan was 5.3 million, with the cumulative amount stolen being Rs404.8 billion [2].

In 2016, an estimated half of all meters used in Pakistan were analog meters [3]. Since then, digital meters have become more incorporated in residential and commercial areas. These offer some advantages, like better efficiency and certain anti-tampering features. However, both have to be read manually, unlike the more advanced and expensive but less common - Automatic Meter Reading (AMR) and Smart Meters, which can transmit their readings at regular intervals to a database controlled by the utility [4]. In the past, there was resistance to Smart Meters in Pakistan, as consumers felt that they were being billed unjustifiably by the utility companies [4]. For this, providing consumers with the appropriate details could dispel such misconceptions, and help bring acceptance towards this new technology.

The advantages of introducing Advanced Metering Infrastructure (AMI) like a real-time load monitoring system include: utility and consumer access to real-time energy consumption data, manual meter readings no longer required, increased cognizance among consumers leading to a more conscious use of energy, tackle the problem of energy theft, actively notice faults and highlight the areas where they occur, improved stability, improved efficiency, and improved health of the grid system, and a reduced need to burn fossil fuels, helping the environment [5-12].

This paper aimed to present an architecture for cost-effective real-time distribution side power monitoring. The system demonstrated the benefits of real-time measurement of energy and shows how it can help improve Pakistan's energy crisis. Results are presented by measuring electrical parameters of power line like single-phase voltage, current, power, frequency, power factor, and harmonics, in real-time, while also implementing features like remote switching, GPS synchronization, and a backup power supply. The system implemented bi-directional communication using LoRa technology, where the measured data was sent to an IoT SCADA server through a gateway implemented on a Raspberry Pi. The data acquisition system was designed to be economical and was also simulated to validate its design. The measurement system was calibrated and tested against a standard lab digital multimeter (Gwinstek GDM-8245) and an oscilloscope (Gwinstek GDS-2000A) to ensure its accuracy.

II. SYSTEM ARCHITECTURE

The system can be divided into 4 components (visible in Fig. 1). The following section provides implementation details of each component.

1. Data Acquisition Unit: This included sensing, signal conditioning, and processing. Sensors for measurement included voltage (ZMPT101B) and current (ACS712 -5A to +5A). The voltage requirement was to accurately measure up to 250V maximum and 180V AC minimum per phase. The ZMPT101B stepped down the 220V RMS input voltage to a 2.5V peak and then added offset to bring it to the range 0-5V peak. For frequency measurement and phase detection, a zero-crossing detector was used. For geo-tagging and clock synchronization, a GPS module (NEO-6M) was included. Signal processing was carried out on an Arduino MEGA 2560 Microcontroller. The system also included a power supply unit to provide power to the different components during normal operation and in the case of an outage and a relay for remote switching of the main line.

2. Wireless Communication Radios: This included the bidirectional communication between the meter(s) and the Data Concentrator/Gateway. It was done using two LoRa Radios; one connected to the Data Acquisition Unit, and one connected at the Gateway. Among the wireless communications considered, LoRa was found to be a cost-effective, low power, long-range communication technology that used very low bandwidth. LoRa was the most viable for metering purposes, as it could send small packets of data at long distances, with very low power consumption, and was also open source for manufacturers to use in their solutions [13]. The LoRa radios used were the SX1276 based Dragino LoRa Shield, and the RF96 based Dragino LoRa GPS Shield.

3. Internet Gateway: The Internet Gateway consisted of a LoRa Radio connected to an Arduino UNO Microcontroller, and a Raspberry Pi. The UNO handled the LoRa Communication with the Data Acquisition Unit and transmitted data serially to the Raspberry Pi. The received data was then uploaded to the SCADA server every 2 seconds. Using the Raspberry Pi allowed both Wi-Fi and Ethernet for Internet access, and to also perform tasks like scheduled status reports.

4. SCADA Server with HMI: To monitor and manage the system, the data was sent from the Gateway, using an MQTT protocol, to an IoT SCADA server operated by the utility. The IoT SCADA server used was Ignition SCADA. It included an interface between the server and connected devices and ensured only authorized devices could access and view the data. It also featured Alarms, Real-Time Status Control, Reporting, Data Acquisition, Scripting, and Scheduling. The Human-Machine Interface (HMI) was accessible from any Internet-capable device, with an authorized username and password. The HMI showed the measured parameters for power consumption, could remotely control the main line on the Data Acquisition Unit and also allow to set over-current limits for automatic shutdown.

III. DESIGN CHALLENGES

A. Voltage Measurement Using ZMPT101B

The module required calibration within the code, done by removing any offset with the voltage switched OFF, and then a multiplication factor to scale the reading from the Microcontroller to the multimeter readout with the supply turned ON. In the datasheet for the ZMPT101B, the maximum output was listed as a 5V peak. However, in testing, it began to saturate close to 4V peak. This was also corroborated by the simulations. This was caused by the LM358 Op-Amp IC, which has a max output voltage swing of VCC – 1.5V, meaning it would saturate at a value depending on the VCC. Since the VCC was fixed at 5V, the Op-Amp saturated around 3.5V. As the bias was 2.5V, and the sensor had a maximum span of 2.2V, the total range was 1.4V to 3.6V. This lowered its resolution and accuracy. Rectifying this would require replacing the SMD resistors.

B. Power Supply of the Meter

A constant supply of operating voltage was key for the meter to run properly, even in the absence of the mains voltage, like in the case of a fault or outage. As the meter was required to be functioning to carry out fault analysis and data collection, all nodes of the network needed to be active at all times. Hence, an energy storage and recharging component was necessary. Fig. 2 shows the architecture of the power supply. The final design incorporated a 220/12 Vrms step-

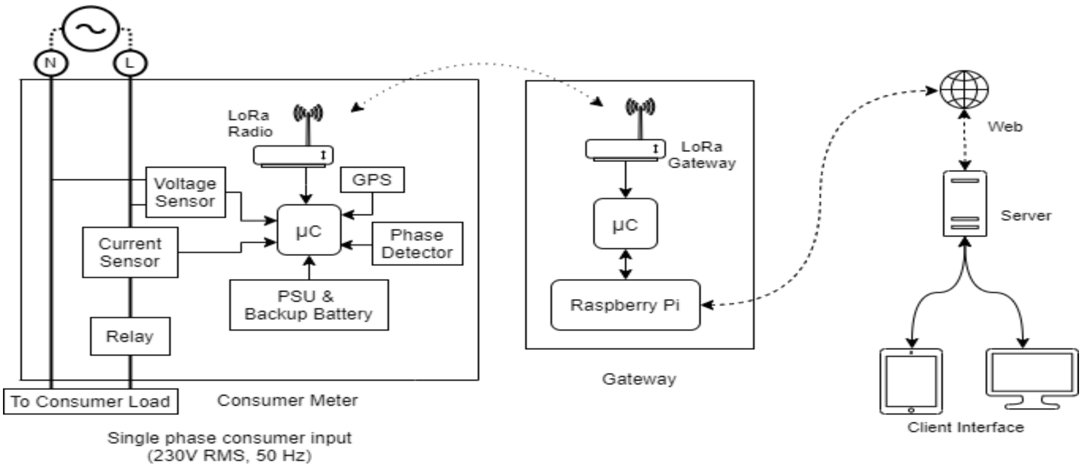

Fig. 1. System Architecture

down transformer whose output was passed through a full-bridge rectifier and a 5V regulator IC (this is all shown as the 5V 2A supply in Fig. 2), a TP4056 charging module with built-in safety circuitry, two ICR18650 cells connected in parallel, and an MT3608 boost converter. As it was designed with ICR18650 Li-Ion cells, and they only had a nominal voltage of 3.7V peak, the MT3608 boost converter was used to raise the 3.7V to 5V. This was used to power the Arduino MEGA 2560, the LoRa module, and the voltage and current sensors of the Data Acquisition node.

C. Frequency Measurement

Due to the high processing and memory requirement for FFT (Fast Fourier Transform), and the constraints of the Microcontroller used, the frequency was found using a zero-crossing detector hardware implementation. The voltage signal output from the voltage sensor (ZMPT101B) was fed into the zero-crossing detector, which gave the output as a square wave. This was input to a digital pin on the Microcontroller, and the time was measured when the pulse was HIGH and when it was LOW. Those times were summed and inverted to get the frequency. While FFT was used for harmonics, its accuracy was poor and could not be used to reliably quote the frequency of the signal.

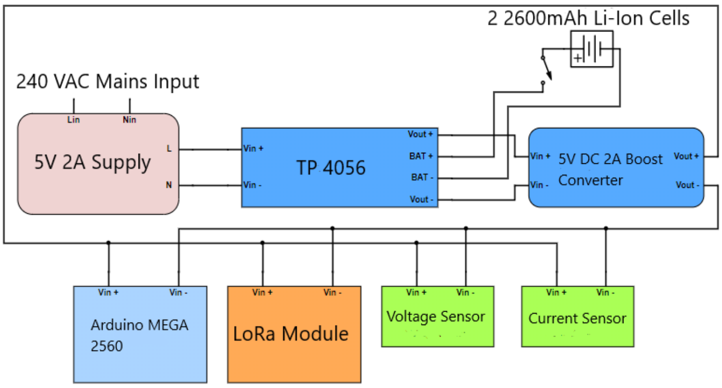

Fig. 2. Power Supply Architecture

IV. DESIGN VALIDATION

A. Data Acquisition System simulation on Proteus software

For the simulation in Fig. 3, the ZMPT101B and the ACS712 5A were constructed on Proteus, the source voltage was set to 230Vrms, the load was two 220V 60W bulbs, and the code dumped on the Microcontroller was the same as the hardware.

B. Theft Detection on Proteus Software

Another set of voltage and current sensor modules were added. The left half was modeled as a distribution meter, and the right was a consumer meter. The distribution current sensor was able to measure all the current, and any load placed between the two meters would be measured by it but not the consumer meter. This difference in current would indicate theft. Fig. 4 shows that without any theft load attached, the Ammeters measure the same reading. With the theft load attached, the current being measured by the Ammeter on the distribution side is greater.

C. Power Supply

To calculate the max current draw of the system: Arduino MEGA 2560 500mA, Dragino LoRa shield 160mA, ZMPT101B 10mA, ACS712 10mA, totalling 680mA. The total current draw was multiplied by a factor of 2 in case more equipment was added later: 1360 mA. This was used to find the time it would take to charge/discharge the battery. The two cells had a total capacity of 5700mAh and operated at a rating between 0.2 C and 1 C. Using these values, the optimal C rating and discharge time were found as: 0.239 C and 4.2 hours. The power supply unit was simulated using MATLAB Simulink, visible in Fig. 5. A bus connected to the Li-Ion battery transmits data of battery voltage, current, and state of charge (SOC%) to the scope. The first 3 resistors connected are the MEGA 2560, LoRa Shield, and the current and voltage sensors. The fourth resistor is to represent any extra load. The State of Charge (SOC) started from 80% and reduced linearly to 0%. The current and voltage stayed

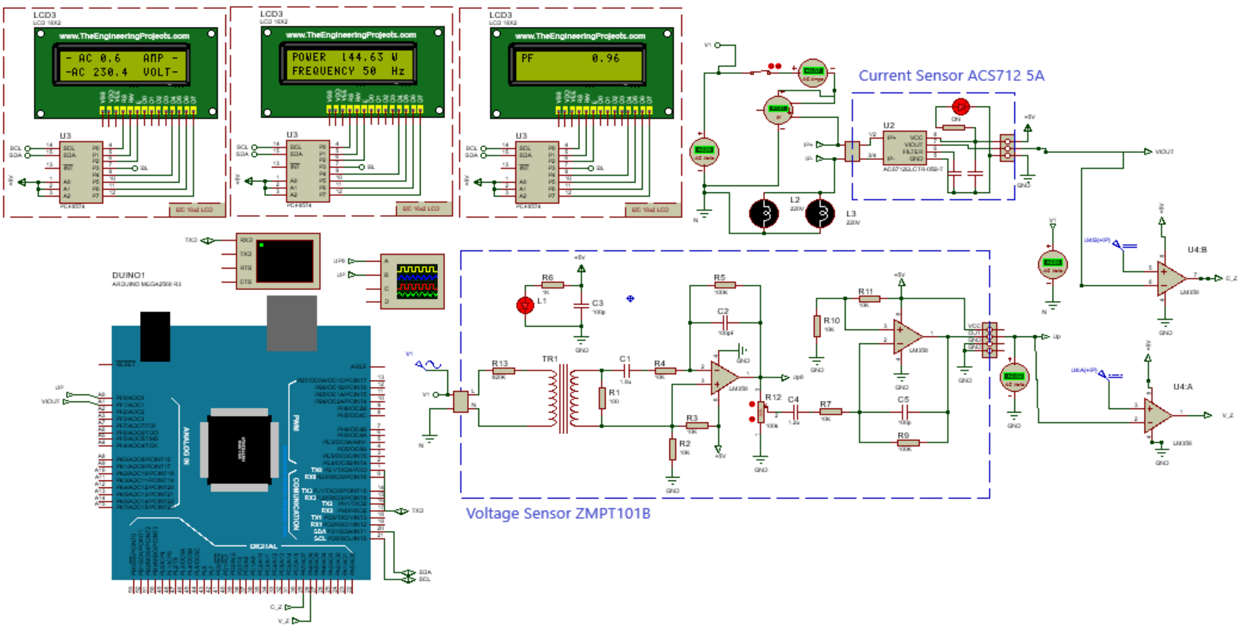

Fig. 3. Simulation of metering system measuring consumption parameters

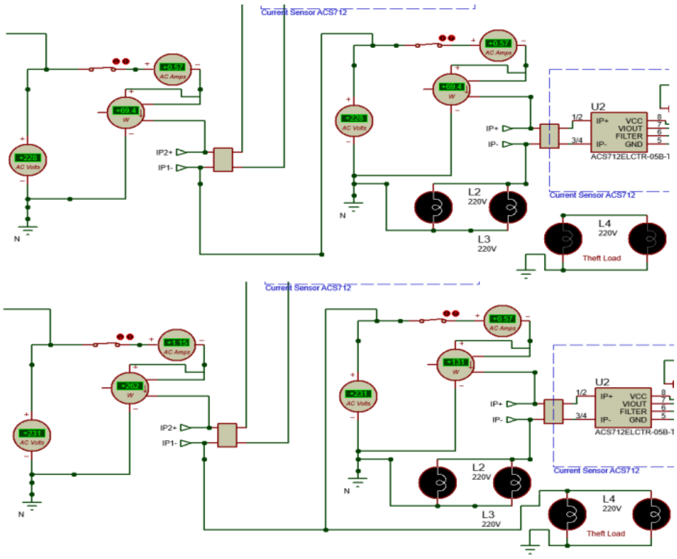

Fig. 4. Theft load detached vs theft load attached

relatively constant at 1.4A and 4V respectively, matching the previously calculated total current of 1360mA. Cursor 2 shows the time taken to discharge the battery at max load as around 15306s = 4.24 hours, matching the calculated time.

V. HARDWARE PROTOTYPING

Fig. 6 shows the End Node and Gateway hardware. The switchboard was for the loads, and the connection on the left was for the mains voltage. It also shows the Raspberry Pi connected to an Internet router. The Power Supply Unit was also constructed and tested in the hardware, visible in Fig. 7.

A. Voltage Measurement

The gain setting mapped 215V input to 2.65V output, which allowed for measuring higher voltages. There was a difference of at most 2V between the sensor reading and the multimeter, which was at most an error of 0.9%. The voltage measurement of the ZMPT101B visible on the HMI, compared to a multimeter is also visible in Fig. 8.

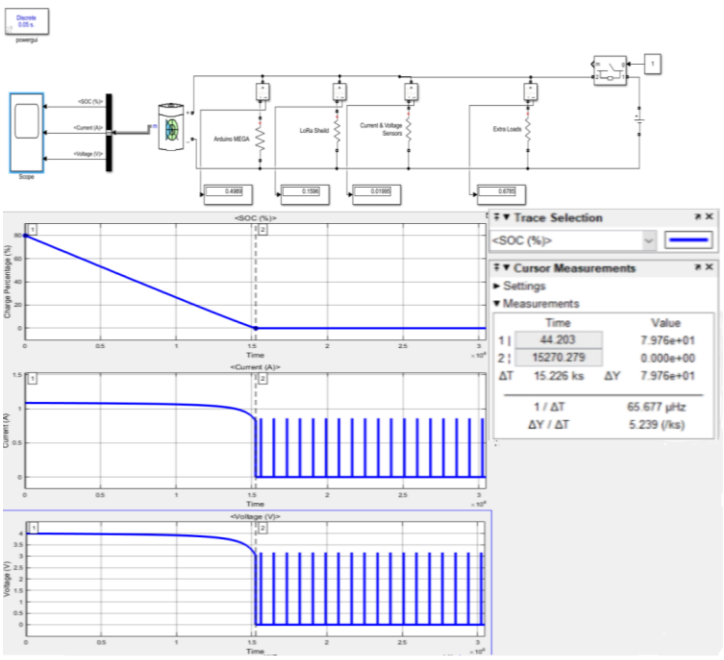

Fig. 5. Simulation of the Power Supply

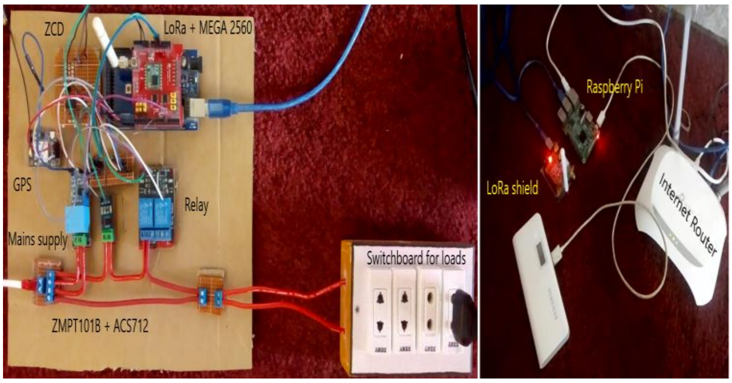

Fig. 6. Hardware implementation of the End Node and Gateway

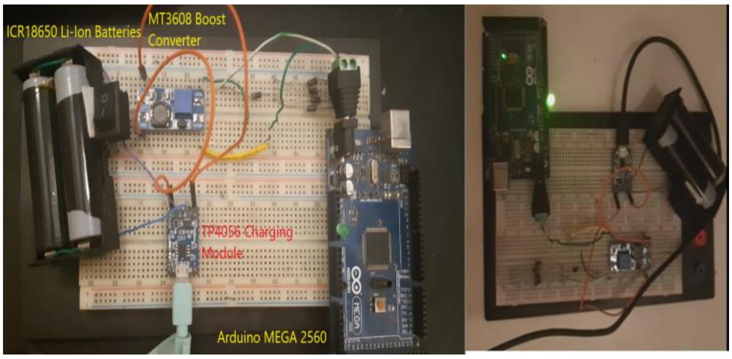

Fig. 7. Implementation of Power Supply Unit

B. Load Test

These tests show waveforms with raw, uncalibrated sensor outputs. The first test was using a Switch Mode Power Supply Laptop Charger. The SMPS uses a Triac for phase control of the AC wave, which produces multiple harmonics. Fig. 9 shows the current and voltage waveforms measured by the sensors. Next was a pedestal fan, which produced a phase difference, with the voltage leading the current, also visible in Fig. 9. Fig. 10 shows the starting current to be higher than normal operation, due to the torque required to set the fan in motion.

C. Frequency Measurement

The square wave zero-crossing detector output is visible in Fig. 11. This was used to find the frequency of the mains input voltage. The frequency calculated from this was 49.5-50.8Hz. An FFT algorithm was also run on the current waveform with the Laptop Charger as the load, to visualize

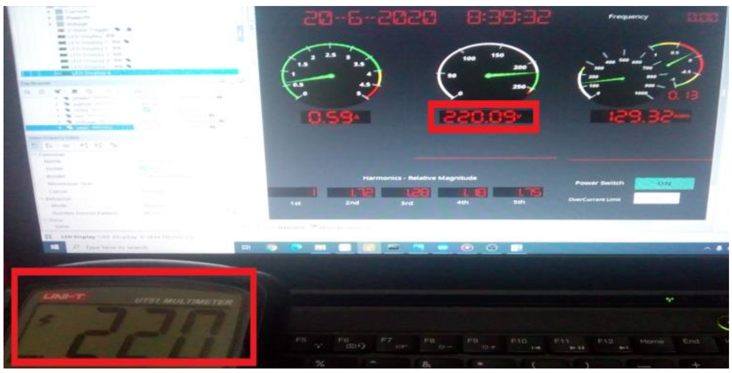

Fig. 8. Voltage calibration of ZMPT101B

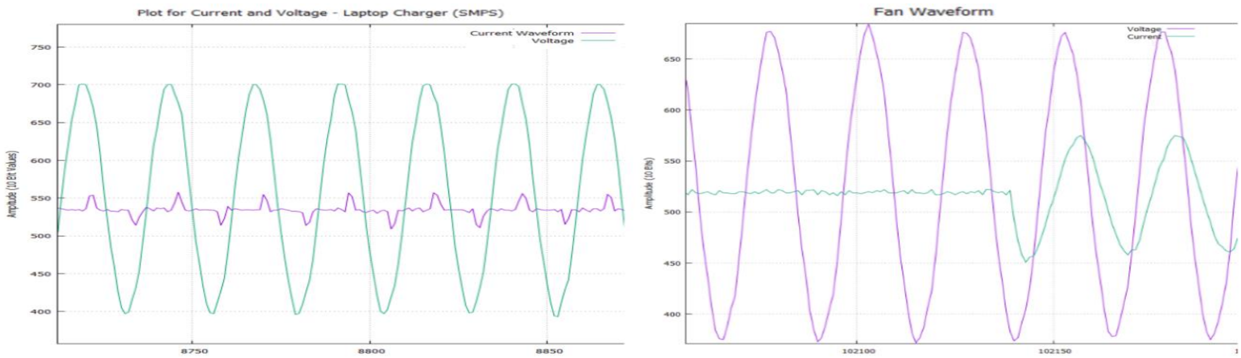

Fig. 9. Laptop charger + Pedestal fan waveforms

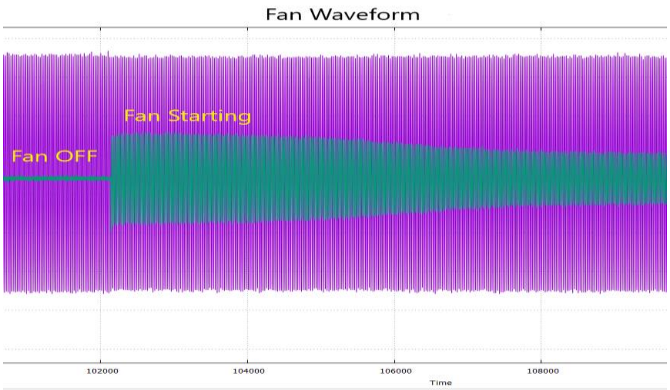

Fig. 10. Fan waveforms when starting

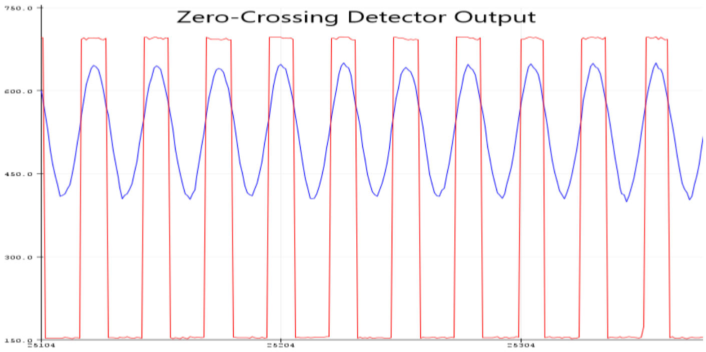

Fig. 11. Zero-Crossing Detector Output

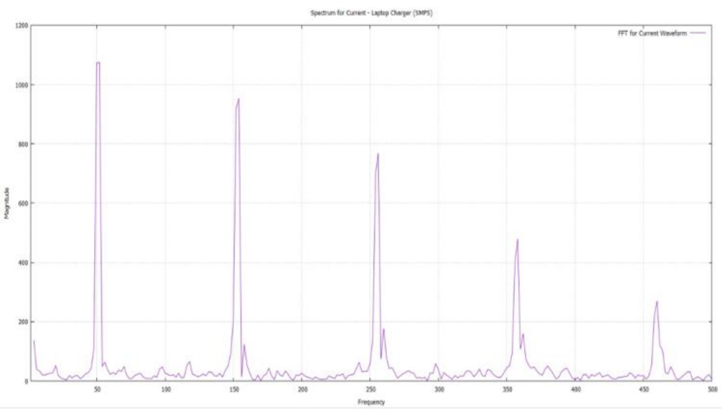

Fig. 12. FFT of the SMPS Current Waveform

the magnitudes of the harmonics, visible in Fig. 12. The peaks had drifted towards higher frequencies, decreasing the reliability of the readings.

D. Gateway, Server, and HMI

The Gateway would receive LoRa data packets containing information of the measured voltage, current, power, GPS time and date, frequency and harmonics from the End Node, parse it into the appropriate data type and upload it to the server through the MQTT protocol. The HMI was updated in real-time (1-2 second lag). Fig. 13 shows the HMI and the Server displaying results. The left side is the pedestal fan load, and the right side is the SMPS laptop charger, which shows increased relative magnitudes for the 3rd and 5th harmonics (also seen in Fig. 12). Graphs for the last 3 minutes were also available, shown in Fig. 14.

VI. CONCLUSION

The proposed architecture effectively measured electricity

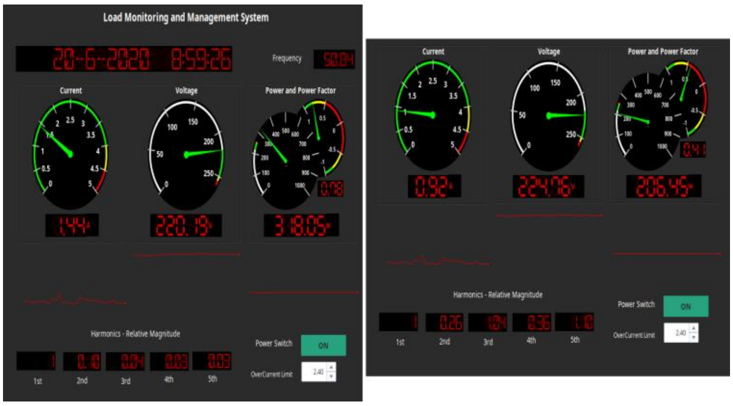

Fig. 13. Server measurements on HMI

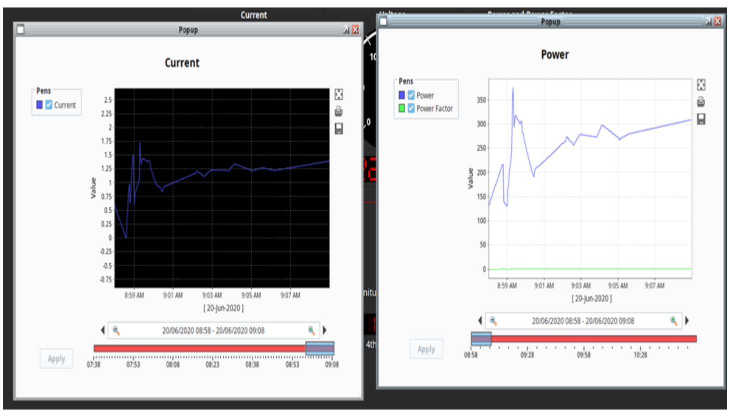

Fig. 14. History of graphs visible on the HMI

consumption parameters, sent them to the Gateway via LoRa communication, and then uploaded them to the SCADA server in real-time. Overall, the project was able to achieve its goal.

Some possible improvements and future work include improving the calibration of the Data Acquisition system to reduce inaccuracies and adding greater security in the LoRa communication to prevent hackers from hijacking the transmission. The system was designed around single-phase power lines, but can also be expanded to multi-phase measurement and analysis. LoRa Mesh Networks can also be explored for increasing the range of the metering devices, and Theft and Fault Detection can be tested on the hardware with multiple meters as well. The same architecture, with different sensors, can be used for measuring and metering other quantities, like water or gas flow rate. Used in conjunction could allow a 3-1 Smart Utility Meter, capable of measuring electricity, gas, and water together. Solar panels, or other renewable sources of energy, could be connected with the meter to incorporate the concepts of energy sharing and net metering.

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