IoT-Based Smart Meter with Energy Theft Detection

M. Muhammad[1], A. Ahmed[1,2], O. Zeyad[1], E. Amr[1], M. Ahmed[1] H. Abdelrahman[1], and Magdy Aboelela[*]
[1] Graduate Engineers, Cairo University, Faculty of Engineering, Credit Hours System, EEE Program, Giza, Egypt
[2]IEEE Member

[*]Correspondence Author, Professor at Cairo University, Faculty of Engineering, Electrical Power Dept., Giza, Egypt, email: aboelelamagdy@gmail.com

***Abstract*—The Internet of Things (IoT) has revolutionized the way we interact with our environment, and the smart meter is one of the most important applications of IoT. This paper presents an IoT-based smart meter designed to measure energy consumption accurately and detect energy theft in real-time. The system is based on the ATmega328p and uses the ESP8266 Wi-Fi module and SIM800 GSM module to establish wireless connectivity and IoT functionality. The smart meter employs AC current and voltage sensors to measure true RMS of power and energy consumption. The system is designed to provide real-time energy consumption data to the utility company, enabling them to manage the power grid more efficiently. Additionally, the system can detect energy theft by comparing the energy consumption data with the expected energy consumption for a given period. The system can also send alerts to the utility company and the end-user in case of any suspicious activity. The proposed IoT-based smart meter can help reduce energy wastage and improve the overall efficiency of the power grid.**

I. INTRODUCTION

Electricity metering is important in utility distribution systems because it measures users' electricity consumption and generates bills, which are a source of revenue. Electricity theft is one of the most serious problems affecting Egypt's power sector; it refers to any activity undertaken by consumers of electricity for them to use electricity without the proper consent of the utility to avoid paying for the energy.

Electricity theft is a major issue around the world, particularly in developing countries. It refers to the illegal use of electricity, which results in losses for the utility companies. Recently, governments have lost about 89.3 billion US dollars per year [1-2]. Electricity theft rates worldwide has been recorded as shown in Fig. 1.

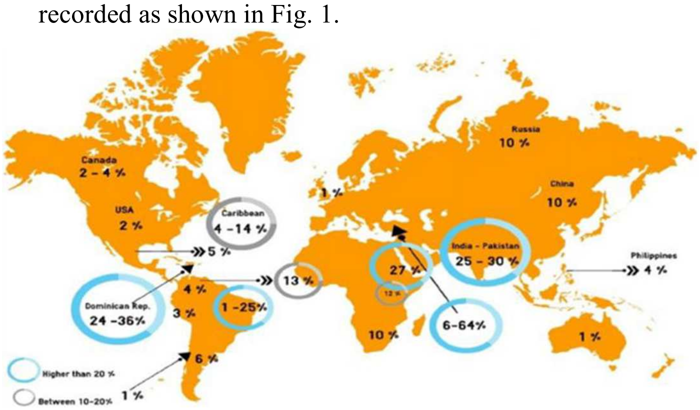

Fig. 1. Electricity theft rates worldwide. (Reproduced with permission from Fehrenbacher 2013)

This paper discusses the IoT-based smart prepaid energy meter as part of a measure to make electricity accessible to all consumers, to overcome the problem of overbilling, meter tampering, fault finding, and to ensure a cost-effective operation, and focuses on the implementation and development of an IoT-based smart meter with energy theft detection. The paper aims to inspect the feasibility and performance of the proposed system design in detecting undesired or anonymous energy consumption that indicates theft. The main objective is to design a system that can accurately calculate the true RMS power and energy consumption using voltage transformers and AC current. The smart meter integrates the ATmega328P microcontroller, ESP8266 Wi-Fi module, SIM800 GSM module to enable wireless connectivity and IoT functionality. The advantage of this system is that a user can understand the power consumed by electrical appliances every while and take additional steps to control them, thereby aiding in energy conservation. The engineering approach introduces the solution that will implement AVR microcontroller that is integrated with Wi-Fi module (ESP8266), GSM module, current and voltage sensors as well as relays for load control extra feature [3-5].

II. PROJECT IMPLEMENTATION

A. Preparation Stage

The project is implemented in multiple phases after getting the required components with consideration of advanced research for power theft detection, as follows:

Measurement modules are tested and checked individually explained as follows:

–Voltage sensor, which is interfaced with the Arduino circuit and by editing the code on Arduino IDE, voltage RMS value can be extracted from the sensor reading that is necessary for power calculations [6-7].

–Current sensor, same steps as voltage sensor, and also current RMS value is extracted from the sensor reading for the power calculations [8-9].

Finally, with the instantaneous RMS values of current and voltage, real power value and true power factor can be calculated accurately, thus the energy consumption can be calculated [10].

Communication modules are tested and checked individually explained as follows:

–Using I2C communication with LCD can improve flexibility and reduce the pin usage which frees up pins in the microcontroller for other uses [11-12].

–Wi-Fi module (ESP8266) can be communicated with through AT, or Hayes, commands through the hardware serial at pins 0,1 of the Arduino UNO.

–GSM module (SIM800L) is interfaced with Arduino UNO and by checking the power requirements it required 5-volts and 2- ampere input, so it is fed using a 12-volts, 2-amperes DC power supply and stepped down to 5-volts using a DC-DC buck converter [13-14].

Selecting *RemoteXY* as an IoT platform for establishing communication systems for the project, *RemoteXY* is Application Enablement Platform (AEP) that is available for free usage and offers a simple method for creating and using a mobile graphical user interface for controller boards to operate through smartphones. The controller contains the interface structure. There is no communication with servers to download the interface when connected. For further cybersecurity protection, the controller downloads the interface structure to the mobile application, turning it into an end-to-end system, which does not require a server to save data but rather works as a buffer online, so that the data of the application design and the data being transmitted to it are always peer-to-peer.

TCP/IP is used by RemoteXY for communication over Wi Fi or Ethernet networks between the microcontroller-based device and the mobile device.

Transceiver module (NRF24L01A RF) uses exclusive communication with the Remote Terminal Unit (RTU) using 2.4 GHz, to send data to the smart meter that compares it and gives feedback via RemoteXY app and SMS [15].

B. How it works

The Smart Meter works by taking reads from the AC Current Transformer of Ratio 5A:5mA as well as from the AC Voltage Sensor *ZMPT101B* through the ADC of the ATMega328p, which is then processed through the measurements function to take samples for every iteration of the super loop, and calculator True RMS value of each as well as extra calculations of Power Factor. The measured values are then updated to the LCD of the meter, using the open source library functions of the I2C LCD configuration, as well as updating the variables of the RemoteXY Platform, which is then sent to the user's phone by the Handler function that communicates with *ESP8266* Wi-Fi Module through AT Commands, and the platform handles the received data to display on the user's phone on the device UI, which is loaded also from the controller in the program. The user is able to control the relay embedded into the meter to allow electricity to the load. The app also stores the power readings with respect to time with every update to the values and, through the online graph feature on the UI, which is saved on the user's application itself with every time the user is connected to the device. A connection flag is added to the LCD of the smart meter indicating if the user is connected to the smart meter as well, which is updated to check if the flag variable of the RemoteXY handler changed as the user is connected. This is illustrated in Fig. 2.

Fig. 2. User Interface Designed for the Smart Meter

A Power Limit can be set by the user to limit his active loads, or when abroad he monitors the load active which must be at minimum. When found otherwise and the load limit is exceeded, the application gives a warning text and beeping sound. A GSM module is added to the project to allow notifications as the load limit exceeds the user using SMS, which is also handled using AT Commands through self-written functions using hardware UART of the controller. The GSM module, since it is connected to the network of the SIM Card, can determine the local network date and time, which is used in the program of the meter to check the billing date, which is calculated also inside the program according to the Energy accumulated with respect to time.

C. Energy Theft Monitoring and Detection

While limiting Power by user is beneficial to limit consumption as well as to detect if something is off to an owned household/unit, a proper theft detection, where the action affects the utility company, must be considered, to rather not penalize users at fault. Energy Theft Detection, in normal, happens between the generation transformer/Switchboard and the targeted households/units, where a cable is extended intersecting from this power line and is used unlawfully by other households or street vendors. Implementing the smart meters with the NRF24 Radio Transceivers as a package and adding a Remote Terminal Unit (RTU), which is also based on ATMega328p, AC Current & Voltage Sensors and NRF24 Transceiver, it can address up to 6 NRF24 at once, which helps in comparing Power from the targeted households and the power calculated at the point of the switchboard or transformer. Fig. 3 illustrates the use of RTU.

According to the readings received from the meters as well as from the RTU, and found that the exceeded power does not add up when compared, with respect to losses and other factors, it can address which meter that may have theft on its line or possible power leak, and informs the utility company through this meter as well as the RTU using advanced communications. Such infrastructure can be implemented in parallel to new cities and also current cities as upgrades, unifying smart meters to buildings as a package. The complete system is displayed in Fig. 4. The hardware connection of the integrated system is depicted in Fig. 5.

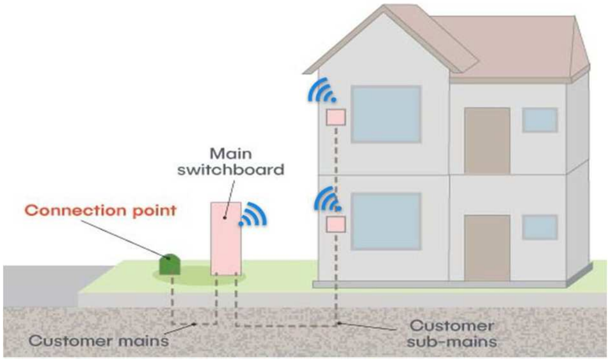

Fig. 3. Smart meters and RTU communication for Theft Monitoring

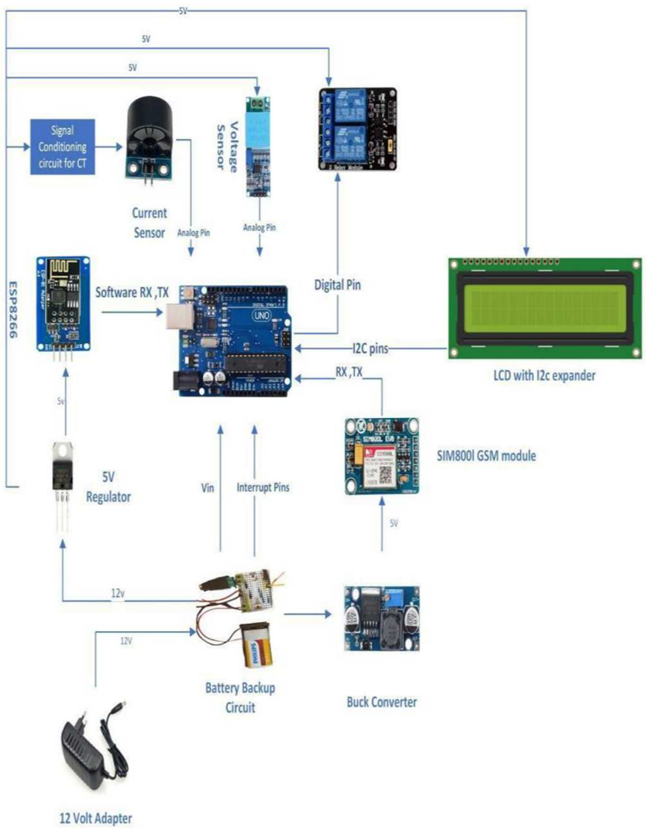

Fig. 4. IoT Smart Meter Schematic Design

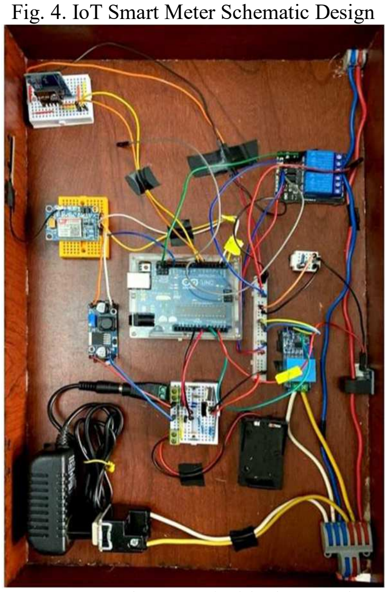
Fig. 5. Components Placement inside the Wood Enclosure

III. Comparing Designs

As reviewed, many papers which present designs with the same approach were limited to only activating the components and using the GSM module for the SMS notification to the users. While these designs were tackled in different papers, our design has approached the way that can be independent considering the powering and backup power, as well as attaching every component to a body in its prototype design.

The theft detection that was mentioned in some papers reviewed were only limited to the power and energy consumption limitation by the user, as an explanation for that, if the consumption is higher than a certain limit it calls for theft using the SMS system as well as mobile application using Wi-Fi module if any. Other papers mentioned rather using advanced theft detection like Power Line Communication, and while they have researched the possibility of such implementation, our design in its theoretical analysis depends completely on IoT technologies using Radio Transceivers between different points along the power line, at the time which the smart meters periodically send their instantaneous power consumption in their households to a Terminal Unit that is placed before the households and compares the power of the meters to its instantaneous power, so as to check on the power that is served to the users and call for a fault or a theft if the power values do not match on a certain line in every certain period of time.

Regarding the infrastructure that can be used in, this theft detection method is quite optimistic, but ensures the data to be sent in a private domain between the smart meters and the terminal unit fast enough with the needed data effectively and efficiently, and said implementation is planned in the future of such project with future versions and will be having the findings and conclusion of the success or failure of the system in the real life application.

This theft detection technique is very hopeful in terms of the infrastructure that can be implemented in, and exact findings and analysis were short in this theoretical, but ensures the data to be sent in a private domain between the meters and the terminal unit fast with the needed data effectively and efficiently, and said implementation is planned in the future of such project with future versions and will having the findings and conclusion of the success or failure of the system in the real life application.

IV. Learnt Outcomes

There are several outcomes that are considered to be learnt for future modifications on this project which are as follows: Consider working with more power development boards instead of Arduino UNO like STM32 or Raspberry Pi or even Arduino Mega that uses ATmega2560 that have more memory so as to add other considerable features to improve the product overall effectively and efficiently.

MQTT protocol (Message Queuing Telemetry Transport) is an extremely simple and lightweight messaging protocol (subscribe and publish) designed for limited devices and networks with high latency, low bandwidth, or unreliable networks. When considering such a protocol and the way of interfacing it and the memory that will be consumed.

Blynk also can be considered in case MQTT is not the best choice for the project as Blynk offers connection to several devices up to three devices for a free account.

Every module coding has to be tested alone before integrated with other modules. This process is called unit testing. Thus, after integration, all features tested together will not affect each other.

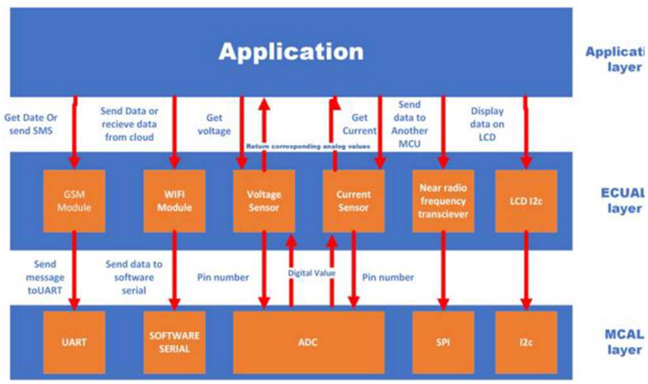

Fig. 6. Layered Model

Sticking to the layered model proposed with the project as it will be easier to upgrade modules or change them without affecting the application code, and changing applications will also be easier as the modules will be finished so the modules will be only included. The interaction of system units is summarized in Fig. 6.

V. Conclusion

One of the main benefits of smart meters with theft detection technology is that they can help reduce losses for energy providers. By detecting and preventing theft, energy providers can save money and reduce the need for expensive investigations and repairs. This can lead to lower prices for consumers and a more efficient and sustainable energy system overall.

In addition to detecting theft, smart meters can also provide valuable insights into energy consumption patterns. By analyzing this data, energy providers can identify areas where energy efficiency improvements can be made, which can help reduce overall energy consumption and lower costs for consumers.

Smart meters with theft detection technology are still relatively new, but they are rapidly gaining popularity and being implemented in many regions worldwide. As technology continues to evolve, we can expect even more advanced features and capabilities that will further improve the efficiency and effectiveness of energy management.

However, there are also some concerns about privacy and security when it comes to smart meters. Some people are worried that the data collected by smart meters could be used for nefarious purposes or that the technology could be hacked. Although this is covered in our project, these concerns will need to be addressed as smart meters become more widespread.

Acknowledgment

We are grateful to CUFE for providing us with the opportunity to conduct our project and for all the resources and support they provided.

References

[1]. World loses $89.3 billion annually to electricity theft - news. Empowers. (n.d.). Retrieved April 29, 2023, from https://eepower.com/news/world-loses-89-3-billion-annually-to electricity-theft/

[2]. Electricity theft rates worldwide. (reproduced with permission from ... (n.d.). https://www.researchgate.net/figure/Electricity-theft-rates Worldwide-Reproduced-with-permission-from-Fehrenbacher 2013_fig1_325927844

[3]. Le, K. (2018). Designing and Implementing an Intelligent Home Automation System Based on Arduino and Android Smartphone. Journal of Electrical and Computer Engineering Innovations, 6(1), 36-48.

[4]. Mohsen, H., Hosseini, M., & Jahanshahi, H. (2016). Home Automation System Based on Raspberry Pi and Arduino. In 2016 3rd International Conference on Control, Instrumentation, and Automation (ICCIA) (pp. 50-54). IEEE.

[5]. Singh, A., & Bajpai, S. (2019). IoT based Smart Home Automation using Raspberry Pi and NodeMCU. In 2019 IEEE 9th International Conference on Power Systems (ICPS) (pp. 277-282). IEEE.

[6]. Hareendran, T. K. (2022, July 7). ZMPT101B AC Voltage Sensor Module Primer. ElectroSchematics.com. https://www.electroschematics.com/voltage-sensor/

[7]. Akbari, W. by M. (2021, June 19). Interfacing ZMPT101B AC voltage sensor module W/ Arduino. Electropeak. https://electropeak.com/learn/interfacing-zmpt101b-voltage-sensor-with arduino/

[8]. WatElectronics. (2023, January 31). ZMCT103C precision current sensor: Datasheet & its applications. WatElectronics.com. https://www.watelectronics.com/zmct103c-precision-current-sensor/

[9]. Maleki, W. by M. (2021, June 19). Interfacing ZMCT103C 5A AC current Transformer module with Arduino. Electropeak. https://electropeak.com/learn/interfacing-zmct103c-5a-ac-current transformer-module-with-arduino/

[10]. Fluke. (2023a, March 29). What is power factor? How to Calculate Power Factor Formula. Fluke. https://www.fluke.com/en/learn/blog/power-quality/power-factor formula

[11]. Kaur, H., & Singh, N. (2019). PCF8574 I2C Interface IC. In Internet of Things: Architectures, Protocols and Applications (pp. 125-133). Springer.

[12]. PCF8574; PCF8574A remote 8-bit I/O expander for I2C-bus with interrupt. (n.d.). Retrieved April 29, 2023, from https://www.nxp.com/docs/en/data-sheet/PCF8574_PCF8574A.pdf

[13]. SIM800L v2.0 5V wireless quad band GSM GPRS module PCB antenna. Electra. (2023, April 2). https://electra.store/product/sim800l-v2-0-5v-wireless-quad-band-gsm gprs-module-pcb-antenna/

[14]. SIM800L v2 tutorial with Arduino. miliohm.com. (2021, December 31). https://miliohm.com/sim800l-v2-tutorial-with-arduino/

[15]. Vjsam, Dejan, Richard, Anders, Jambotkar, S., Duke, J., Shaun, Dola, Mamad, Lucas, Rudolf, Sveto, Joseph, C., Herbert, Dawg, M., Landau, S., Kushwaha, D., Vedat, Caldwell, B., … Manish. (2022, February 27). NRF24L01 – how it works, Arduino Interface, circuits, codes. How to Mechatronics. https://howtomechatronics.com/tutorials/arduino/arduino-wireless communication-nrf24l01-tutorial/