Open Source SCADA Systems for Small Renewable Power Generation

by

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Abstract

Low cost monitoring and control is essential for small renewable power systems. While large renewable power systems can use existing commercial technology for monitoring and control, that is not cost-effective for small renewable generation. Such small assets require cost-effective, flexible, secure, and reliable real-time coordinated data monitoring and control systems. Supervisory control and data acquisition (SCADA) is the perfect technology for this task. The available commercial SCADA solutions are mostly pricey and economically unjustifiable for smaller applications. They also pose interoperability issues with the existing components which are often from multiple vendors. Therefore, an open source SCADA system represents the most flexible and the most cost-effective SCADA solution. This thesis has been done in two phases. The first phase demonstrates the design and dynamic simulation of a small hybrid power system with a renewable power generation system as a case study. In the second phase, after an extensive study of the proven commercial SCADA solutions and some open source SCADA packages, three different secure, reliable, low-cost open source SCADA options are developed using the most recent SCADA architecture, the Internet of Things. The implemented prototypes of the three open source SCADA systems were tested extensively with a small renewable power system (a solar PV system). The results show that the developed open source SCADA systems perform optimally and accurately, and could serve as viable options for smaller applications such as renewable generation that cannot afford commercial SCADA solutions.

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List of Abbreviations and Symbols

SCADA	Supervisory Control and Data Acquisition
IoT	Internet of Things
HMI	Human Machine Interface
PLC	Programmable Logic Controller
MTU	Master Terminal Unit
RTU	Remote Terminal Unit
FID	Field Instrumentation Device
REST	Representative State Transfer
API	Application Programming Interface
GUI	Graphical User Interface
ADC	Analog-to-Digital Converter
I/O	Input/Output
PV	Photovoltaic
MQTT	Message Queuing Telemetry Transport
OLED	Organic Light-Emitting Diode
MPPT	Maximum Power Point Tracking
HPS	Hybrid Power System
HOMER	Hybrid Optimization of Multiple Energy Resources
BEOpt	Building Energy Optimization

Chapter 1

Introduction and Literature Review

1.1 Introduction

Electricity has become one of the basic amenities of man due to its wide usage in various aspects of life. With the recent quest for a greener environment, there is an extended use of more renewable energy and less fossil fuel for power generation. Thus, more renewable generation sources such as solar photovoltaic and wind turbines are continuously being injected into today's power systems to form hybrid power systems, and to provide electricity for mankind. This trend is expected to continue in the coming decades [1]. However, an increased ratio of renewable generation sources may cause several issues in the power grid. To reduce these issues, energy storage systems are often incorporated into the renewable generation systems. Examples of such issues include the following. First, difficulty in system frequency control due to fluctuations in the outputs of renewable generation sources. By convention, frequency control is mostly managed by the output change capability of thermal generators and this implies inefficient operation as thermal generators are not operated to full capacity when used for frequency control purposes [1]. This is so because renewable generating units themselves only supply a negative margin in most cases, thus with greater penetration of renewable generation, there is a further decrease in the efficiency of thermal generators as they try to increase the output margins. Energy storage systems can mitigate this output fluctuations in renewable generation systems, which will lead to a reduction in the margins of thermal generators, and thus lead to higher efficiency in their operations. Secondly, renewable energy is affected by weather conditions and since weather conditions are largely unpredictable, the output is undependable. This makes connecting them to the grid difficult. Although some measures are available to cope with these challenges such as increasing the amount of renewable generation installed (overcapacity), and spreading renewable generators over a wider geographical area to take advantage of varying weather conditions from place to place and of smoothing effects expected from the complementary wind and solar generators, energy storage systems represent the most cost-effective and reliable measure considering the cost of extra renewable generation and the challenges of constructing new transmission facilities [1].

Furthermore, it is important to ensure the correct balance between electricity supply and demand as an imbalance will damage the stability and quality (voltage and frequency) of the power supply. Due to the need for a continuous and flexible supply in the power system to avoid these issues, generating plants are usually equipped with two essential functions, in addition to their basic generating function. First, a "kilowatt function", to generate enough power (KW) when necessary. Secondly, a frequency control function, fine-tuning the output to follow the continuous fluctuations in demand, using extra power from the "kilowatt function" when necessary. However, renewable energy facilities such as solar and wind do not posses both a KW function and a frequency control function unless they are suitably modified. Such modifications could be in decreasing power (negative power margin) or a phase shift inverter. Energy storage systems in renewable energy facilities help to compensate for such difficulties with a KW function and a frequency control function. Also, in the event of failures in the power network, energy storage systems help in the continuous supply of power to consumers [1, 2]

From the discussions above, the importance of renewable power generation systems, as well as their interconnected energy storage systems cannot be overemphasized. Thus, there is a need to implement a safe, timely, reliable and sophisticated means of managing the operations of the entire generation system. While it may be necessary to have local means of implementing this management, it is equally important to have a coordinated control either as a standalone system or with other components in the grid when grid-wide applications are desired. In most cases, power electronic converters provide a means of connecting the renewable generation and energy storage systems to the grid. Power electronic systems also help in the synchronization of the various generating systems to the utility grid, including the converter which modulates the waveforms of current and voltage to a level that can be directly fed into or taken from the grid. Sometimes, the converter could be connected to a transformer to provide the required voltage before the grid connection, thus increasing the efficiency of the entire system [1]. The converter is managed by a controller which defines the set points and parameters of the renewable generation and energy storage systems, including the magnitude of active and reactive power, and state of charge (SOC) of the storage system. In many applications, the energy storage systems, the power electronic converters and other devices connected to the grid are from multiple manufacturers and vendors, and so compatibility and interoperability of the systems in terms of communications and electrical connections are imperative. Furthermore, because these components are usually distributed over large geographical areas, sometimes in harsh environments, such as deep offshore and swamps, the control strategy is even more critical. Thus, due to this complex nature of the entire system and control strategies, local workforce may not be cost-effective, hence, there is the need for a reliable system for managing the entire power generation system remotely [1, 2]. In this thesis, Supervisory Control and Data Acquisition (SCADA) system is proposed for the remote monitoring and control of the renewable power generation systems. In the proposed SCADA system, key parameters from the power generation system such as Current, Voltage, and Power are measured, processed, and transmitted to the control platform, and based on the real-time parameters, and the perceived conditions of the entire network, the control platform, which is an element of the proposed SCADA system, is able to manage the power generation system for optimum operation.

1.2 Background

SCADA is an acronym formed from the first letters of the term “Supervisory Control and Data Acquisition”. It is a technology that enables a user to collect data from one or more distant facilities and/or send limited control instructions to those facilities. The major function of SCADA is for acquiring data from remote devices such as batteries, valves, pumps, transmitters, etc. and providing overall control remotely from a SCADA Host software platform [3, 4, 6]. SCADA makes it unnecessary for an operator to be assigned to stay at or frequently visit these remote locations when the facilities are operating normally. First developed in the 1950s, SCADA has evolved from its use in telephone relay systems and minicomputers [3]. The first “SCADA” systems utilized data acquisition by means of panels of meters, lights and strip chart recorders. Supervisory control was exercised by the operator manually operating various control knobs. These devices were and are still used to do supervisory control and data acquisition on plants, factories and power generating facilities [3–8]. Below is an overview of the generations of SCADA Architectures [5]:

- **First Generation - Monolithic SCADA:** The original SCADA system was created during a time when networks did not exist. It involved standalone systems with virtually no connectivity to other systems. It was implemented using two identically equipped mainframe systems where Wide Area Networks (WANs) communicated with only Remote Terminal Units (RTUs). The system used mostly proprietary software, and redundancy was achieved by the connection of a back-up mainframe to all the RTUs. The Monolithic SCADA architecture is shown in Figure 1.1.

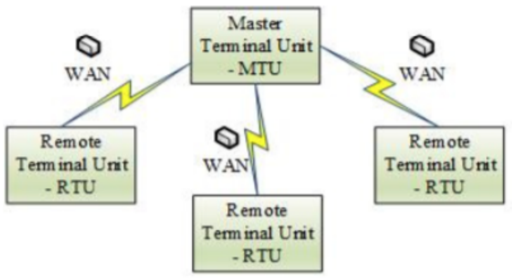
Master Terminal Unit - MTU
WAN
WAN
WAN
Remote Terminal Unit - RTU
Remote Terminal Unit - RTU
Remote Terminal Unit - RTU

Figure 1.1: First Generation - Monolithic SCADA [5].

- **Second Generation - Distributed SCADA:** The second generation of SCADA took advantage of LAN technology for distribution of system functions and processes across multiple systems. The systems were cheaper and more miniaturized than its predecessor. In almost real-time, information was shared across stations that each had their own tasks. Distribution increased the processing power, reliability and redundancy of the system, but it was not capable of reaching beyond the limits of the local environment, and the LAN Protocols used were mostly proprietary. The Distributed SCADA architecture is shown in Figure 1.2.

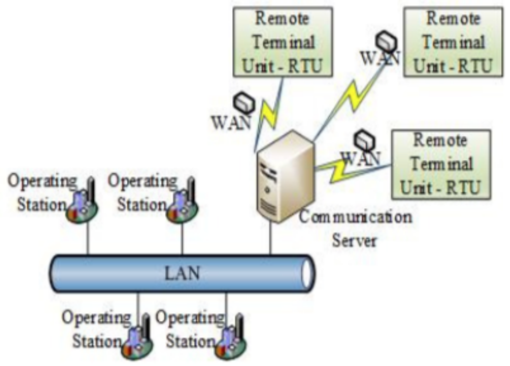

Figure 1.2: Second Generation - Distributed SCADA [5].

- **Third Generation - Networked SCADA:** This generation of SCADA involved open system architecture with multiple networked systems communicating over WANs, sharing master station functions and utilizing PLCs for monitoring purposes. With distributed SCADA functionality across a WAN, this generation was much like the 2nd generation. However, unlike the 2nd generation, it was able to connect to the internet and third-party peripherals using Internet Protocol (IP). This SCADA architecture is still in use today. However, due to technological advancements, SCADA systems have now developed using advanced software, high performance microprocessors and wireless, cloud and Internet of Things (IoT) technologies, leading to the fourth generation SCADA. The Networked SCADA architecture is shown in Figure 1.3.

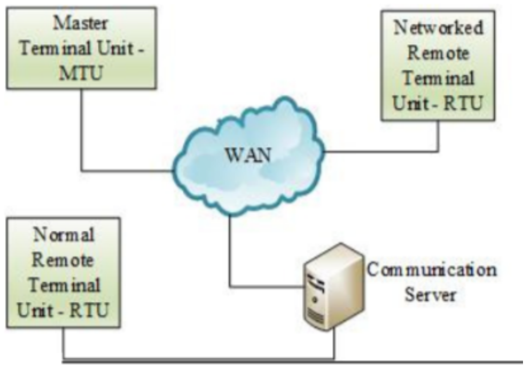
Master Terminal Unit - MTU
Networked Remote Terminal Unit - RTU
WAN
Normal Remote Terminal Unit - RTU
Communication Server

Figure 1.3: Third Generation - Networked SCADA [5].

- **Fourth Generation - Internet of Things (IoT) based SCADA:** Combining the conventional SCADA with the cloud, IoT provides SCADA systems with an alternative to PLCs and involves the use of data modelling and complex algorithms, thereby resulting in increased data accessibility, flexibility, availability, scalability, and cost efficiency. The proposed open source SCADA systems in this thesis will be built under this IoT-based architecture as will be seen later in this work. The Internet of Things SCADA architecture is shown in Figure 1.4.

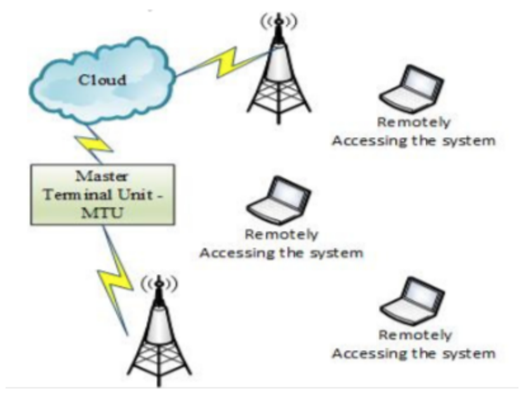
Cloud
Master Terminal Unit - MTU
Remotely Accessing the system
Remotely Accessing the system
Remotely Accessing the system

Figure 1.4: Fourth Generation - Internet of Things (IoT) based SCADA [5].

1.2.1 Why is SCADA Needed?

SCADA being one of the vital technologies for automation and with common, tedious tasks, being increasingly automated rather than performed by humans, SCADA has become ubiquitous [3,4]. More specifically:

- SCADA gives us the ability to remotely control different process systems in various locations.
- It helps to create logs and reports about the current and previous states of process systems.
- It gives us the ability to send important information and data to Engineers and Operators in real time.
- It helps to reduce/eliminate human errors.

Essentially, a SCADA system performs four basic functions:

- Data Acquisition
- Networked Data Communication
- Data Presentation

- Monitoring and Control

1.2.2 Elements/Levels of SCADA Systems

There are four basic elements or levels of a SCADA system which allow it to perform the various functions outlined in Section 1.2.1 [3, 4]. They are summarized below:

- **Field Instrumentation Devices (FIDs):** Like Tom DeMarco rightly said, "you cannot control what you cannot measure", meaning that instrumentation is a key component of a safe and optimized control system. These devices include Sensors, Actuators, Transmitters, and so on, which are directly connected to the process systems being managed, and they help to measure the various control parameters such as current, voltage, power, temperature, pressure, state of charge, etc.

- **Remote Terminal Units (RTUs):** These are small computerized units, micro-controllers, micro-processors (such as Programmable Logic Controllers (PLCs)), etc. deployed in the field at specific sites and locations, and they help to collect the control information locally from the field instrumentation devices, process the information and parse them on to the master station for human machine interactions.

- **Master Terminal Units (MTUs)/SCADA Host Platforms:** These are larger computer consoles or servers that serve as the central processor for the SCADA system. At the heart of this unit is the device that issues all the commands, gathers all the data, stores the necessary information, parses other information to the associated systems, interfaces with the various operators of the process facilities and provides a human machine interface (HMI) to the administrator where the system can automatically be monitored and managed in response to the FID (sensor) inputs.

- **Communication Networks:** These help to connect and transmit data from the field-based RTUs/PLCs to the SCADA Host Platform usually located remotely at the field office or central control centre using various communication protocols such as TCP/IP, Ethernet, Wi-Fi, Fieldbus, Modbus, Distributed Network Protocol (DNP), Profibus, DirectNet, and so on.

1.2.3 Applications of SCADA

SCADA finds applications in various fields, including [3]:

- Electric Power Generation, Transmission and Distribution
- Oil and Gas Production Facilities
- Buildings, Facilities and Environments.
- Mass Transit
- Water and Sewage
- Traffic Signals

1.2.4 Desired Characteristics in a SCADA System

In order for a SCADA system to effectively perform the enumerated functions above, some important characteristics are necessary in the SCADA system. They include the following [9]:

- **Dynamism:** This means that SCADA nodes are not static, but flexible to allow the connection of new nodes and disconnection of existing nodes.
- **Retrofit:** SCADA solutions should allow upgrading/updating and the addition of new technologies/features to the existing installations.

- **Ease of Installation/Use:** : SCADA systems should be easy to deploy and to use. For instance, sensors should not need a separate energy source and the system should have wireless capabilities to reduce the cost of installing a monitoring network.

- **Redundancy:** There should be redundancy in nodes to increase the reliability of the SCADA system.

- **Low Power Consumption:** Since a SCADA system is required to operate 24/7 so as to effectively monitor the process facility being managed, it is important that the power consumption is as minimal as possible. This will help to keep the operating cost of the system within a reasonable range.

- **Reliability and Availability:** A SCADA system for a renewable power generation system, as well as its associated energy storage systems must be highly reliable as a failure in such a SCADA system could affect the overall power system stability since the renewable generation system and the energy storage systems are important components of a hybrid power system and play a key role in ensuring the stability of the entire system. SCADA failures are said to occur in such systems when an operator is unable to retrieve data from or issue control commands to the primary plants associated with one or more busses [10]. A. G Bruce [10] presented a method of evaluating SCADA system reliability using aggregate assessment of system reliability which can define reliability in terms of absolute cost. In another development, H. Guozhen et al. [11] proposed possible solutions for SCADA system communication reliability using PV power plants as a case study. In their work, the authors believed that the reliability of a SCADA system is mainly affected by communication security and device failure.

- **Security:** This is discussed in Section 1.2.5 below:

1.2.5 SCADA System Security

Security in a SCADA system is a serious issue both from the operational point of view and economic point of view as the resultant unavailability of the critical infrastructure being managed in the events of attacks can disrupt the related operations which could cost a huge amount of money. Conventional SCADA systems already lack proper security measures; however, with the integration of complex new architectures for the new Internet based on the concepts of IoT, cloud computing, mobile wireless sensor networks, and so on, there are more issues at stakes in the security and deployment of these classical systems [5]. It is a general belief that the conventional SCADA system was not originally built to operate within the enterprise environment. Many therefore believe that the interconnection of SCADA and business systems across the enterprise network pose the greatest threats to SCADA as the SCADA components are conventionally unable to deal with the exposure to viruses, worms, and malware that are commonly found today within the enterprise network [12]. Even though the convergence of SCADA systems and control networks into conventional IT systems has widened the SCADA security vulnerability spectrum, the benefits of interconnecting SCADA and enterprise network are numerous, especially with the new IoT-based architecture, and so tackling the related security challenges is the right step to take. Many literatures have reviewed the security threats in a SCADA system, each proposing various solutions. S. D. Antón et al. [13] have presented the security challenges in the classical SCADA system. In their work, they highlighted the common attacks at the various levels of the SCADA system. These are summarized below:

- **Attacks on RTUs/PLCs:** In contrast with office IT systems which mostly handle data, PLCs/RTUs control cyber-physical systems such that they operate and interact with devices in the real world. Therefore, attacks on these devices have an impact on both physical entities and the entire operations. Attacks on PLCs/RTUs include unauthorized execution of malicious remote or local codes, unauthorized data extraction, partial or full degradation of the availability of a service or resource, and maliciously obtaining higher privileges on the system.

- **Attacks on Communication Network/Fieldbus Level:** Industrial networks support a vast landscape of fieldbus communication protocols both proprietary and open source, including Modbus, Profibus, CAN, Ethernet, Local Interconnect Network, Media Oriented System Transport, FlexRay, Powerlink, etc. Each of these protocols has its security flaws. Such attacks include Man in the Middle (MitM) and DoS. Authentication and Encryption are some possible solutions to these kinds of attacks but even so, they are not 100% efficient [13].
- **Attacks on Wireless Systems:** Some wireless communication protocols used in industrial environments for SCADA systems include Bluetooth Low Energy, ZigBee, Z-Wave, Radio Frequency Identifier, Long Range Wide Area Network (LoRa), and Wireless Local Area Network. Since there is no physical access control to the wireless channel, an adversary within the range of the wireless signal can listen to the communication and explore its vulnerabilities to deploy various attacks such as MitM and DoS [13].
- **Physical or Hardware Attacks:** These are among the most difficult forms of attacks to handle as an adversary with physical access to a device or system could easily inflict damage on the device, rendering it unusable and creating a DoS. These also include attacks on embedded devices such as PLCs, where input and sensor values are falsified, leading to undesired system behaviours [13]. An example of such attacks is *Ghost in the PLC* attacks [13]. There are also other attacks associated with office IT infrastructures such as *phishing and spear phishing*.

Elsewhere, S. Rautmare in literature [14] classified security threats associated with SCADA systems more generally into Application exploits, Backdoor attacks, Operating system (OS) exploits, Authorized user exploits, Configuration change exploits, and Tampering. According to the author, some of the hard SCADA system security challenges include [14]: (1) Disruption of process through acquiring control of SCADA network, (2) Difficulty in detecting illegal configuration changes in real time, (3) Insider threat, (4) Integration, (5) Performance and cost of the chosen security solution, (6) Security threats from open, unbounded and interconnected networks, (7) Network latency and response of control system network to the security solution. In addition to these security challenges stated above which classical SCADA systems face, literature [5] presented some of the security challenges involved in the new IoT-based SCADA systems. These security challenges include [5]: (1) Data on the cloud is only separated internally since the same cloud can be accessed by other clients, (2) Difficulty in keeping track of data logging in the cloud-based system, (3) The lack of proper authentication and encryption mechanisms for IoT-based SCADA systems, (4) Difficulty in implementing proper solutions for protecting the embedded devices at the core of industrial IoT-based SCADA systems, (5) SCADA system applications running on the cloud can be easily searched and abused by attackers, (6) Security threats from other web applications in the cloud, (7) The SCADA system integrated into the cloud will have all the same risks as a typical cloud infrastructure, such as vulnerabilities from the cloud and external individual service providers, (8) System commands and information can be modified, sniffed, lost, or spoofed during communication as the reliance on cloud communication makes the SCADA systems more open.

Furthermore, the author in [14] proposed some recommendations to improve upon the conventional SCADA system security, including the following: (1) Implementation of a security policy, (2) Enabling inherent security features of SCADA components, (3) Disabling unused ports and services, (4) Implementing audits at regular intervals, (5) Defining information security roles and responsibilities, (6) Evaluating information security risk profile,

(7) Establishment of change and configuration management process, (8) Deploying an effective intrusion detection system/intrusion prevention system, (9) Ensuring restricted internet access in critical process control area and associated machines, (10) Isolating business traffic from process control network, (11) Ensuring that only process control applications are running over SCADA servers, (12) Ensuring secured communication tunnels, (13) Use of multi-factor authentications, and (14) Identifying unguarded access points. In addition to these classical SCADA system security recommendations, literature [5] presented more recommendations to specifically tackle the security challenges in the IoT-based SCADA systems. They include: (1) Network segregation, (2) Continuous monitoring and analysis, (3) Log analysis, (4) Network traffic monitoring, (5) Memory dump and file integrity analysis, (6) Regular update and patching, etc. In this thesis, some of these recommendations are considered in developing the IoT-based open source SCADA system solutions.

1.2.6 Classes of SCADA Systems

Generally, there are two classes of SCADA hardware and software; Proprietary (Commercial) and Open Source.

- **Proprietary (Commercial) SCADA:** A Proprietary system is one in which all major components are from one manufacturer and the standards are often specific to that system and developed by the manufacturer [6]. Companies develop Proprietary SCADA Hardware and Software systems which they sell as turnkey solutions. With a Proprietary SCADA system, the responsibility for system reliability and security rests solely with the manufacturer, which leaves the user vulnerable to a single manufacturer/supplier as the manufacturer/supplier could be slow to respond to technological changes in a subsystem of the SCADA system. The customer is also at risk if the manufacturer/supplier goes out of business. This solution is largely expensive since the manufacturer/supplier is not under the same competitive pressure to keep prices down after the initial sale [6]. There is also the problem of flexibility with the already existing devices and network. For example, in a large Electrical Utility system, the devices in the SCADA system are required to communicate with all other devices connected to the network, and if such devices are from different vendors, then the SCADA must support each vendor's protocol and the implementation of such a system increases costs and requires more engineering time. Known proprietary SCADA manufacturers/suppliers include Siemens, Allen Bradley, General Electric, Emerson, Schneider Electric, Modicon, Mitsubishi, Omron, and so on.

- **Open Source SCADA:** An Open Source system allows a user to "mix and match" components and choose the most appropriate from several suppliers [6]. The user enjoys greater flexibility as the user is not beholden to a single supplier. This means that with an Open Source system, no one supplier is responsible for overall system performance. In an Open Source SCADA system, the major components adhere to certain standards which allow them to be interchanged with similar components manufactured by others to the same standards. These standards govern the interconnections between major system components such as Instrumentation and Remote Terminal Units (RTU) (covering connection types, contact ratings, isolation, current levels, voltage levels, etc.); RTU and communications bearer (covering impedance, communication protocols, signalling techniques and frequencies); and communications bearer to Master Station [6]. There are a few open source SCADA systems available on the market today, each with its strengths and weaknesses. In this thesis, taking some of the security recommendations presented earlier into consideration, various low-cost, open source SCADA systems are designed, developed and implemented. The proposed SCADA systems are based on the Internet of Things (IoT) SCADA architecture as will be seen later in this work.

1.3 Literature Review

The research communities all over the world have been working assiduously to solve the problems associated with proprietary SCADA systems, and to offer various open source remote monitoring and control solutions using a combination of open source hardware, servers, software and IoT platforms. However, each of these solutions has its flaws, some of which tend to outweigh the accrued benefits of the resulting SCADA system. The related works under the various open source elements or categories are presented below:

1.3.1 Open Source Hardware

Some of the available open source hardware include PLCs, PIC micro-controllers, and PCs. Their related SCADA solutions in literatures are presented below:

1.3.1.1 PLC-Based Systems

W. Xibin et al. [15] presented a PLC-based SCADA system for oil storage and related applications. The structure of the developed SCADA which the authors called *Ring Road SCADA* comprised of PLC of AB company to serve as a controller and a special network ControlNet for data exchange. In addition, the control system comprised of two CPU modules of the same specifications and two heat standby System Redundancy Modules (SRM) to realize the heat standby data of a dual-CPU, and a special ControlNet formed communication network consisting of four ControlNet Bridge Redundant (CNBR) modules and a Communication Interface Card (PCIC card) to exchange data between operation station and down PLC, and to complete the control order sending and data uploading. Some of the identified features of the developed PLC-based SCADA included data collection by the data modules, real-time monitoring and management, local and remote-control capabilities, high reliability, flexible configuration and ease of expansion, as well as low-cost.

However, although PLC-based SCADA systems are robust, the systems are very complex, and thus less reliable, and they rely heavily on highly developed electronic companies to produce sophisticated PLCs. In addition, they are generally expensive, they usually have software and hardware restrictions, they require different operating skills such as system analysts and programmers, the operator can see only as far as the PLCs, and with thousands of Inputs and Outputs (I/O) and sensors involved, there is a lot of wire to deal with [12].

1.3.1.2 PIC Micro-controller-Based Systems

To address some of the drawbacks associated with PLC-based SCADA systems and to further reduce SCADA costs, S. Sahin et al. [16] presented an open source, economical peripheral interface circuit (PIC) micro-controller based SCADA system using various experimental setups to illustrate the implementations of their proposed system. Some of the components used in their proposed solution include the PIC16F877 micro-controller together with a large RAM and an internal EEPROM, an eight-channel, 10-bit A/D converter for real time monitoring applications, RS232 connection for data transfer to and from a standard parallel port available in most computers, LEDs, high-voltage outputs and inputs embedded into the control cards, LabVIEW commercial software for the SCADA front panel GUI and block diagrams which held the data flow and graphical source codes. One disadvantage pointed out in this system was the lack of the combination of internet-based communication technologies which is an important part of a distributed system like SCADA [16]. Elsewhere, M. Zahran et al. [12] proposed a PIC micro-controller based SCADA system using Atmel (AT328) micro-controllers as the RTUs, a client Laptop PC with an open source SCADA software to serve as the MTU where HMIs were created, and an Ethernet controller to serve as system server.

In general, although PIC micro-controllers are cheap and portable, it is more difficult to handle PIC micro-controllers compared to other more advanced micro-controllers such as an Arduino. For example, it is challenging to interface devices with PIC compared to an Arduino.

1.3.1.3 PC-Based Systems

In a PC-to-PC (PtP) SCADA, standard PC configurations are placed on both the MTU and RTU sides of the communication link. The PC-based RTU will usually have custom software and is usually in charge of communication with the PC-based MTU, direct control of parameters, intelligent decision making and data storage [17]. E. Babovic et al. [17] presented a PC-to-PC SCADA solution using cheap and open source components, including PC-based MTU with user friendly HMI, mobile communication devices (such as GPS) and channels, and one or more PC-based RTU stations with simple hardware controller devices using a modified Spiral Model for the development of their work. In their experiment using Microsoft Visual Basic 6.0, two PCs were connected over simple LAN connection, and the MTU and RTU software modules which they developed with C++ maintained the connections using Winsock control and helped to ensure that commands from the MTU were executed by the hardware controller modules. Elsewhere, S. U. Abdi et al. [18] presented the design and implementation of PC-based SCADA training system for the natural gas transmission and distribution industry. The architecture of their proposed PC-based SCADA training system included a central monitoring and control station connected to PC-based RTUs via Industrial Ethernet, and Winsock control in Visual Basic 6.0 used to connect multiple terminals to each other and to provide easy access to network services. Their VB-based HMI design allowed real-time monitoring of pressure, temperature, level, light, humidity, security switches, AC input, A/D and D/A conversion values. Although PC-based SCADA systems are platform/protocol independent, low cost, simple to implement, easy to maintain, ensure ease of expansion and further development, they are less reliable than the conventional SCADA systems. Hence, the reason why PLCs are generally preferred to PCs for automation systems.

1.3.1.4 ESP8266-Based Systems/Web-based Wireless Sensor Solutions

T. Turc et al. [19] have proposed a web-based wireless SCADA using low cost ESP8266 module. In their work, the authors presented two methods of implementing the proposed SCADA solution. In the first method called *Periodic Unidirectional Transfer*, data flowed from the data acquisition system towards a centralized Web Server. The data acquisition system (DAS), which was a PLC, bridged the gap between the sensors and the communication channel, collected data from sensors and periodically sent the data to the Web Server without expecting any acknowledgement of successful receipt. On the other hand, the Web Server continuously listened on the channel and whenever it received commands, it processed the received commands and stored the processed sensor parameters in a database, and then the database was made available to the Web Clients such that the web clients were not in direct communication with the DAS. The ESP8266 module, a low-cost module with TCP/IP Wi-Fi capabilities was used to implement the wireless network communication and the sender made use of a hardware device called Access Point (AP) guarded by a security key (SK) to connect to the wireless network. According to the authors, even though this first method was simple, it was unreliable as it couldn't prevent data from being occasionally lost since the recipient had no means of acknowledging information receipt [19]. To address this drawback and to ensure that the monitoring system was able to track important parameter changes in the process of data transfer, the authors proposed an alternative method of implementing the web-based wireless sensor SCADA called *on-demand bidirectional data transfer* using the same ESP8266 module. In this case, the Web Client transmitted update requests to the DAS in one direction, and the DAS replied with the requested information in the opposite direction. However, while this second method of implementation was more responsive, it made the system more complex [19].

ESP8266 Wi-Fi modules can serve both as a server and as a client and they continue to gain popularity due to their low cost, flexible design, enhanced functions, and IoT architecture but they are mostly proven in home automation domains and they still need a lot of improvements for robust applications and high reliability [20, 21].

1.3.1.5 Arduino-Based Systems

In [22], an open source, low-cost SCADA to monitor and control a Water Pumping Station was developed using Arduino micro-controller board as the Remote Terminal Unit (RTU). The Arduino board was used to implement a standalone data acquisition and control unit which monitored and controlled equipment in the field as the field equipment were connected to the Arduino board while the Arduino was in turn connected to the MTU for remote control, and a Tablet for local control in the field. In their application, the Arduino board was programmed with C++ to measure the Ultrasonic sensor inputs and send the values through USB to the HMI, while at the same time listening to the incoming commands, such as turn on the pump. Although Arduino based systems are simple to implement and support a wide array of sensors, including third party sensors, using them as standalone systems require a lot of efforts to accomplish some tasks such as scheduling and database storage [23]. Furthermore, even though Arduino and ESP8266 web-based systems are much more superior compared to PIC based systems, novel Arduino plus IoT based systems play much more superior roles compared to the web-based system [21].

1.3.2 Open Source SCADA Software Solutions

Various open source SCADA software solutions exist on the market. Examples of such solutions include Rapid SCADA, Tango SCADA, PV Browser, Mango, PySCADA, FreeSCADA, IntegraXor, and so on. A. M. Grilo et al. [9] presented an integrated Wireless Sensor and Actuator Networks (WSAN) and SCADA solution for monitoring critical infrastructures using an Internet Protocol (IP) (Gateway), and Web-based services together with the open source and web-based Mango SCADA which provided an integrated platform accessible from the internet. The authors demonstrated this solution by using it to monitor and control an electrical power grid. They also addressed some of the challenges faced in developing a typical SCADA system, including Real-time Communications, Quality of Service (QoS), Management Support, and Security. The main disadvantage of using a standard SCADA software like Mango and Rapid SCADA is that they communicate using several protocols, and it is difficult to customize the protocols without a specific training on the system [21]. These open source SCADA software solutions are also not 100% free.

1.3.3 Open Source Server Options

Just like the open source SCADA software solutions, there are also open source SCADA server solutions available today. Examples of such servers include LabView, KingView, and Simulink-based systems. Some of the related works in this domain are presented below:

M. Regula et al. [24] presented an open source SCADA system for power quality monitoring and control in a smart micro-grid using LabView. The system operated with nine measured and remotely managed nodes, each node containing ON/OFF button, which could be used to control power switching element of universal measuring block. This block of network each time sent a file with analog measured parameters and their average values were displayed on the main window of LabView SCADA system for monitoring. Elsewhere, X. Zhaoxia et al. [25] presented an open source SCADA system to monitor an Islanded DC micro-grid, including wind turbine, photovoltaics, and battery units, based on KingView 6.55. The SCADA system established data communication between the host and the slave computers through intelligent modules and different communication techniques. The developed SCADA system was able to monitor real-time parameters such as voltages, currents, or powers, and store the important parameters into an SQL database. In their solution, the host computer (server) was a KingView configuration software installed on a Windows PC with RS 232C Communication capability, and many intelligent modules were connected to this host computer through a cable in one case (Modbus TCP/IP) and through an RS-232/485 converter in another case (Modbus TCP/IP) while remote monitoring was established using GPRS service platform.

In yet another development, R. M. J. Rathnayaka et al. [26] presented a scalable open source SCADA server solution together with a cost-effective communication media for multi-protocol smart grid devices. In their solution, an OPC Server was designed with MatLab/Simulink to bridge windows-based software applications and process control hardware, as well as to serve as a middleware to establish communications in the multi-protocol environment. Furthermore, they used the low-cost cellular (GPRS/3G) communication protocol to transfer the data between the Simulink-based OPC SCADA central server and the field installed devices (RTUs).

Even though it is quite straightforward to implement LabView/KingView, and Simulink-based systems, they are expensive compared to other low-cost technologies [21].

1.3.4 Internet of Things (IoT) Based SCADA Systems

The Internet of Things (IoT) based SCADA domain involves the use of one or more IoT platforms as the Master Terminal Unit, or SCADA Host Server. Examples of open source IoT platforms include Ubidots, Thingspeak, SiteWhere, OpenIoT, DeviceHive, KaaIoT, Blynk, Emoncms, Thinger.IO, ThingsBoard, Freeboard, etc [27]. A few researchers have proposed some solutions to implement IoT-based SCADA systems using IoT platforms. For example, R. J. Tom et al. [28] proposed an IoT-based SCADA system integrated with Fog Router and Cloud for power distribution automation to monitor and control consumer utilization, power outage, power quality, and pole transformer health. They implemented their proposed solution by dividing the distribution automation sensing area into three segments; (1) Smart metering for monitoring and controlling the home supply, (2) Line sensors for monitoring the voltage and the current supply in the lines, and (3) Intelligent Electronic Devices (IEDs) to monitor the parameters like temperature, loading, voltage, current and supplied power. Also, for monitoring the Transformers, Power lines and Smart meters, Fog Router was placed in between the Pole Transformer and the Consumer side. The smart sensors and meters used the IP based communication built upon the IEEE 802.15.4, known as IPv6 Low-power wireless Personal Area Network (6LoWPAN) to collect and send voltage, current and power consumption data from homes to the Fog Routers. The IEDs fixed on the Pole Transformers also used 6LoWPAN communication to reach the Fog Routers. The Fog Routers thus acted as the 6LoWPAN gateway, where the data from smart meters, line sensors, and IEDs were collected in real-time for analytics while using backbone network like 3G/4G for communicating with the IoT-Cloud platform such that the acquired data were available to numerous operators with predetermined access keys.

Elsewhere, S. Blanch-Torné et al. [29] proposed an agent-based DCS in the form of an IoT-based SCADA architecture. In their solution, they showed how Public Key Infrastructure (PKI) functionalities built with distributed features can be integrated into the DCS of an industrial control system to act as a multi-agent based IoT SCADA since the main difference between a SCADA and a DCS is the centralization of the monitoring and control over the field instruments in the SCADA. Their architecture comprised of a DCS with multiple agents embedded in it to act like processes in a system, and a cloud storage. The agents included Interface agent, host agent, agent controller, process agent, and instrument agent, all connected to the naming service, PKI service and permanent storage. Each of these agents played various roles found in a typical SCADA system to implement their proposed solution. The agents also formed a kind of P2P network and they communicated with each other in a Handshake process within a secure channel to address the main security threats in such a system.

In another development, my predecessor, S. L. Jayasinghe [21], developed an open source low-cost SCADA system for the monitoring and control of a grid-tied inverter connected to an Energy Storage System by using ThingSpeak Local Server and Python. In implementing his proposed solution, he developed Python-based program which allowed a user to obtain data from the serial port and post the data to the ThingSpeak local server platform where the user could view and download data from the ThingSpeak server platform. Furthermore, he also developed a graphical user interface (GUI) to interact with the SCADA system, and to show the current data values, as well as allow the user to set the controlling variables. The developed system was tested with an Inverter at the University of New Brunswick and it gave a satisfactory performance. However, as noted in his work, one main drawback of using the ThingSpeak Local Server was that it consumed a lot of power, about 52 W, which is high and not suitable for small-scale energy storage systems [21]. Also, the ThingsSpeak server is mainly built for Linux Operating Systems which makes installing it in the more flexible Windows Operating Systems, or systems with less power demands difficult [21].

In this thesis, three different low-cost, low-power, reliable and secure open source SCADA system solutions are designed and implemented using various open source hardware, software and IoT platforms.

1.4 Problem Statements/Motivations

With increasing number of small renewable generation systems, low cost monitoring and control is necessary to ensure proper operation and maintenance. Small renewable power systems are usually distributed over large geographical areas, sometimes in harsh environments. While it may be necessary to have local means of managing the operations of such systems, it is equally important to have a reliable, timely, flexible, cost-effective and sophisticated coordinated monitoring and control solution. A SCADA system is the perfect solution for this task. However, the available proprietary SCADA systems are largely pricey, and therefore economically unjustifiable for smaller applications. With the proprietary SCADA systems, there are also the problems of interoperability and high power consumption, as well as the need to use expensive standard communication systems as these components are usually from multiple manufacturers and vendors. Therefore, this research aims to investigate and study the available proven proprietary (commercial) SCADA systems to ascertain their components and functionalities, as well as the available open source SCADA packages, and subsequently design and implement open source SCADA options with similar functionalities as the proprietary SCADA systems on the market, and finally test each of the developed open source SCADA options using a small photovoltaic system.

1.5 Research Objectives

The problem statements and motivations mentioned in Section 1.4 led to the formulation of the key objectives of this research work. These are summarized below:

1. To design, dynamically model and simulate a small hybrid power system made up of a small renewable generation system and energy storage systems as a case study to show the needs and importance of such systems, the distributed nature of the power generation components, and to show that these components are usually from multiple manufacturers, hence the need for open source SCADA systems to manage the operations of the entire system.

2. To study the available proprietary SCADA systems, and design some reliable, low-cost, low-power and secure open source SCADA options with similar functionalities as the studied proprietary SCADA systems.

3. To study and test the available open source Internet of Things (IoT) platforms and choose the best options to develop the proposed IoT-based open source SCADA options.

4. To test each of the developed IoT-based open source SCADA systems with an actual renewable power generation system together with energy storage systems to acquire important parameters like Current, Voltage and Power, remotely monitor them and initiate supervisory control actions using the developed human machine interface (dashboards, alarms, etc.) on the chosen IoT platforms.

1.6 Research Contributions/Problem Solutions

The contributions of this research work to solve the enumerated problems in Section 1.4 are summarized as follows:

1. A house in Nigeria has been chosen for the small hybrid power system design, dynamic modelling and simulation. Thermal modelling of the house has been carried out to ascertain the energy needs. Having known the energy needs, the determination of the optimal renewable energy mix and sizing of the energy storage systems and other power generation sources and components have been carried out to meet Objective 1 stated in Section 1.5.

2. Taking some of the SCADA system security and reliability recommendations in literature into considerations, the main data cloud server in each of the designed/proposed IoT-based open source SCADA systems is locally installed on own machines, and self-hosted on own (MUN) network to ensure data integrity and data security, system availability, and hence system reliability.

3. Selection and testing of each of the elements of the proposed IoT-based open source SCADA system options to achieve the low-power objective mentioned in Section 1.5.

1.7 Thesis Organization/Summary

This research has been done as a part of the NSERC Energy Storage Technology Network (NESTNet) project. NSERC Energy Storage Technology Network (NESTnet) is a network of 15 Universities, representing 8 Provinces in Canada, and 26 industry and government partners set up to drive progress in energy storage technologies with the aim to create more reliable, environmentally friendly and efficient electric power systems in the country [30]. The research is carried out under four major Themes. Theme 2 investigates Power Electronic Converters for energy storage systems. The projects documented in this thesis fall under Theme 2.4 which has to do with SCADA interface for energy storage systems.

A manuscript style format has been adopted in the preparation of this thesis. A summary of the thesis and each of the chapters is presented as follows:

Chapter 2 presents the design and dynamic simulation of a hybrid power system made up of a small renewable energy generation system and energy storage systems. The research work in this chapter has been done as a case study to demonstrate the importance of such systems and to show that the components of such power generation systems are usually from multiple manufacturers, and geographically distributed in nature, hence the need for open source SCADA systems to remotely monitor and manage their operations. The work in this chapter helps to meet Objective 1 of this thesis stated in Section 1.5. This paper has been published in the INTERNATIONAL JOURNAL OF PHOTOENERGY, Special Issues on Advanced Solar Technologies in Buildings, Volume 2019, Article ID 6501785, 13 pages, https://doi.org/10.1155/2019/6501785.

Chapter 3 presents one of the designed low-cost, low-power, secure and reliable IoT-based open source SCADA systems using a locally installed and self-hosted Emoncms IoT Server platform, Arduino Uno micro-controller, Raspberry Pi single-board computer, Ethernet and Node-RED data transfer tool. The work in this chapter serves as a part of Objectives 2 and 3 stated in Section 1.5. This paper has been peer-reviewed, accepted and presented in the conference proceedings of the 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE), Edmonton, AB, Canada. The paper has also been published on IEEE Xplore Database as a part of the IEEE CCECE 2019 conference proceedings (doi: 10.1109/CCECE.2019.8861827).

Chapter 4 presents a second designed low-cost, low-power, secure and reliable IoT-based open source SCADA system using a locally installed and self-hosted Thinger.IO IoT Server platform, ESP32 Thing micro-controller and Wi-Fi. The work in this chapter also serves as a part of Objectives 2 and 3 stated in Section 1.5. This paper has been published in the ELECTRONICS JOURNAL, Special Issue on Modern Mechatronics and Automation—An Open-Source Approach.
Electronics 2019, 8(8), 822; https://doi.org/10.3390/electronics8080822.

Chapter 5 presents a third and final designed low-cost, low-power, secure and reliable IoT-based open source SCADA system using a locally installed and self-hosted Things-Board IoT Server platform, ESP32 micro-controller with OLED display, Wi-Fi, and the lightweight IoT-domain MQTT data transfer protocol. The work in this chapter also serves as a part of Objectives 2 and 3 stated in Section 1.5. This paper has been published in the AIMS ELECTRONICS AND ELECTRICAL ENGINEERING JOURNAL, Topical Section on Intelligent Systems, Automation and Control. AIMS Electronics and Electrical Engineering, 2020, 4(1): 57-86. doi: 10.3934/ElectrEng.2020.1.57. Also, a short and modified version of the work in this chapter has been presented in the conference proceedings of the 28th Annual Newfoundland Electrical and Computer Engineering Conference (NECEC 2019), St. John's, NL, Canada.

The designed IoT-based open source SCADA systems in Chapters 3, 4 and 5 have been tested with a Small Renewable Power Generation System (Solar Photovoltaic (PV) System with MPPT and Battery Energy Storage System) to meet the fourth and final objective of this research work as stated in Section 1.5.

Chapter 6 presents the conclusions and recommended future works of the thesis.

The Appendices present the supporting documentations of Chapters 3 to 5 that would otherwise clutter the thesis.

Appendix A presents the Bill of Materials and Power Consumption analysis of the designed SCADA system in Chapter 3 which weren't included in the CCECE 2019 paper due to page limitations. This Appendix also presents the JavaScript Codes used in the realization of the Emoncms-Node-RED flows used in the data transfer phase of the project, and the Arduino Codes used in the Data Acquisition and Logging Phase of the project.

Appendix B presents the Arduino-ESP32 Codes used in the Data Acquisition and Data Logging Phase of the designed SCADA system in Chapter 4.

Appendix C presents the Arduino-ESP32-ThingsBoard-MQTT Codes used in the Data Subscription and Data Publishing Phase of the designed SCADA system in Chapter 5.

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Co-authorship Statement

I am the principal author in all the research papers used in the preparation of this thesis, and my thesis supervisor, Dr. M. Tariq Iqbal, is the Co-author in all the papers. As the principal author, I carried out most of the research work, performed the literature reviews, carried out the designs, hardware implementations, experimental setups and analysis of the results in each of the manuscripts. I also prepared the original manuscripts and subsequently revised each of them based on the feed-backs from the Co-author and the peer reviewers throughout the peer-review processes. The Co-author, Dr. M. Tariq Iqbal, supervised the entire research work, reviewed and corrected each of the manuscripts, acquired the research funding, provided the research components and contributed research ideas throughout the research and in the actualization of each of the manuscripts.

Chapter 2

Design and Simulation of a Hybrid Power System for a House in Nigeria*

Preface

A version of this manuscript has been published in the ***International Journal of Photoenergy, Special Issues on Advanced Solar Technologies in Buildings, Volume 2019. Article ID 6501785****. I am the primary author, and I carried out most of the research work, performed the literature reviews, carried out the system design, modelling, and simulations, and analyzed the results. I also prepared the first draft of the manuscript and subsequently revised the final manuscript based on the feedback from the co-author and the peer review process. The Co-author, Dr. M. Tariq Iqbal, supervised the research, acquired and made available the research funding, provided the research components, reviewed and corrected the manuscript, and contributed research ideas in the actualization of the manuscript.*

*This chapter is a version of "Design and Dynamic Modelling of a Hybrid Power System for a House in Nigeria", L. O. Aghenta and M. T. Iqbal, *International Journal of Photoenergy* **Vol. 2019**, Article ID 6501785, 13 pages (2019).

Abstract

This paper presents the design and dynamic modelling of a hybrid power system for a house in Nigeria. Thermal modelling of the house under consideration is carried out using BEOpt software to accurately study the heat loss through the walls, windows, doors and roof of the house. The analysis of this thermal model is used to determine hourly load data. Design of an optimum hybrid power system for the house is done with HOMER Pro software. The hybrid power system is made up of a diesel generator and a standalone PV system. The proposed PV system consists of PV arrays, DC – DC Boost Converter, Battery Energy Storage System, MPPT Controller, Single Phase Full Bridge Inverter, Inverter Voltage Mode Controller (PI Controller), and Single Phase Step-up Transformer. Dynamic simulation of the proposed PV system component of the hybrid power system is carried out in MATLAB/SIMULINK environment to study the power quality, harmonics, load impact, voltage transients etc. of the system, and the simulation results are presented in the paper.

Index Terms: Renewable Energy, Thermal Modelling, BEOpt, HOMER Pro, Solar PV, MPPT, Modelling and Simulation.

2.1 Introduction

Electricity is one of the basic amenities of man because of its wide usage in various aspects of life. Thus, the need for a reliable source of power supply cannot be over emphasized. Unfortunately, electrical power supply in developing countries like Nigeria is unreliable, thereby making life difficult. Nigeria is a federal republic in West Africa, bordering Benin in the west, Chad and Cameroon in the east, and Niger in the north. Its coast in the south lies on the Gulf of Guinea in the Atlantic Ocean. It comprises 36 states and the Federal Capital Territory, where the capital, Abuja is located [1]. Nigeria is often referred to as the "Giant of Africa", owing to its large population and economy. With 186 million inhabitants, Nigeria is the most populous country in Africa and the seventh most populous country in the World [1]. Nigeria is the 12th largest producer of petroleum in the world and the 8th largest exporter, and has the 10th largest proven reserves. Apart from petroleum, Nigeria is also blessed with other natural resources, including natural gas, tin, iron ore, coal, limestone, niobium, lead, zinc and arable land. Despite these abundant natural resources, the country is unable to generate enough electricity to support the national population. Presently, the amount of generated power is about 9% of the required power needed to completely electrify the country (about 80,000 MW capacity is required but barely 7,445 MW is installed) [2]; thus, the country continues to experience extreme electricity shortage and prolonged periods of power outages such that a typical Nigerian household has electric power supply for 5 hours a day on the average. Over the years, households have had to rely mostly on private power generators to meet their electricity needs. However, the growing price of petroleum products to power these generators is a major concern for the average household. Also, the noise and fumes from these generators are having significant impacts on the environment as the fumes continue to contribute to the carbon footprints of the houses. To avoid these negative environmental impacts of fossil fuels usage, it is important to find ways to economically utilize clean and sustainable sources of energy such as wind, solar energy, etc. to meet the electricity needs of the house. Various literatures presented in [5] have reported abundant solar resource potential of between 3.5 kWh/m^2/day and 7.0 kWh/m^2/day across Nigeria and average sunshine duration of 6.25 hours per day. This is corroborated by the April 2018 weekly Agro-meteorological Data for the Dekad bulletin of the Nigerian Meteorological Agency (NiMet) [6], which shows an average solar irradiation for a Northern city like Zaria to be 23.4 MJ/m^2/day (6.5 kWh/m^2/day) and that for a Southern city like Benin City to be 17.3 MJ/m^2/day (4.81 KWh/m^2/day). Despite these large solar resources, Nigeria is yet to fully integrate solar energy into its energy generation mix.

2.2 Literature Review

Individuals and researchers across Nigeria have over the years taken advantage of the availability of abundant solar resources, and its ease of use to design PV systems to meet their private energy needs. Y.N. Udoakah et al. [8] designed a 1 KVA PV System for Electrical Laboratory in the Faculty of Engineering at the University of Uyo to solve the problem of sudden power failures during laboratory sessions. The major components of their off-grid PV system design included two 150 W Solar Panels connected in parallel (PV module), an inverter unit, one 12 V, 100 AH deep cycle battery, charge controller unit, and an automatic control unit to automatically switch from the inverter to the public power supply whenever the public power was available and vice versa. Elsewhere, C. O. Okoye et al. [5] proposed a standalone solar PV system design solution and cost model analysis using both intuitive and numerical methods. The authors considered constant electrical load demands of a house each in three different major cities in Nigeria; Onitsha, located in the South-East region, Kano, located in North-West region, and Lagos, located in the South-West region as case studies using the 2016 meteorological solar radiation data sets for these cities in their analysis. In their solution, they used intuitive and numerical methods to calculate the required PV area and capacity, the number of PV modules, the corresponding capacities of the battery, the inverter, and the charge controller while using Life Cycle Cost Analysis model to investigate the optimal cost solution for the PV system design which takes into account the initial capital investment, the present cost of the battery, the inverter, the charge controller, and the balance of system cost to estimate the net present value of the PV system as well as the estimated future value of the system using appropriate discount rates for each of the components of the PV system. D. O. Akinyele et al. [9] proposed an off-grid PV System design solution to solve electrical power problems in two rural households in Nigeria using HOMER software for the modelling and analysis of the PV system and cost. In their research, they considered energy consumption scenarios of two households in Agwandodo settlement in Gwagwalada, Abuja with moderate loads. Considering the average loads and operating hours of the domestic appliances for each of these houses, they used both MATLAB and HOMER tools to obtain the daily load profiles for the two houses. They then used HOMER software to obtain the optimized component sizes of the stand-alone PV systems for the houses and costs.

In yet another development, M. S. Adaramola et al. [10] presented the feasibility analysis of hybrid PV solar-diesel power system application for the remote areas in the Northern part of Nigeria using Jos and its environs in Plateau State as a case study. In their solution, electrical energy of 1.5 MWh/day with daily peak load of 236 KW was simulated for rural areas with a population of about 1500 households and with the assumption that each household consumed 1 kWh of energy per day. The values were then used to determine the ratings of the other components of the proposed hybrid PV solar-diesel system including PV modules, diesel generator, battery and power converter.

In most of the above mentioned papers, the energy requirements for their hybrid/PV system design have been estimated by calculating the power requirement of each device in the house and estimating the approximate number of hours each device would utilize power in a day. The problem with this method of estimating energy needs for PV system design is that it does not consider the type and size of the locations of electrical appliances, the building materials, orientation and dimensions of the house, as well as heat loss through the walls, windows, doors and roofs of the house. Also, the Intuitive and Numerical methods of estimating energy requirements presented in the other papers above have some drawbacks. Although the intuitive methodology is relatively simple to compute compared to the numerical method, it has the drawback of often over sizing or under sizing the entire system due to not modelling the interactions among the subsystem components [5]. The numerical method, on the other hand, is a complex solution prone to errors as it involves a lot of parameter estimations.

In this paper, the enumerated shortcomings above are addressed in designing a hybrid power system. This paper involves three major tasks. First, a detailed thermal modelling of the chosen house using BEOpt software is completed. Secondly, optimum hybrid power system design using HOMER Pro software is presented. Finally, Matlab/Simulink dynamic simulation of the optimum PV System component of the proposed hybrid power system is presented along with the simulation results. Specifically, the contributions of this study include:

- Thermal modelling of the house, taking into account important parameters such as the type and size of the house, location and orientation of the house, materials used in building the house, number and types of appliances in the house, and number of occupants, as well as heat loss through the walls and windows. Such modelling resulted in a detailed hourly and annual load profile of the house. This, to the best of the authors' knowledge from reviewed literature has never been done for the determination of load profiles in that region.

- Determination of the optimal renewable energy mix and conventional diesel generator size of the hybrid power system for the specific house in Nigeria.

- Assessment of the optimal system configuration to achieve energy independence for the house.

- Matlab/Simulink dynamic simulation of the PV System component of the proposed hybrid power system to study the power quality, harmonics, load impact, and voltage transients under various conditions specific to the house under consideration.

2.3 Thermal Modelling of the House in BEOPT

In order to design a hybrid power system for a household, it is important to accurately determine the energy needs of the household for which the system is being designed. This can be achieved through thermal modelling of the house [12]. Building Energy Optimization (BEOpt) software, developed by the National Renewable Energy Laboratory, provides capabilities to evaluate residential building designs and identify cost-optimal solution at various levels of whole-house energy savings along the path to zero net energy [12, 13]. It provides detailed simulation-based analysis based on specific house characteristics, such as size, architecture, occupancy, vintage, location, and utility rates. BEOpt can be used to analyze both new construction and existing home retrofits, as well as single-family detached and multi-family buildings, through evaluation of single building designs, parametric sweeps, and cost-based optimizations [13]. The chosen house is located in Benin City (Latitude 6 deg. 20' 0" N and Longitude 5 deg. 38' 0" E), Edo State, Nigeria. It is a South-facing Bungalow building with a total area of 2,375 sqft; one front door and one back door, one big living room, five bedrooms, three bathrooms, one kitchen, windows of various sizes, corridors, concrete walls, ceilings and aluminum roofs. The side view of the house is shown in Figure 2.1. Using the specific parameters of the house for BEOpt thermal modelling and simulations (Figure 2.2), the house was found to require an annual energy consumption of 17,485 KWh/year (about 2 KW average load) as shown in Figure 2.3. The generated daily, monthly and yearly load profiles of the house are shown in Figure 2.4. However, the PV system component of the hybrid power system is designed for a load of 1.5 KW with the assumption that the extra refrigerators and heavy air conditioners included in BEOpt simulation will be removed before switching to the PV system.

Figure 2.1: House Side View.

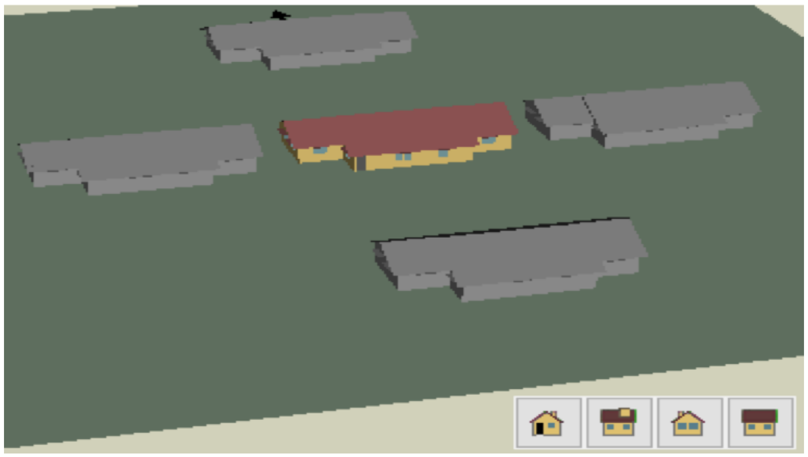


Figure 2.2: BEOpt Software House Design.

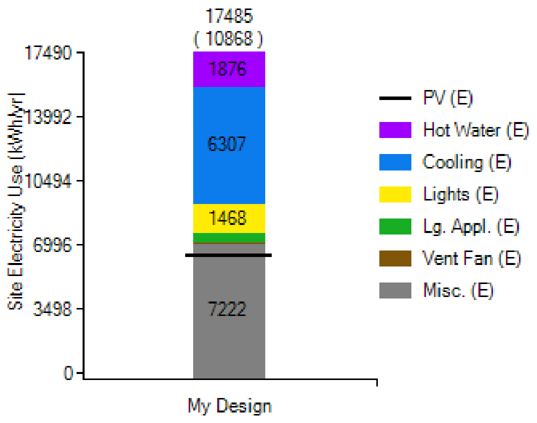
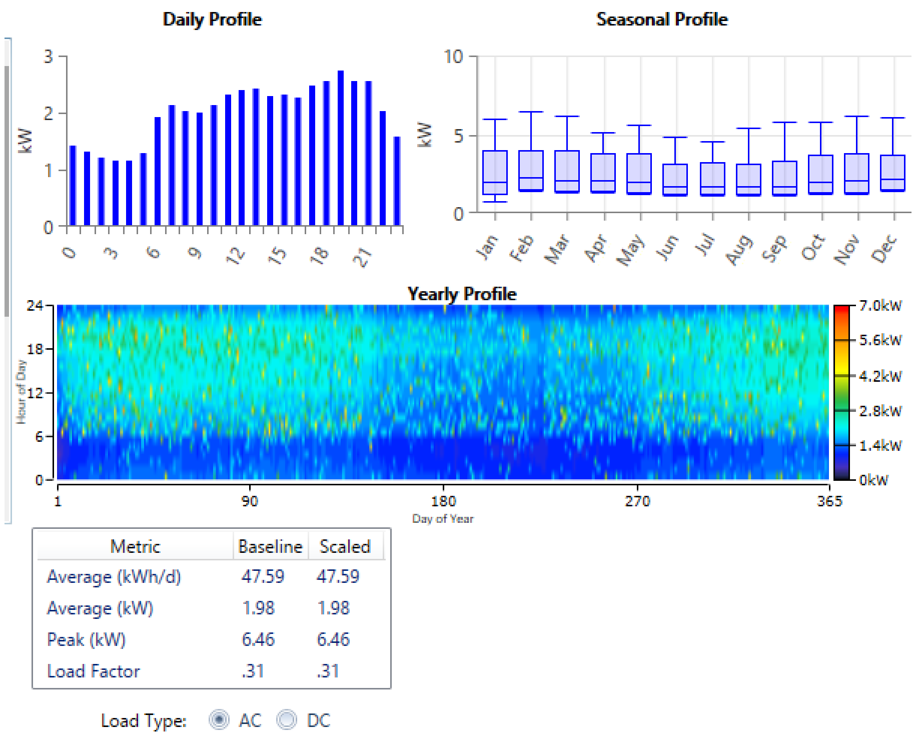


Figure 2.3: House Annual Energy Consumption from BEOpt Simulation.



Metric	Baseline	Scaled
Average (kWh/d)	47.59	47.59
Average (kW)	1.98	1.98
Peak (kW)	6.46	6.46
Load Factor	.31	.31

Load Type: [✓ AC] DC

Figure 2.4: Daily, Monthly and Annual Load Profile of the House from BEOpt Simulation.

2.4 Optimum Hybrid Power System Design with HOMER PRO

A hybrid power system is made up of various components. In designing a hybrid power system, factors such as the size of the components, system configurations, adequacy of the various renewable energy resources in that region, project economics with changing loads and component costs, life cycle of the system, net present cost of the system, cost of energy to the end user, maintenance costs, and annual operating costs of the hybrid system will help the decision maker to determine the most cost-effective solutions of the hybrid system to meet the electrical loads for which it is being designed [11]. Hybrid Optimization of Multiple Energy Resources (HOMER) software, developed by the National Renewable Energy Laboratory models micro-power systems with single or multiple power sources: e.g.

Photovoltaics, Wind turbines, etc. and helps to design off-grid and grid-connected systems in the most cost-effective ways by taking the factors above into consideration [11, 14]. It simulates various configurations to find the least cost combinations that meet the electrical loads being considered. HOMER's optimization and sensitivity analysis capabilities help to answer important design questions such as; "Which technologies are most cost-effective? What size should components be? What happens to the project's economics if costs or loads change? Is the renewable energy resource adequate?", etc [14]. From the house thermal model with BEOpt software, the generated Annual Hourly Load Data (Figure 2.4) for the house was exported into HOMER Pro software for generator/PV System sizing and optimum hybrid power system design. The simulation was done using solar irradiation data of the house location (Figure 2.6), actual PV modules, converters, and batteries, and the optimized hybrid power system configuration is shown in Figure 2.5. Figure 2.7 shows HOMER optimized hybrid power system design based on the technical and economic data available. Such a system, designed for 25 years life cycle, will have a total Net Present Cost (NPC) of USD 106,307.90, a levelized Cost of Energy (CoE) of USD 0.4734 per kWh and an Annual Operating Cost of USD 5,650.04. The system will also have an excess energy of 14.9% which can be used to power the bulbs outside the fence of the house. The diesel generator will help to provide backup power during prolonged extreme weather conditions when the primary battery backup power from the PV system is unavailable. The rest of this paper is dedicated to the design and dynamic modelling of the proposed PV system component in the optimal Hybrid Power System.

2.5 The Proposed PV System Components

The proposed PV System is a standalone PV system comprising of PV Arrays, DC – DC Boost Converter. MPPT Controller, Battery Bank, DC – AC Converter (Inverter), Inverter

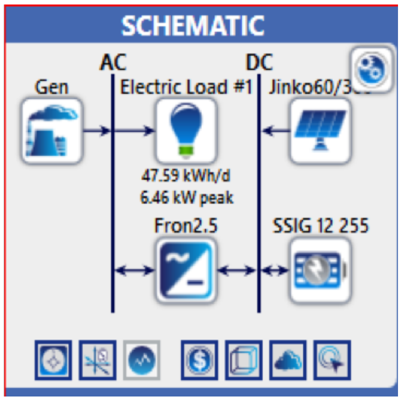
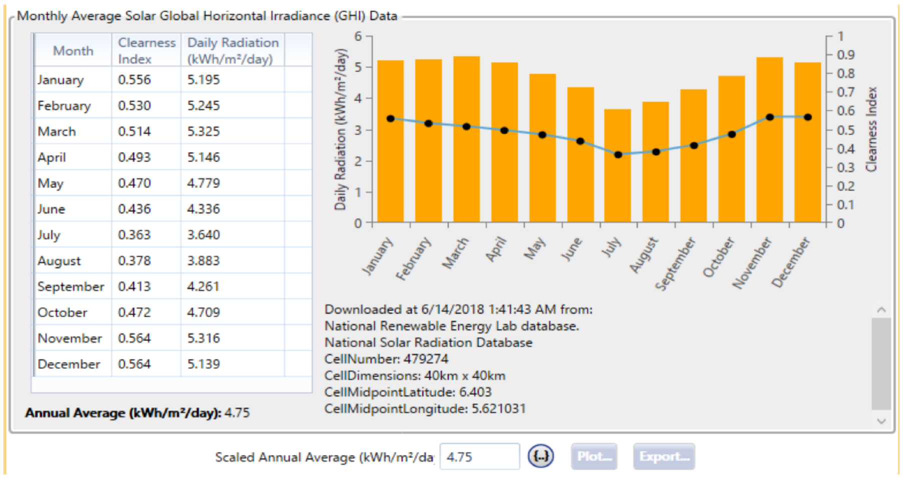


Figure 2.5: HOMER Optimized Hybrid Power System Configuration.



Month	Clearness Index	Daily Radiation (kWh/m²/day)
January	0.556	5.195
February	0.530	5.245
March	0.514	5.325
April	0.493	5.146
May	0.470	4.779
June	0.436	4.336
July	0.363	3.640
August	0.378	3.883
September	0.413	4.261
October	0.472	4.709
November	0.564	5.316
December	0.564	5.139

Annual Average (kWh/m²/day): 4.75

Downloaded at 6/14/2018 1:41:43 AM from:
National Renewable Energy Lab database.
National Solar Radiation Database
CellNumber: 479274
CellDimensions: 40km x 40km
CellMidpointLatitude: 6.403
CellMidpointLongitude: 5.621031

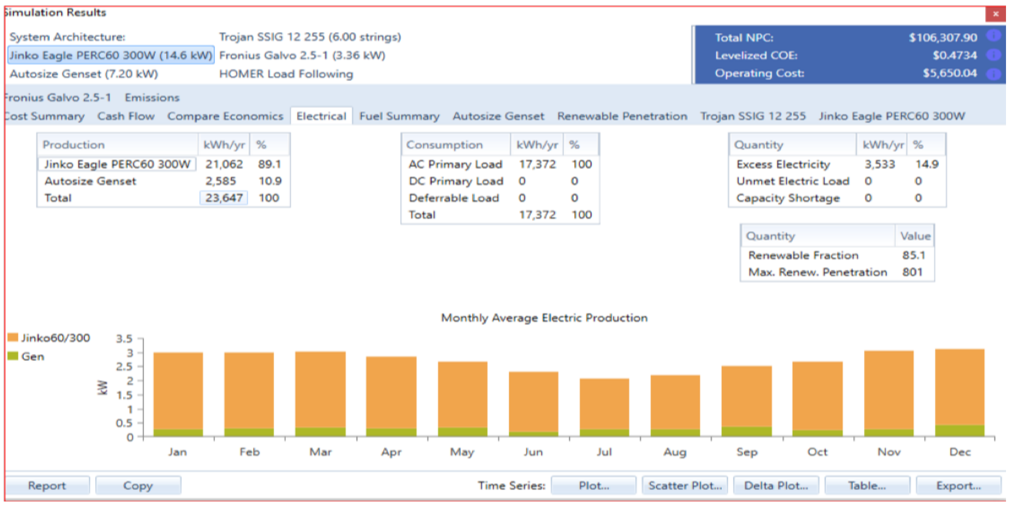
Scaled Annual Average (kWh/m²/da 4.75

Figure 2.6: Downloaded Solar Irradiance of the House Location.

Voltage Mode Controller, Single Phase Step-up Transformer, and the Single-Phase AC Loads of the house under consideration. Figure 2.8 shows a block diagram of the proposed PV System.

2.5.1 PV Arrays

Photovoltaics (PV) are used to convert sunlight directly into electricity [3, 4]. A Solar Cell is a PN junction diode with current flowing in the reverse direction. A number of Solar Cells make up PV Modules. PV array consists of strings of modules connected in parallel, each string consisting of modules connected in series [4]. Temperature and irradiation



Simulation Results

System Architecture:	Trojan SSIG 12 255 (6.00 strings)
Jinko Eagle PERC60 300W (14.6 kW)	Fronius Galvo 2.5-1 (3.36 kW)
Autosize Genset (7.20 kW)	HOMER Load Following

Total NPC:	$106,307.90
Levelized COE:	$0.4734
Operating Cost:	$5,650.04

Production	kWh/yr	%
Jinko Eagle PERC60 300W	21,062	89.1
Autosize Genset	2,585	10.9
Total	23,647	100

Consumption	kWh/yr	%
AC Primary Load	17,372	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	17,372	100

Quantity	kWh/yr	%
Excess Electricity	3,533	14.9
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value
Renewable Fraction	85.1
Max. Renew. Penetration	801

Figure 2.7: HOMER Optimized Results and Parameters.

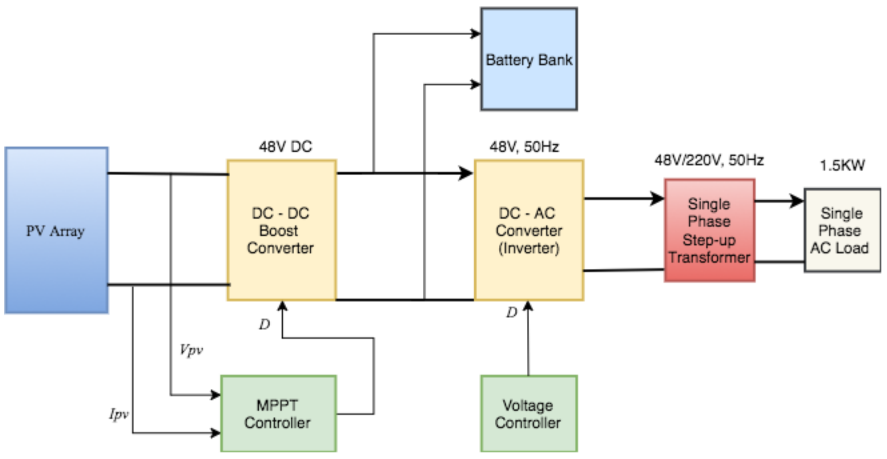


Figure 2.8: Proposed PV System Block Diagram.

level are the two main factors that affect PV array outputs. Change in temperature and irradiation level results in change in voltage and current, as well as power generated by PV systems [16]. Figure 2.9 shows a solar cell model using a current source I_L (light-generated current), diode (I_0 and n_I parameters), series resistance R_s, and shunt resistance R_{sh} to represent the irradiance and temperature-dependent I-V characteristics [16]. The diode I-V characteristics for a single module are defined by Equations 2.1 and 2.2 below [16]. The PV array used for this project is the Jinko Solar JMK300M-72 PV Array manufactured by Jinko Solar. The array comprises of 4 strings of 12 panels PV modules to give an output power of maximum 14.4 KW (12x4x300 = 14.4 KW). The I-V and P-V characteristics of the PV Array at various temperature and irradiation levels are shown in Figure 2.10

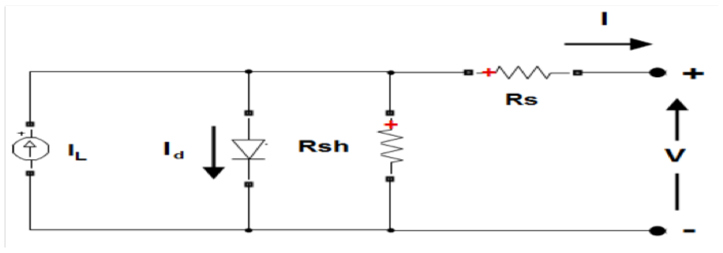


Figure 2.9: Diode Model of a PV Module [16].

$$I_d = I_0[exp(\frac{V_d}{V_T}) - 1] \tag{2.1}$$

$$V_T = \frac{KT}{q} \times nl \times Ncell \tag{2.2}$$

where: I_d = diode current (A), V_d = diode voltage (V), I_0 = diode saturation current (A), n_I = diode ideality factor, a number close to 1.0, K = Boltzman constant = 1.3806e-23 J.K-1, T = cell temperature (K), and $Ncell$ = number of cells connected in series in a module

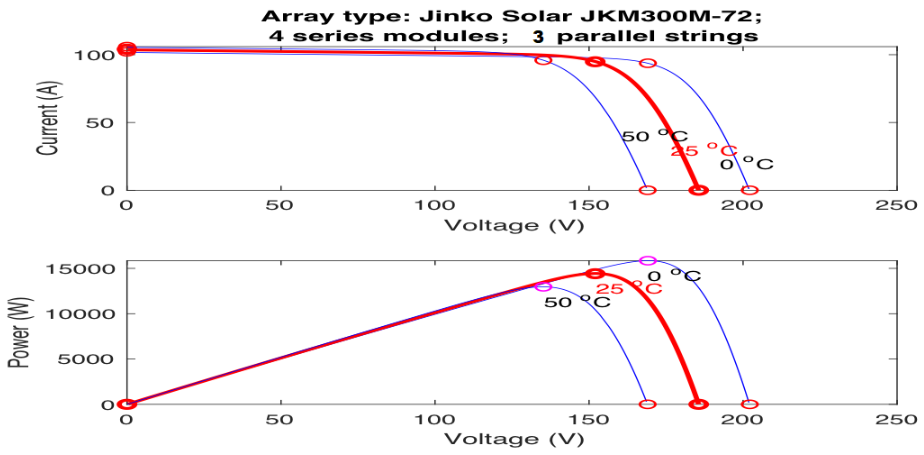


Figure 2.10: I-V and P-V Characteristics of Jinko Solar JMK300M-72 PV Array.

2.5.2 DC - DC Boost Converter

The DC – DC Boost Converter stabilizes and steps up (boosts) the unregulated DC voltage from the PV array to a DC bus voltage output, 48 V, needed to charge the battery. The output voltage of the DC – DC Boost Converter is fed into the Inverter for conversion to AC voltage. The circuit diagram of the DC – DC boost converter is shown in Figure 2.11. From the circuit diagram, the output Voltage and Current of the DC – DC Boost Converter are given by Equations 2.3 and 2.4 respectively [19]. From the equations, it can be seen that the output of the converter depends on both the input and the duty cycle, D. Therefore, with a fixed input, the output can be controlled by controlling its duty cycle.

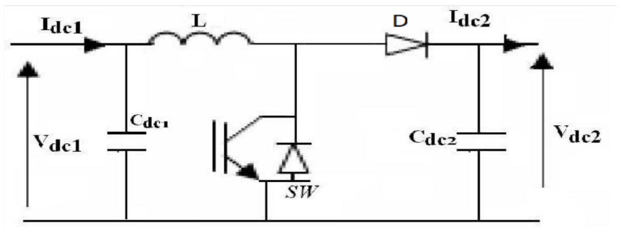


Figure 2.11: DC - DC Boost Converter Circuit Diagram [19].

$$V_{dc2} = \frac{1}{(1 - D)} \times V_{dc1} \tag{2.3}$$

$$I_{dc2} = (1 - D) \times I_{dc1} \tag{2.4}$$

where: D = Duty Cycle of the Converter

2.5.3 MPPT Controller

At any given time, the point on the I-V curve where the solar module operates is called the Operating Point (OP) and it corresponds to a given irradiance (G) and temperature (T), which are geographical conditions. Without any external electrical control, the module OP is largely dictated by changes in the line and the load seen by the module at its output [4].

The I-V curve represents the power produced and delivered to the load. Therefore, it is important that the solar module operates at its maximum power point (MPP). For maximum power output, it is important to force the module to operate at the OP corresponding to maximum power point. With changes in G and T, the I-V curve changes, which means that the previous MPP (OP) is no longer valid, a new MPP is created. Thus, to have MPP at all times, changes in the I-V curve have to be tracked to know the new MPP; a process called maximum power point tracking (MPPT). This is achieved using various algorithms. In this paper, the Incremental Conductance MPPT algorithm is chosen due to its efficiency and accuracy [4]. The algorithm has as its inputs the voltage and current from the PV array and the generated pulses are used to control the duty cycle, D, of the DC – DC Boost Converter. This algorithm is independent of the solar panel characteristics, rather the panel terminal voltage is changed according to its value relative to the maximum power point voltage. Equations 2.5 and 2.6, and Figure 2.12 illustrate the algorithm. Figure 2.13 shows the Flow Chart of this algorithm. In this project, the algorithm is implemented using Simulink blocks.

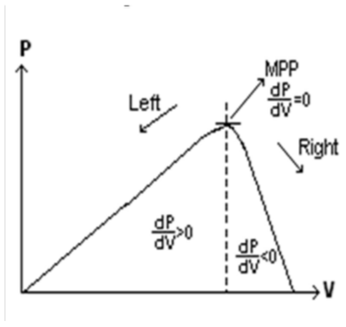


Figure 2.12: MPPT Process [4].

$$P = V * I \tag{2.5}$$

$$\frac{dP}{dV} = \frac{d(I * V)}{dV} = V * \frac{dI}{dV} + I = 0 \tag{2.6}$$

where: P = Power, V = Voltage, I = Current, dI/dV = incremental conductance, and I/V = panel conductance. At MPPT, $dI/dV = -I/V$ or $dP/dV = 0$

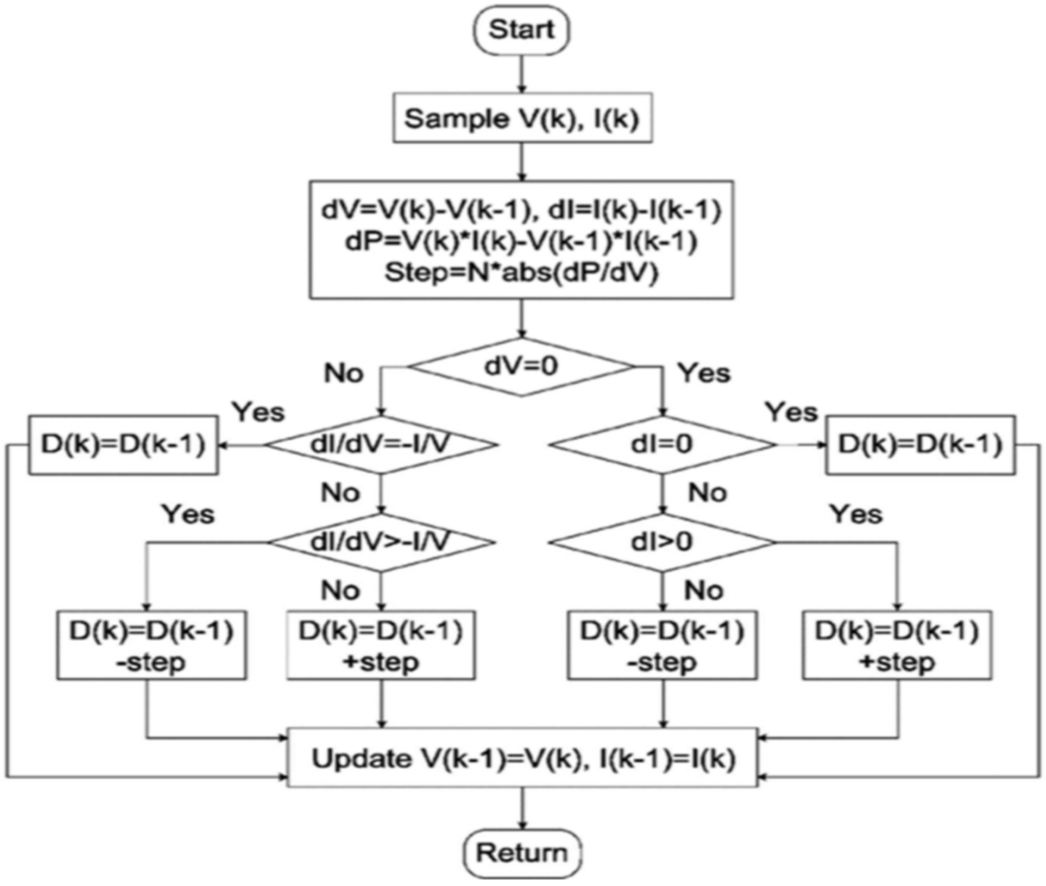


Figure 2.13: Incremental Conductance MPPT Flow Chart [4].

2.5.4 Battery Energy Storage System

The main purpose of the battery bank is to store extra electrical power generated by the solar PV system, and to deliver the stored electrical power to the household electrical loads whenever the PV system is unavailable. The battery system is made up of 24 total batteries (6 strings in parallel, each string size being 4 batteries) of the 12 V Trojan SSIG 12, 255 Lead Acid Battery type. The battery nominal voltage is 48 V (12 V x 4), the total capacity is 1,542 Ah (257 x 6) and its autonomy is 29.9 hours which means that the battery system can power the house for almost one and half days if the PV system is out for maintenance or not producing power due to bad weather conditions. Simulink block model for a lead acid battery is used to model these battery parameters.

2.5.5 DC - AC Converter (Inverter)

An Inverter converts a DC input supply voltage into a symmetric AC voltage of desired magnitude and frequency [17]. The single-phase voltage source inverter in this system converts the fixed DC voltage (48 V) from the DC – DC Boost Converter into a single-phase AC voltage (48 V) with a fixed frequency of 50 Hz. In this paper, a single-phase full bridge inverter with Insulated-gate bipolar transistor (IGBTs) switches is considered. It consists of four choppers; four switches/gates S1, S2, S3 and S4, and four transistors T1, T2, T3 and T4. With T1 and T2 turned on simultaneously, input voltage appears across the load, while for T3 and T4, voltage is reversed (-Vs). Figure 2.14 shows a typical full bridge IGBT based single-phase inverter [20].

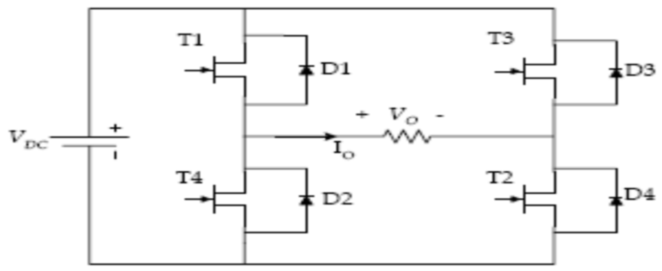


Figure 2.14: The Full Bridge IGBT based Single-Phase Inverter [20].

2.5.6 Inverter Voltage Mode Controller

The inverter output voltage is easily affected by variations on the line and other system parameters [17]. Therefore, there is the need for a proper control scheme to maintain a constant voltage regardless of system disturbance. The Voltage Mode Controller scheme is proposed in this work due to its reliability and ease of implementation [17, 20]. As shown in Figure 2.15, the DC voltage from the Boost Converter is sensed and compared with a reference value. The error produced is sent to a PI controller and the PI controller produces an output which is a DC quantity. This DC quantity is multiplied by a sinusoidal value to convert it into an AC value which is then compared with a triangular waveform to produce pulses for controlling the inverter switches/gates [17].

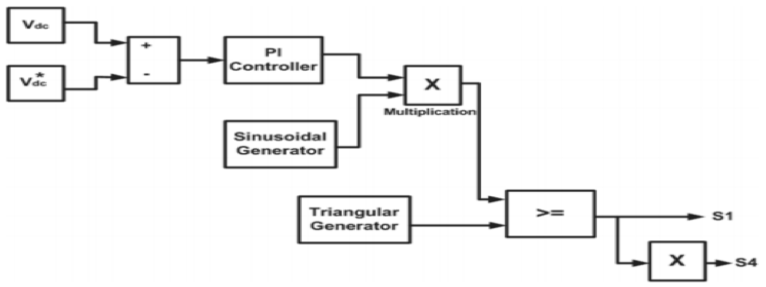


Figure 2.15: Inverter Voltage Mode Controller Block [17].

2.5.7 Single Phase Step-up Transformer

A transformer is an electrical device used to transfer electrical energy from one level to the other at the same frequency by means of a changing magnetic field. It consists of two windings, the primary and secondary windings, separated by a Magnetic Core. When a transformer is used to “increase” the voltage on its secondary winding with respect to the primary, it is called a Step-up transformer and when it is used to “decrease” the voltage on the secondary winding with respect to the primary, it is called a Step-down transformer [21]. In this research, a single-phase Step-up transformer is used to step up the 48 V voltage output from the inverter to 220 V at 50 Hz to match the household AC loads.

2.6 Proposed PV System Dynamic Simulation with MATLAB/SIMULINK

Dynamic Modelling and Simulation is the necessary first step in design, optimization and performance analysis. In order to study the dynamic behaviours of the PV system component of the proposed hybrid power system with respect to power quality, harmonics, load impact, and voltage transients, the PV system component was simulated in MATLAB/SIMULINK environment under various conditions specific to the house. The complete Matlab/Simulink model is shown in Figure 2.16. Each of the subsystems has been developed using standard equations, calculated and standard parameters from the manufacturers' data sheets.

2.6.1 Dynamic Simulation Results

The most important dynamic simulation results are shown from Figures 2.17 to 2.22. Figure 2.18 shows the Solar Irradiance and Temperature on which the PV array is made to operate, as well as the generated power output. Figure 2.19 shows the current, state of charge (SoC) and voltage (48 V) of the battery and from the SoC, it can be seen that the battery is being charged by the PV system for future use. Figure 2.20 shows the constant DC voltage output (48 V) of the DC-DC Boost Converter while Figure 2.21 shows the generated AC voltage and frequency of the inverter (48 V, 50 Hz) fed to the transformer. The transformer steps this voltage up at the same frequency to 220 V for the house hold AC loads as shown in Figure 2.22. All dynamic simulations were done for 3 seconds only.

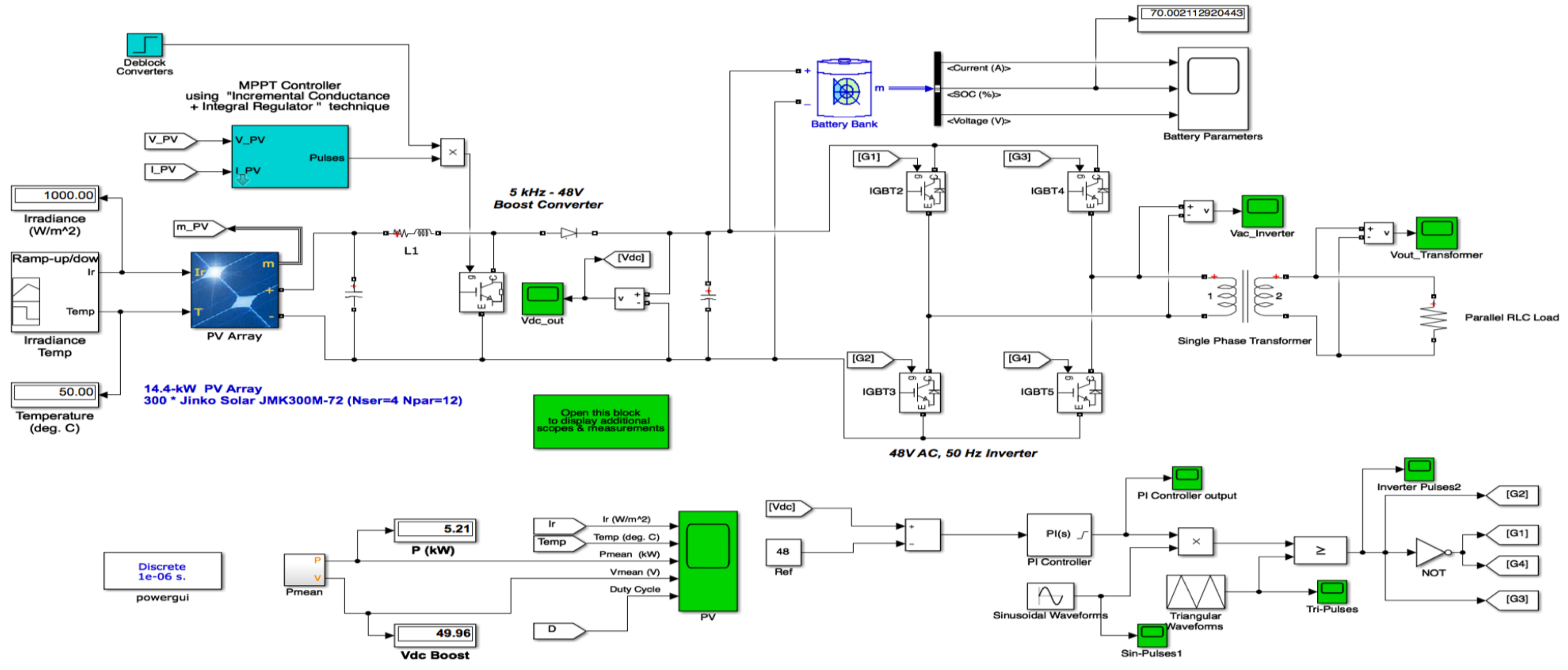


Figure 2.16: MATLAB/SIMULINK Model of the Proposed PV System.

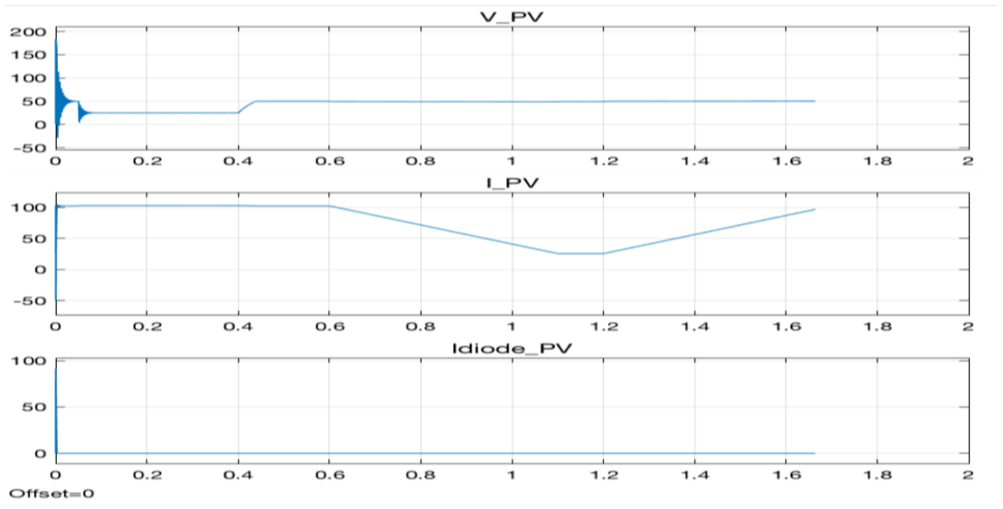


Figure 2.17: PV Array Voltage and Current.

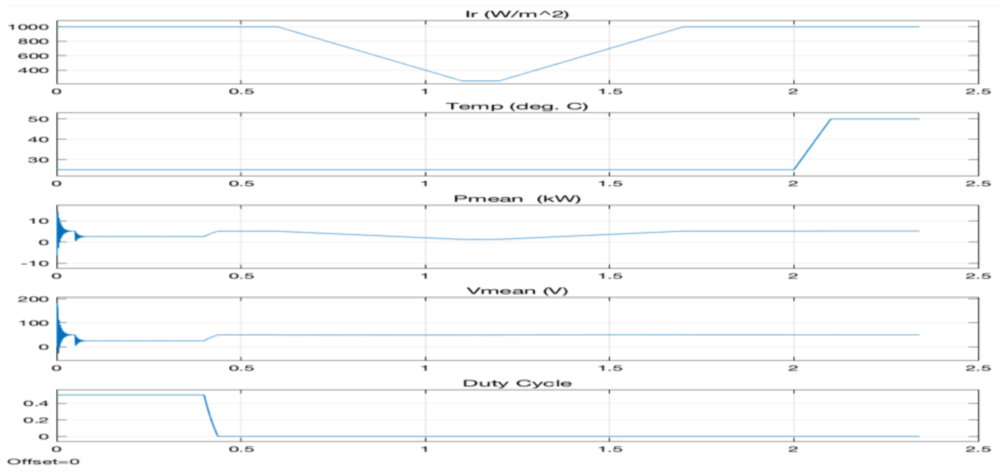


Figure 2.18: Solar Irradiance, Temperature and Generated Power.

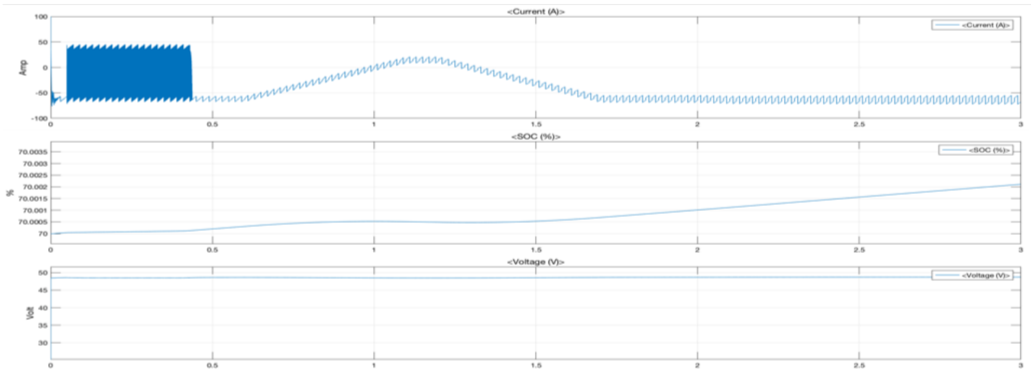


Figure 2.19: Battery Current, State of Charge and Voltage.

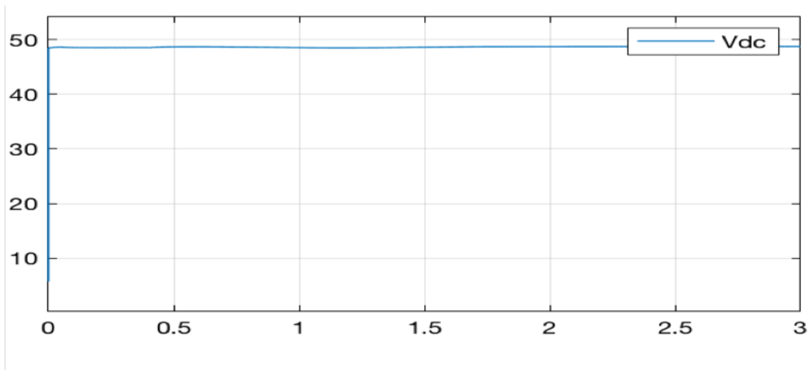


Figure 2.20: DC-DC Boost Converter Output Voltage.

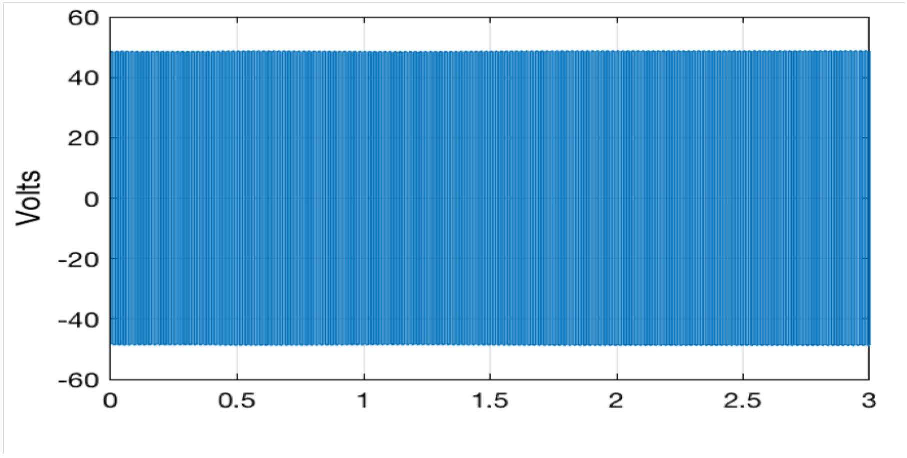


Figure 2.21: Inverter Output Voltage.

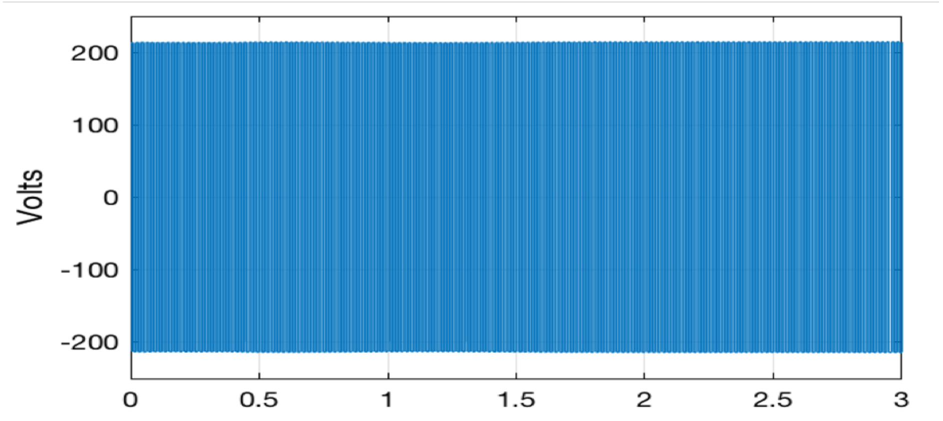


Figure 2.22: Single Phase Step-up Transformer Output Voltage/Load Voltage.

2.7 Future Works

In the future, Battery Management System (State of Charge Controller) can be included and a more sophisticated Inverter Control Scheme (e.g: Voltage Oriented Control, VOC) is recommended for faster response in cases of severe system disturbance such as sudden overload. Also, hardware implementation of the proposed Standalone PV System can be carried out for real-life testing.

2.8 Conclusions

In this paper, thermal modelling of a house in Benin City, Edo State, Nigeria has been carried out with BEOpt software, taking into account important parameters such as the type and size of the house, location and orientation of the house, materials used in building the house, number and types of appliances in the house, and number of occupants. This is because the actual energy needs of a house has been found to be affected by these parameters. Having known the energy needs of the house (17,485 KWh) from BEOpt Thermal Modelling, HOMER Pro software package was used to find an optimum standalone hybrid power system solution for the chosen house. To achieve this, the generated annual load profile of the house from BEOpt thermal modelling simulation was imported into HOMER Pro software, and through its Add/Remove window, various components of the proposed hybrid power system, such as solar PV arrays, diesel generator, converters, and battery were selected for simulation. This simulation took into account the project parameters such as project lifetime, and economic parameters (i.e., costs gotten from the components' manufacturers' websites), as well as the available solar irradiance in that region which was downloaded from the National Solar Radiation Database with HOMER resource window. In HOMER Pro, various systems were simulated and techno-economic analysis was carried out considering factors such as the size of the components, system configurations, adequacies of the various renewable energy resources, project economics with changing loads and component costs, life cycle of the system, net present cost of the system, cost of energy to the end user, maintenance costs, and annual operating costs of the hybrid power system in determining the optimum solution of the hybrid power system to meet the electrical loads of the house. The optimum hybrid power system was found to comprise of a conventional diesel generator and a solar PV system with battery energy storage systems. In order to test the power quality, harmonics, load impact, and voltage transients of the proposed solar PV system component of the hybrid power system, dynamic simulation was carried out in Matlab/Simulink environment under various system conditions.The simulated results show that the solar PV system with energy storage systems is fully capable of powering the house, and could serve as a potential solution to the energy crisis in that region.

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Chapter 3

Low-Cost, IoT-Based Open Source SCADA System using Emoncms, Arduino Uno, Raspberry Pi and Node-Red*

Preface

A version of this manuscript has been peer-reviewed, accepted and presented in the conference proceedings of the ***2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE), Edmonton, AB, Canada.*** *The paper has also been published on IEEE Xplore Database as a part of the* ***IEEE CCECE 2019 conference proceedings (doi: 10.1109/CCECE.2019.8861827).*** *I am the primary author, and I carried out most of the research work, performed the literature reviews, carried out the system design, hardware implementations, experimental setups and analysis of the results. I also prepared the first*

*This chapter is a version of "Development of an IoT Based Open Source SCADA System for PV System Monitoring", L. O. Aghenta and M. T. Iqbal, *CCECE 2019*, doi: 10.1109/CCECE.2019.8861827).

draft of the manuscript and subsequently revised the final manuscript based on the feedback from the co-author and the peer review process. The Co-author, Dr. M. Tariq Iqbal, supervised the research, acquired and made available the research funding, provided the research components, reviewed and corrected the manuscript, and contributed research ideas in the actualization of the manuscript.

Abstract

This paper presents the development of a low cost, open source Supervisory Control and Data Acquisition (SCADA) system for solar photovoltaic (PV) system monitoring and remote control. The proposed SCADA system is based on the Internet of Things (IoT) SCADA architecture which incorporates web services with the conventional SCADA for a robust supervisory control and monitoring. It comprises of analog Current and Voltage sensors for acquiring the desired data from the solar PV system, Arduino Uno micro-controller which serves as a Remote Terminal Unit to receive the acquired sensor data, Raspberry Pi with a Node-RED programming tool for parsing the acquired data (Communication Channel), and Emoncms Local Server IoT Platform for data storage, monitoring and remote control (Master Terminal Unit). The developed SCADA system was set up to monitor and control a 260 W, 12 V solar PV panel in the Electrical and Computer Engineering Laboratory at Memorial University, and some of the created Dashboards and Charts showing the acquired data on Emoncms server where an operator can monitor the data in the cloud using both a computer with internet access, and Emoncms mobile app are presented in the paper.

Index Terms: Low Cost, Open Source SCADA, EMONCMS, Arduino Uno, Raspberry Pi, Node-RED, Instrumentation and Control.

3.1 Introduction

SCADA is an acronym formed from the first letters of the term “Supervisory Control and Data Acquisition”. It is a technology that enables a user to collect data from one or more distant facilities and/or send limited control instructions to those facilities. The major function of SCADA is for acquiring data from remote devices such as batteries, valves, pumps, transmitters, etc. and providing overall monitoring and control remotely from a SCADA host software platform [2, 12]. As in the energy industry across the globe, power system assets, such as inverters are usually distributed over large geographical areas, sometimes in harsh environments. While it may be necessary to have local means of managing the operations of these assets, it is equally important to have a reliable, flexible, cost effective and sophisticated coordinated control. SCADA system is the perfect solution for this task. SCADA makes it unnecessary for an operator to be assigned to stay at or frequently visit these remote locations when the facilities are operating normally. Essentially, a SCADA system performs four basic functions; data acquisition, networked data communication, data presentation, and remote monitoring and supervisory control.

SCADA performs these essential functions using its four basic elements; Field Instrumentation Devices (FIDs) such as sensors and actuators connected to the systems being managed, Remote Terminal Units (RTUs) such as single board computers for acquiring remote data from field instrumentation devices, Master Terminal Units (MTUs) for handling data processing and human machine interactions, and lastly SCADA Communication channels for connecting the RTUs to the MTUs [2].

Generally, there are two classes of SCADA hardware and software; Proprietary and Open Source. In a proprietary system, all major components are from a single manufacturer and the standards are often specific to that system, and developed by the manufacturer. With a proprietary SCADA system, the responsibility for system reliability and security rests solely with the manufacturer, which leaves the user vulnerable to a single manufacturer/supplier as the manufacturer/supplier could be slow to respond to technological changes in a subsystem of the SCADA system. The customer is also at risk if the manufacturer/supplier goes out of business, and the solution is largely expensive. There is also the problem of flexibility with the already existing devices and network. An Open source system allows a user to "mix and match" components and choose the most appropriate from several suppliers. This means that with an open source system, no single supplier is responsible for overall system performance. An open source solution also represents the most cost effective solution as the user is not beholden to a single supplier. In an open source SCADA system, the major components adhere to certain standards which allow them to be interchanged with similar components manufactured by others to the same standards [12]. Therefore, in this paper, an open source SCADA system solution is proposed.

3.2 Literature Review

There are four generations of SCADA system architecture and they include; the first generation (Monolithic), the second generation (Distributed), the third generation (Networked), and the fourth generation (Internet of Things based SCADA architecture) [12]. The Internet of Things concept has to do with connecting physical objects with embedded electronics, software, sensors and connectivity to enable data interchange between these devices and an operator over a common network or the web [1, 3–5].

Various researchers across the globe have in the past designed SCADA systems based on the IoT architecture. In [4], a form of IoT based SCADA system is implemented using Raspberry Pi3 as the sensor gateway, DHTII temperature and humidity sensors to acquire the desired data, and IBM Bluemix cloud platform to receive, visualize and manage the acquired sensor data over the web while using Node-Red and Web Socket Protocol for data exchange and communication between the cloud platform and the Raspberry Pi connected sensors. [3] presented an IoT-based urban climate monitoring system using Arduino Nano, Raspberry Pi2 and Adafruit IO IoT web server. Elsewhere, [6] presented the implementation of a web-based monitoring and control system for real-time electrical data measurement in a hybrid wind/PV/battery system using web-based InTouch for graphical user interface. In [5], the proposed IoT-based SCADA system uses Raspberry Pi3 along with Intel Edison board for sensor inputs, and the acquired sensor data are sent to Amazon Web Services (AWS) IoT platform using MQTT brokers in Node-Red. At the AWS IoT platform, various monitoring and control schemes are initiated using Amazon's Voice Service called Alexa. In another development, [2] developed a low cost SCADA system for CO_2 Enhanced Oil Recovery based on the IoT SCADA architecture using sensors and actuators connected to wellheads, Arduino Yun, Ubiquiti NanoStation wireless Ethernet/IP addressable radios physically connected to the Arduino Yun, and a web enabled central server running MySQL DBMS database for Graphical User Interface. In a recent development, [1] presented the design of an IoT-based sensing and solar house monitoring and automation system using NodeMCU combined with ESP8266 micro-controller as the sensor gateway for communication and data acquisition, and a combination of Blynk and EmonCMS web server for collecting and visualizing the acquired data, and for remote control of home appliances and devices. Also, authors in [7–10] have implemented various forms of IoT-based SCADA systems.

In most of the above mentioned papers, the IoT platform, like the Amazon Web Services presented in [5], the IBM Bluemix in [4], Adafruit IO in [2], and EmonCMS web server in [1], for data storage, monitoring and control is hosted in the cloud, which leaves the stored data vulnerable to web attacks. However, security in a SCADA system is a serious issue both from the operational and economic points of view as the resultant unavailability of the critical infrastructure being monitored in the events of attacks can disrupt the related operations which could cause a huge loss. Therefore, in this paper, local EmonCMS server is used as the IoT platform for data acquisition, storage, monitoring and control. The hardware is installed on a private Linux-based machine and is managed by the user. The local EmonCMS server has all the functionalities of the web-based EmonCMS server, with additional data security as the user is able to manage the server locally [11]. The local EmonCMS server solution is also less expensive as the user only buys the hardware on a one-off basis while the user on the web-based EmonCMS server continuously pays for data storage [11]. Also, the power consumption of the local EmonCMS server is minimal [11]. Furthermore, the data communication modes between the sensor gateways and the IoT platforms presented in some of the literatures are complex and require advanced programming skills, like in the case of Python Script in [2]. To address this shortcoming, the simple, secure Node-Red sensor wiring is proposed for data transfer from the gateway to EmonCMS server.

The remaining part of this paper is dedicated to the design, experimental setup and testing of the proposed IoT-based SCADA system.

3.3 The Proposed SCADA System Design

The proposed low cost, open source SCADA system is based on the Internet of Things (IoT) SCADA architecture. The schematics of the system design configuration is shown in Figure 3.1. The system is made up of analog Voltage and Current sensors, Arduino Uno micro-controller, Raspberry Pi2 single-board computer with Node-Red programming tool for data transmission, and EmonCMS local server IoT Platform for sensor data monitoring and remote control.

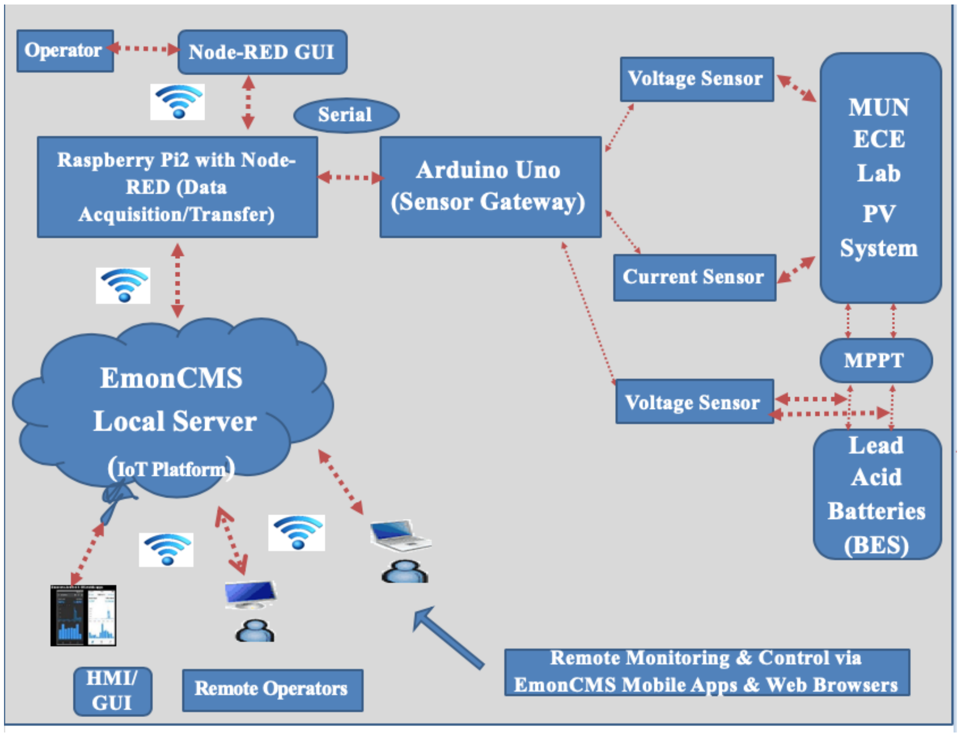

Operator
Node-RED GUI
Serial
Raspberry Pi2 with Node-RED (Data Acquisition/Transfer)
Arduino Uno (Sensor Gateway)
Voltage Sensor
Current Sensor
Voltage Sensor
MUN ECE Lab PV System
MPPT
Lead Acid Batteries (BES)
EmonCMS Local Server (IoT Platform)
HMI/ GUI
Remote Operators
Remote Monitoring & Control via EmonCMS Mobile Apps & Web Browsers

Figure 3.1: Block Diagram of the Proposed IoT-based SCADA System.

3.3.1 Sensors

Sensors are the Field Instrumentation devices in the proposed SCADA system as they are connected directly to the PV system being managed to acquire the desired data [2]. Three analog sensors are used in our setup; one ACS 712 Hall Effect Current Sensor, and two MH Electronic Voltage Sensor modules. The properties of these sensors and their usage in this project are described below:

3.3.1.1 ACS 712 Hall Effect Current Sensor

The ACS 712 Hall Effect Current Sensor is manufactured and supplied by Allegro MicroSystems, LLC. It is a low cost, fully integrated, Hall Effect-based linear current sensor IC with a low-resistance current conductor. In this project, the 30 A model is used to measure the DC current from the solar PV system. To achieve this, its VCC pin is powered with the 5 V on the Arduino Uno board, the OUT pin is connected to Analog pin A0 on the Arduino, and its GND pin is connected to the GND pin on the Arduino while the two Input pins are connected in series to the PV system to measure the DC current flowing through the system.

3.3.1.2 MH Electronic Voltage Sensor module

This low-cost voltage sensor uses the concept of voltage divider to measure the supply voltage across which it is connected. In this project, two voltage sensors are used. One voltage sensor is connected in parallel to the PV system to measure the voltage across it while a second voltage sensor is connected in parallel across the lead acid battery system to measure the stored battery voltage. For the first voltage sensor, PIN S is connected to Analog PIN A1 on the Arduino Uno board, PIN – is connected to a GND pin on the Arduino while its GND and VCC pins are connected in parallel across the PV panel output to measure the voltage across the PV system (PIN + on the sensor is not used). The second sensor is connected to the battery in a similar fashion using Analog PIN A2 on the Arduino Uno board.

3.3.2 Arduino Uno Board

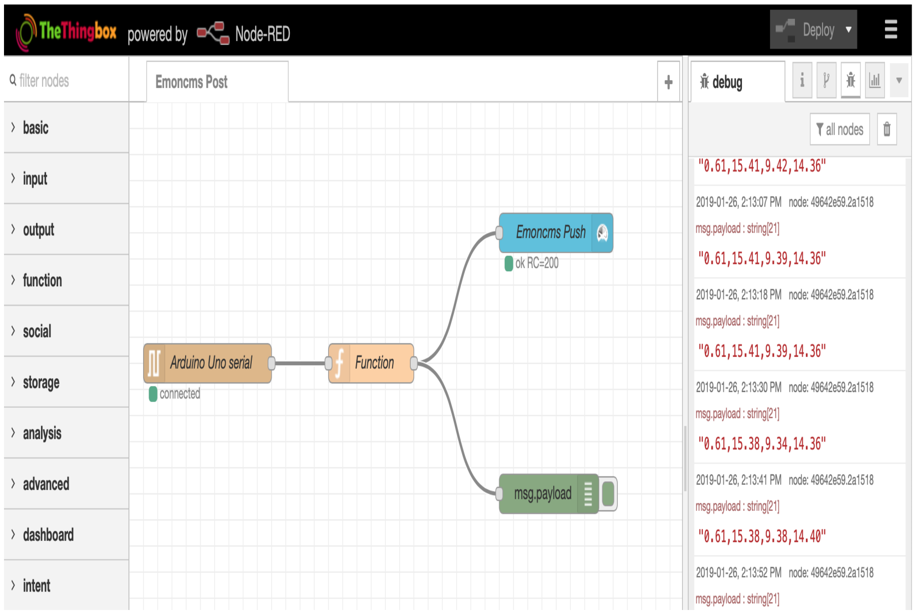
Arduino Uno is a basic, low-cost micro-controller board based on the ATmega328P. It has 14 digital input/output pins, 6 analog inputs (A0 to A5), a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button [10]. In this project, the current and voltage sensors are connected to the Arduino board as described in the sensor section above. First, an Arduino sketch to measure the voltage and DC current from the PV system, and calculate the PV power output from the voltage and current values, as well as to separately measure the voltage stored in the battery via the second voltage sensor is written in the Arduino IDE and uploaded to the board. Secondly, having uploaded the program to the Arduino board, the Arduino board is connected through its USB cable to a USB port on the Raspberry Pi2 to power the Arduino, and to parse the measured and calculated sensor data to the Raspberry Pi using the specified Baud Rate.

3.3.3 Raspberry Pi Board

The Raspberry Pi2 model B used in this project is a 85*56mm single board computer device with BCM2836 quad core ARMv7 processor [3]. In this application, the Node-RED programming tool needed to send the acquired data to EmonCMS IoT platform is installed on the Raspberry Pi. The Raspberry Pi is connected to MUN network using an Ethernet cable which means that any other machine on the network with the right authorization, the EmonCMS server in this case, can communicate with the Node-RED installed on the Raspberry Pi.

3.3.3.1 Node-RED

Developed by IBM, Node-RED is an open source programming tool for wiring together hardware devices, APIs and online services in a smart way [4]. It can be installed on a Linux-based Platform and it provides a browser-based editor that makes it easy to wire together flows using various nodes in the palette that can be deployed to its runtime in a single-click [4, 5]. In this application, the Node-RED is installed on the Raspberry Pi. A Node-RED flow is written to acquire the sensor data from the Arduino Uno Serial port connected to the Raspberry Pi, and post the acquired data to EmonCMS local server using its IP address, input API Key and Node ID. As shown in Figure 3.2 below, the Node-RED flow used consists of an Arduino Uno Serial block which receives sensor data from the Arduino board, a Function block with "JavaScript functions" for parsing the acquired sensor data, an Emoncms Push block containing Emoncms server parameters for posting the sensor data to the platform, and msg.payload block for debugging. The acquired sensor data being posted to Emoncms IoT platform are displayed on the Node-RED display window as shown in the Figure (right hand side).



```
"0.61,15.41,9.42,14.36"
2019-01-26, 2:13:07 PM   node: 49642e59.2a1518
msg.payload : string[21]
"0.61,15.41,9.39,14.36"
2019-01-26, 2:13:18 PM   node: 49642e59.2a1518
msg.payload : string[21]
"0.61,15.41,9.39,14.36"
2019-01-26, 2:13:30 PM   node: 49642e59.2a1518
msg.payload : string[21]
"0.61,15.38,9.34,14.36"
2019-01-26, 2:13:41 PM   node: 49642e59.2a1518
msg.payload : string[21]
"0.61,15.38,9.38,14.40"
2019-01-26, 2:13:52 PM   node: 49642e59.2a1518
msg.payload : string[21]
```

Figure 3.2: Node-RED Flow for EmonCMS Data Logging.

3.3.4 EMONCMS Local Server IoT Platform

EMONCMS is a powerful open-source web-app for processing, logging and visualizing energy, temperature and other physical/environmental data [11]. It is a low-cost IoT platform (under $500 CAD), highly flexible, and it is a part of the OpenEnergyMonitor.org project. It has a Local Server option where a user purchases (one-off) the hardware and installs it on a standalone or networked Windows or Linux based machine for proper management. It also has a web-based server option which can be accessed using its URL just like every other web application. Both the web-based and local server options have IoT capability as the data stored in them can be accessed remotely with an internet enabled computer or with an internet enabled phone via EMonCMS mobile app or phone browser [11]. However, the local server EmonCMS option is more secured as the user has a better control of the server and stored data. A free open source version is available on Github.com.

EmonCMS IoT platform allows the operator to create all kinds of visualization dashboards and events for remote monitoring and supervisory control. It also allows an operator to create customized reports in the form of charts, data logs and alarms which can be viewed either locally, via email notifications, via web browsers, and EmonCMS mobile apps [11].

In this project, the EmonCMS local server receives the PV voltage, PV current, measured PV power, and stored battery voltage from the Node-RED program installed on the Raspberry Pi. At EmonCMS Inputs, the Node-RED program identifies the specified Node ID and displays the data. These Input data are logged automatically, as set up by the operator, to EmonCMS Feeds in order to maintain a history of the received data. The data at both the Inputs and Feeds are stored, while remote monitoring, and control access/commands are initiated via Dashboards and Events created by the operator.

3.3.5 MUN ECE Laboratory PV System Overview

The Memorial University Electrical and Computer Engineering Laboratory PV system is a 260 W, 12 V PV panel with Maximum Power Point Tracking (MPPT) system. Electrical batteries are connected to the MPPT to store the energy from the solar panels for use during prolonged extreme weather conditions. In this project, the SCADA system is set up to acquire the PV voltage, current and power, and the stored battery voltage for remote monitoring and supervisory control.

3.4 Experimental Setup of the Proposed SCADA System

The proposed SCADA system is set up in MUN ECE Laboratory as shown in Figure 3.3. On the wall is the PV System being monitored, and for testing purposes, one module is used. The inputs of the current and voltage sensors (sensors shown in the Figure) are connected to the PV module and the battery system (batteries are below the table in the Figure) using electrical cables, and the sensor outputs are connected via cables to an Arduino Uno board (left). The Arduino Uno is connected to a Raspberry Pi (right) via a serial USB cable such that the Arduino parses the acquired sensor PV data to the Node-RED program on the Raspberry Pi via this serial USB cable. The Raspberry Pi is connected to MUN network using an RJ45 Ethernet cable (the blue cable in the Figure). Hence, the Node-RED program installed on the Raspberry Pi sends the received data to EmonCMS server using the developed Node-RED wiring flows on the Raspberry Pi via the MUN network (wired network with the Ethernet cable).

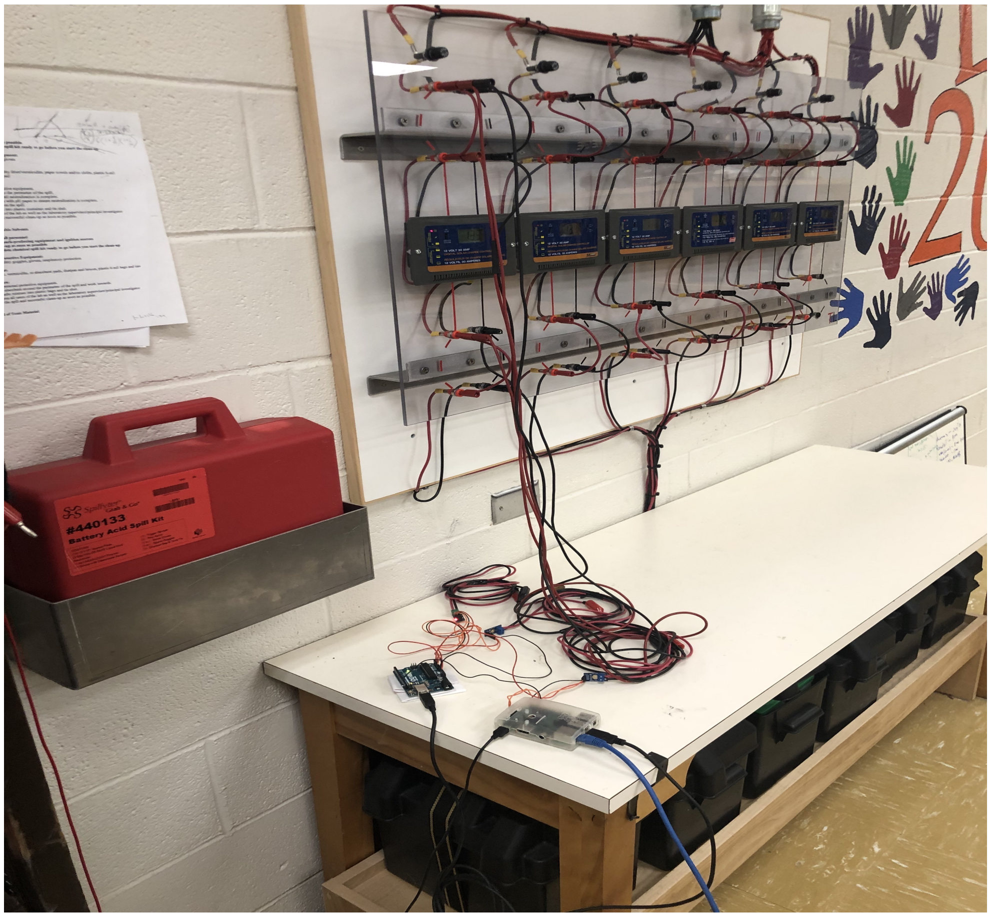


Figure 3.3: Experimental Setup of The Proposed SCADA System.

3.5 Testing, Results and Discussions

The proposed SCADA system was set up in MUN ECE Laboratory to acquire data from the PV system, and post it, using Node-RED to EmonCMS local server for remote monitoring and supervisory control. Figure 3.4 shows the data flow from the PV system to Emoncms IoT Platform.

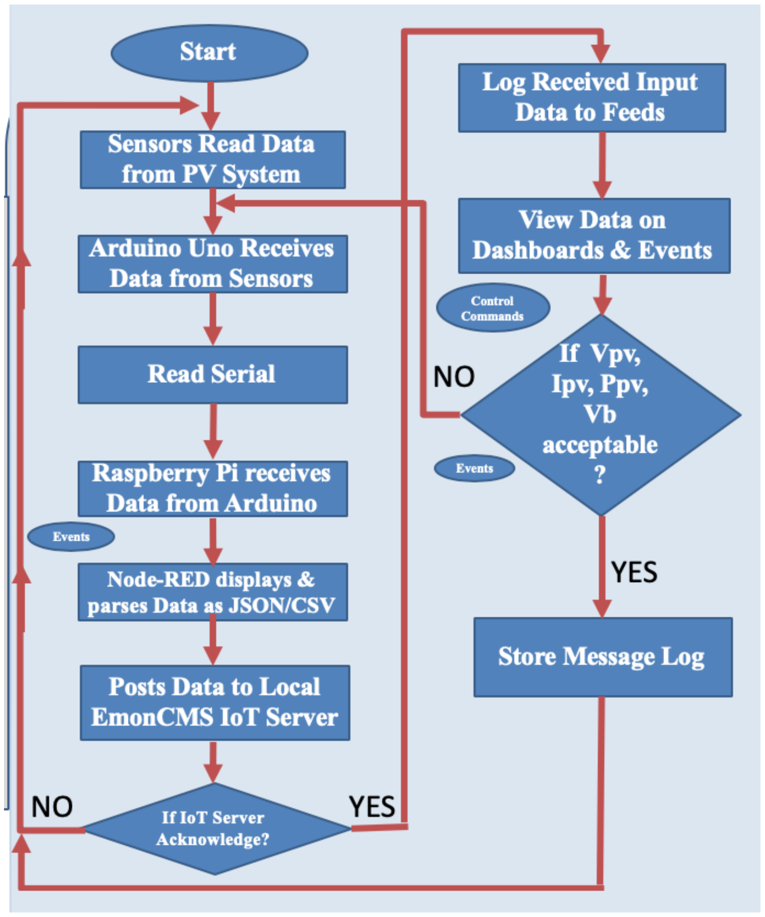

Start
Sensors Read Data from PV System
Arduino Uno Receives Data from Sensors
Read Serial
Raspberry Pi receives Data from Arduino
Events
Node-RED displays & parses Data as JSON/CSV
Posts Data to Local EmonCMS IoT Server
NO
If IoT Server Acknowledge?
YES
Log Received Input Data to Feeds
View Data on Dashboards & Events
Control Commands
NO
If Vpv, Ipv, Ppv, Vb acceptable ?
Events
YES
Store Message Log

Figure 3.4: Flow Chat of the Proposed SCADA System Data Acquisition.

3.5.1 Results

The system was tested for two weeks. The data received at EmonCMS Input window were automatically logged to the Feeds window. Having received the PV system data, customized dashboards and reports in the form of charts, data logs and alarms were created on EmonCMS IoT Platform. These dashboards, events and reports which could be viewed either locally, through email notifications, web browsers, and EmonCMS mobile apps help an operator to monitor the stored data, view trends in the stored data, and initiate supervisory controls remotely. Figures 3.5 and 3.6 show two of the created dashboards for real-time data visualization and raw-data visualization respectively. In Figure 3.5, real-time values of PV Voltage, Current, and Power, and Battery Voltage are being visualized respectively, and the time intervals and time stamps for each data received are displayed. In Figure 3.6, raw values for PV Voltage, Current, and Power, and Battery Voltage are being visualized respectively at various time intervals shown in the Figure. The vibrations of the raw data show the changes in the values of the received data due to the fluctuating environmental conditions affecting the PV System. Although the recorded voltage and current values are low at this time due to the snow conditions in St. John's at this time of the year, the voltage and current sensors are capable of measuring up to 25 V and 30 A respectively. However, the acquired sensor data match the values measured locally using conventional current and voltage digital multimeters. Aside Figures 3.5 and 3.6 shown, EmonCMS Mobile App was also connected to EmonCMS local server IoT Platform by scanning the barcode of the platform using the Mobile App for a more flexible remote monitoring. Other Scheduling and Visualization features such as bargraphs, histgraphs, and timecompare are available on EmonCMS IoT Platform [11].

3.5.2 Discussions

Some of the key features of the developed IoT based SCADA system are enumerated below:

- **Internet of Things based SCADA System:** It is based on the Internet of Things SCADA architecture and it has the four basic elements of a SCADA system listed earlier in this paper.

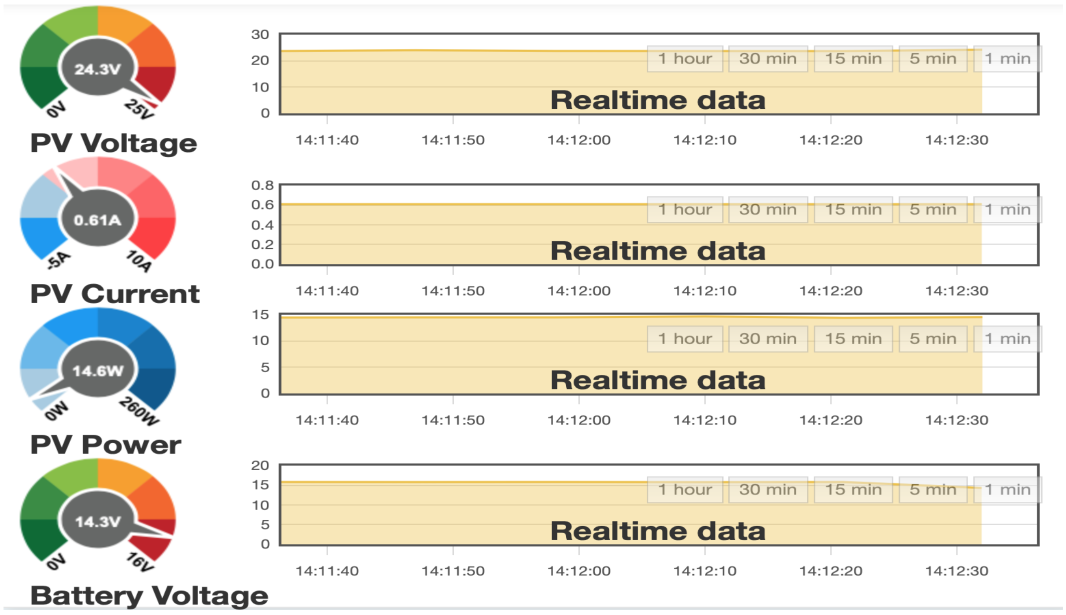


Figure 3.5: Created EmonCMS Dashboard showing Real-time Data Visualization.

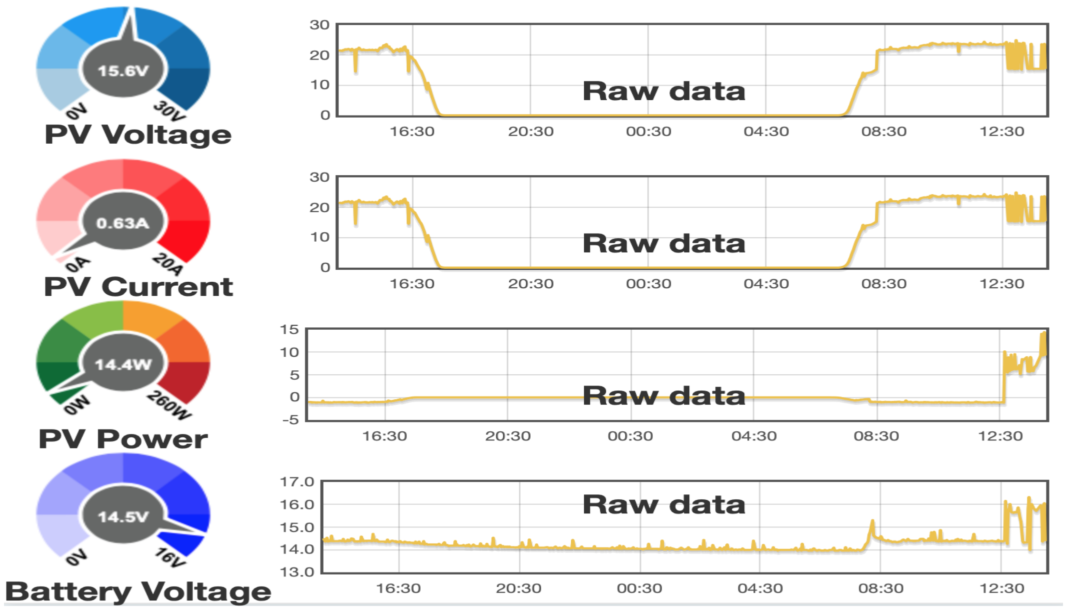


Figure 3.6: Created EmonCMS Dashboard showing Raw Data Visualization.

- **Low Cost, Open Source:** All the components of the proposed system are manufactured and supplied by different manufacturers (mix and match) which is one of the key characteristics of an open source system.

- **Data Acquisition and Historic Storage:** The SCADA system stores the received data and maintains data history. It also supports adjustable data log and storage rate.
- **Remote Monitoring and Supervisory Control:** It enables an operator to create Events and Dashboards for remote monitoring and supervisory control via web browsers and EmonCMS Mobile App.
- **Reporting:** It presents reports to the operator and key decision makers in the form of charts, data logs, and alarms (local, email, web, and mobile app).

3.6 Conclusions

In this paper, the development of a low cost, open source Internet of Things based SCADA system has been presented. The developed SCADA system has all the four basic elements needed in a SCADA system, including field instrumentation devices, remote terminal units, master terminal units, and SCADA communication channel. The experimental setup of the developed SCADA system was carried out in MUN ECE Laboratory and it was used to acquire, and remotely monitor and control a 260 W, 12 V solar PV panel system. The system has been tested and upon testing, the system was able to carry out the desired functions of a SCADA including data acquisition, networked data communication, data presentation, remote monitoring and supervisory control. The developed SCADA system can also be applied in other industries to remotely monitor and control critical infrastructures such as electric power generation, transmission and distribution systems, buildings, facilities and environments, oil and gas production facilities, mass transit systems, water and sewage systems, and traffic signal systems.

Acknowledgements

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Chapter 4

Low-Cost, IoT-Based Open Source SCADA System using Thinger.IO and ESP32 Thing*

Preface

A version of this manuscript has been published in the ***Electronics Journal, Special Issue on Modern Mechatronics and Automation — An Open-Source Approach. Electronics 2019, 8(8), 822; https://doi.org/10.3390/electronics8080822.*** *I am the primary author, and I carried out most of the research work, performed the literature reviews, carried out the system design, hardware implementations, experimental setups and analysis of the results. I also prepared the first draft of the manuscript and subsequently revised the final manuscript based on the feedback from the co-author and the peer review process. The Co-author, Dr. M. Tariq Iqbal, supervised the research, acquired and made available the research funding,*

*This chapter is a version of "Low-Cost, Open Source IoT-Based SCADA System Design Using Thinger.IO and ESP32 Thing", L. O. Aghenta and M. T. Iqbal, *Electronics* **Vol.8, No. 8**, p. 822, electronics8080822 (2019).

provided the research components, reviewed and corrected the manuscript, and contributed research ideas in the actualization of the manuscript.

Abstract

Supervisory Control and Data Acquisition (SCADA) is a technology for monitoring and controlling distributed processes. SCADA provides real-time data exchange between a control/monitoring centre and field devices connected to the distributed processes. A SCADA system performs these functions using its four basic elements: Field Instrumentation Devices (FIDs) such as sensors and actuators which are connected to the distributed process plants being managed, Remote Terminal Units (RTUs) such as single board computers for receiving, processing and sending the remote data from the field instrumentation devices, Master Terminal Units (MTUs) for handling data processing and human machine interactions, and lastly SCADA Communication Channels for connecting the RTUs to the MTUs, and for parsing the acquired data. Generally, there are two classes of SCADA hardware and software; Proprietary (Commercial) and Open Source. In this paper, we present the design and implementation of a low-cost, Open Source SCADA system by using Thinger.IO local server IoT platform as the MTU and ESP32 Thing micro-controller as the RTU. SCADA architectures have evolved over the years from monolithic (stand-alone) through distributed and networked architectures to the latest Internet of Things (IoT) architecture. The SCADA system proposed in this work is based on the Internet of Things SCADA architecture which incorporates web services with the conventional (traditional) SCADA for a more robust supervisory control and monitoring. It comprises of analog Current and Voltage Sensors, the low-power ESP32 Thing micro-controller, a Raspberry Pi micro-controller, and a local Wi-Fi Router. In its implementation, the current and voltage sensors acquire the desired data from the process plant, the ESP32 micro-controller receives, processes and sends the acquired sensor data via a Wi-Fi network to the Thinger.IO local server IoT platform for data storage, real-time monitoring and remote control. The Thinger.IO server is locally hosted by the Raspberry Pi micro-controller, while the Wi-Fi network which forms the SCADA communication channel is created using the Wi-Fi Router. In order to test the proposed SCADA system solution, the designed hardware was set up to remotely monitor the Photovoltaic (PV) voltage, current, and power, as well as the storage battery voltage of a 260 W, 12 V Solar PV System. Some of the created Human Machine Interfaces (HMIs) on Thinger.IO Server where an operator can remotely monitor the data in the cloud, as well as initiate supervisory control activities if the acquired data are not in the expected range, using both a computer connected to the network, and Thinger.IO Mobile Apps are presented in the paper.

Index Terms: open source; SCADA; Thinger.IO; Internet of Things; ESP32 Thing; Raspberry Pi; automation; instrumentation and control

4.1 Introduction

The acronym, SCADA, stands for Supervisory Control And Data Acquisition. A SCADA system is a collection of both software and hardware components that allows for the supervision and control of plants and industrial processes both locally and remotely. The system involves the examination, collection, and processing of data in real time, as well as data logging for historical purposes. The architectural design of a standard SCADA system starts with Remote Terminal Units (RTUs), and/or Programmable Logic Controllers (PLCs). These RTUs and PLCs are micro-controllers or microprocessors that communicate and interact with Field Instrumentation Devices (FIDs) such as sensors, actuators, valves, pumps and transmitters. These communication data are routed from the controllers or processors via a SCADA Communication Channel to the SCADA computers known as Master

Terminal Units (MTUs) where the data are interpreted and displayed on a Human Machine Interface (HMI) allowing operators and important decision makers to analyze and react to process events [1–5].

SCADA technology has evolved over the past 30 years as a method of monitoring and controlling distributed processes [5]. Before the emergence of SCADA, plant personnel had to monitor and control industrial processes via selector switches, push buttons, and dials (for analog signals), which meant that plants needed to maintain a good number of personnel on site during production to be able to carry out these manual monitoring and control tasks. As industrial processes grew and sites became more remote in nature, relays and timers were used to assist in the supervision and control of processes, which meant that fewer number of personnel were required on site to oversee their operations. While relays and timers provided a decent level of automation, they required more resources to manage their operations. The need to automate more processes, which coupled with the difficulties associated with the previous monitoring and control solutions gave birth to the first generation SCADA systems in the 1970s called Monolithic SCADA, and they were stand-alone units. With the advent of Local Area Network (LAN) and HMI softwares in the 1980s and 1990s, and with computer systems getting smaller and smarter, it became possible to connect SCADA systems to related systems which gave rise to the second generation SCADA called Distributed SCADA. Unfortunately then, the communications were typically proprietary which meant that the connections outside of the vendors of a particular SCADA system were not possible [2–4].

Later in the 1990s and 2000s, SCADA began to implement open system architectures with communication protocols that were no longer vendor specific, leading to more connection capabilities in the form of a wide area network. This resulted in a more improved SCADA system called Networked SCADA system (3_{rd} generation). With computer technologies growing rapidly, this SCADA was quickly out of date as other technologies were becoming more efficient and more in tune with the latest Information Technology (IT) developments. SCADA manufacturers had to rise to the challenge to come up with a SCADA architecture with great advantages over older SCADA systems. This is the Internet of Things SCADA architecture (4_{th} generation) which incorporates cloud services with the conventional SCADA system for more robust monitoring and control [6]. This SCADA allows for real-time plant information to be accessed from anywhere around the world using various operating systems and platforms [2, 3, 7]. The Internet of Things (IoT) concept has to do with the connection of physical objects with embedded electronics, software, sensors and connectivity to enable data interchange between these devices and an operator over a common platform or the web [6–10].

Presently, as in the past, automation companies such as Emerson, Siemens, Schneider Electric, and Allen Bradley develop various forms of SCADA hardware and software which they sell as turnkey solutions to end users. Examples of such solutions include Ovation SCADA communication server (Emerson), Simatic WinCC (Siemens), Clear SCADA server (Schneider Electric), and Micro SCADA (Allen Bradley) [3, 11]. Currently, these systems come with various IoT-based MTUs for data visualization and process management such as the Totally Integrated Automation (TIA) portal in Siemens' Simatic WinCC [11]. In addition to the huge initial capital costs of buying these SCADA systems, which are in thousands of dollars, the end user is made to pay for annual maintenance and support fees to use the SCADA system solutions. For very large companies, like most companies in the Oil and Gas sectors, the costs of owning these commercial SCADA systems might be justifiable or affordable. However, for smaller companies with no enormous financial resources, but with the need to deploy SCADA solutions to monitor and control their distributed facilities, such as companies in the power sector or renewable generation systems, these commercial SCADA solutions do not represent a profitable choice. With the commercial systems, there is also the problem of interoperability with the existing infrastructures, for example power electronic converters in a power system [12]. Seamless communication among devices in modern power systems is the key to successful SCADA implementation [13,14]. Therefore, a low-cost, open source SCADA solution represents the most viable solution [4, 7, 12].

In this work, we propose a low-cost, open source SCADA system based on the most recent SCADA architecture, which is the Internet of Things [6,10,15]. Our proposed SCADA system uses reliable and commonly available components to achieve the four basic functions of a SCADA system which the available commercial SCADA systems also perform: Data acquisition, networked data communication, data presentation, and remote monitoring and supervisory control [1, 9].

The remainder of this paper is organized as follows. In Section 4.2, we present the related works, problem statements, and the proposed SCADA system as a solution to the identified problems. In Section 4.3, we present system descriptions, including the proposed SCADA system design configurations. In Section 4.4, we present the components of the proposed SCADA system and the detailed description of each of the components. Section 4.5 presents the implementation methodology, Section 4.6 presents the prototype design, Section 4.7 presents the experimental setup of the proposed SCADA system, and Section 4.8 presents the testing carried out and the results. In Section 4.9, the key features of the designed SCADA system are discussed, including the system cost and power consumption analysis. The paper is concluded in Section 4.10, and future work presented in Section 4.11.

4.2 Literature Review

The research communities all over the world have tried to solve the problems associated with commercial SCADA systems (high costs and compatibility issues) by developing various open source SCADA solutions, each with varying costs and functionalities. Rajkumar et al. [16] have proposed a low-cost, open source SCADA system using Arduino Uno micro-controller as the sensor gateway, and ZigBee Radio Modules for data transmission from their field instrumentation devices such as flow sensors, temperature sensors, level sensors, control valves, and pumps to a data processing software, which they created with Java, where reports on the state of the process facility are generated and visualized. In [17], a form of low-cost web-based SCADA solution is proposed. In this solution, Radio Frequency (RF) Receivers connected to a controller circuitry collect plant data, and the data are made available to the controller which, in turn parses the data to a driver circuitry for set point verification before the data get transmitted via the internet to a web-based SCADA server for visualization. The proposed solution here is complex as it involves the use of a mathematical model for data verification in the controller and driver circuitries before transmission to the web-based SCADA server.

Elsewhere, Merchan et al. [18] implemented an open source SCADA system by using the general purpose programming platform, Python. Their proposed system is made up of three layers: a Device Layer, which is the process plant being managed, a Controller Layer, which comprises of two PLCs, and lastly, a Supervision Layer comprising of HMI SCADA client, and Python Open Platform Communications Unified Architecture (OPC-UA) Server with Structured Query Language (MySQL) Database, both installed in a Raspberry Pi3. Here, communication between the control devices is via Ethernet. This solution uses a lot of components which means more power consumption and less reliability of the resultant SCADA system. The authors in [19] have implemented a form of open source SCADA system for the monitoring of the level and flow rate of water in a container by using the open source SCADA platform called OpenSCADA where HMIs are created for data visualization. The major issues here are that the OpenSCADA software is not entirely free as it requires user subscriptions, and the proposed solution involves a large amount of logical programming for accurate data acquisition and visualization in the OpenSCADA platform.

Similar to [19], Avhad et al. [20] have proposed a form of open source automation system using Vijeo Citect SCADA software as the MTU, AtMEGA 2560 micro-controller as the RTU for sensor data collection, and ModBus protocol as the communication channel between the MTU and the RTU. In another development, Mononen et al. [21] proposed a low-cost open source SCADA system comprising of sensor network for data collection, and a microprocessor for data processing and transmission via UDP Ethernet frame to a cloud environment. The cloud environment is composed of virtual machines running user-defined algorithms in the cloud for accurate data processing and handling. Just like [21], the authors in [7] have developed a low-cost SCADA system based on IoT technology where the RTU is connected to the field devices through TCP/IP and supported on a NoSQL database. The functionalities of their developed system were evaluated using a traffic management process. The major problem with these systems is that they are complex systems which will be difficult for an ordinary end-user to use. Furthermore, the solution in [21] is prone to errors as it requires a great deal of user-defined algorithms in the cloud.

In this paper, we present the detailed design of a SCADA system using very few low-cost, low-power, and completely open source components. In our proposed SCADA solution, a locally installed Thinger.IO Server IoT Platform serves as the Master Terminal Unit where HMIs are created for data visualization and processing, and the versatile Sparkfun ESP32 Thing micro-controller serves as the Remote Terminal Unit for receiving and sending the sensor data from the Field Instrumentation Devices (sensors), while a local Wi-Fi Network provides the Communication Channel between the MTU and the RTU, resulting in a form of industrial network as implemented by the commercial SCADA vendors all over the world [3, 9, 11].

The authors in [22–24] have used Thinger.IO to implement their respective remote monitoring and automation systems. In their systems, the acquired sensor data are sent to Thinger.IO cloud platform where HMI dashboards are created for data visualization.

In [22], the visualized data are used for smart home energy decisions, while the acquired data in [23] are used for RESTful motion detection where the operator is notified of process changes via the Thinger.IO platform. The implemented system in [24] is a smart emergency response system using the powerful IoT properties of the Thinger.IO platform. Unlike our work where a locally installed Thinger.IO IoT server is used, these authors have used the web-based Thinger.IO platform requiring the public internet for access which means that the resulting monitoring solutions are vulnerable to internet attacks. Security in a SCADA system is a serious issue as attacks on a SCADA system can compromise the critical process facilities being managed [4, 9, 25, 26]. To ensure the security of a SCADA system, several techniques can be used. Some of these techniques include a security technique focused on the communication channel or network as discussed in [27–29], a technique focused on protecting the hardware components as in [30], and a data-driven technique focused on protecting the cloud server as discussed in [6, 25, 31, 32], or a combination of two or more of these techniques [27, 33]. The SCADA system proposed in this work considers a combination of some of these security techniques, including the private network management and the data-driven private cloud server management techniques. Here, because the main cloud server is locally hosted on Memorial University (MUN) network, the operator has full control of the security of the system and can take several measures to protect the data in the cloud, such as ensuring access control, whitelists, authentication, authorization, firewalls, regular risk assessment, continuous monitoring and log analysis, updating and patching regularly, etc. [6, 15, 25, 28]. This is why we propose a locally installed Thinger.IO IoT server in this work, and to the best of our knowledge from reviewed literatures, and related works, we have not found a SCADA system solution where a locally installed Thinger.IO IoT server has been used.

It should be noted that the SCADA system solution presented in this paper is similar in functionalities to our previous open source IoT-based SCADA system [9], where we used a locally installed EMONCMS IoT server as the Master Terminal Unit, and Arduino Uno and Raspberry Pi as the RTUs to receive sensor data, with Node-RED flows, which used Ethernet for communication, serving as the Communication Channel between the MTU and the RTUs. However, as the components and the design and implementation methodologies used in both systems are totally different, the work presented here is not a continuation of our previous work but rather a different open source SCADA system solution meant to tackle the shortcomings in the available commercial SCADA systems, and the reviewed open source SCADA system solutions. Also, in our previous open source SCADA system solution, more components were used which meant more difficulty in implementation and usage, more power consumption, less reliability, and more cost. Furthermore, unlike our previous SCADA system solution where a single configuration was considered, two configurations are tested and presented in this current work. The first configuration is one in which data on the Thinger.IO IoT platform are accessible over the internet as long as the user is within the Memorial University network and has the authorizations to connect to the network. In this case, the Raspberry Pi micro-controller hosting the Thinger.IO IoT Server is connected to MUN Network using an RJ45 Ethernet cable. The second configuration is such that only the users connected to the locally created Wi-Fi Network (this connection is either wireless or via network cables to the LAN ports of the Wi-Fi Router) can connect to the Thinger.IO IoT platform for data visualization, remote monitoring and supervisory control. This second configuration creates a form of industrial network which is only accessible to authorized users on the network. In either configurations, the proposed SCADA system solution here will help to tackle the mentioned setbacks in the systems presented in literatures, high cost and compatibility issues in the available commercial SCADA systems, and the minor setbacks in our previous SCADA system solution by using fewer components which are known to consume less power, and are less expensive, while ensuring the same robust SCADA functionalities as in both our previous work and the available commercial

SCADA system solutions.

The rest of this paper is dedicated to the system and components descriptions, implementation methodology, prototype design, experimental setup and testing of the proposed low-cost, open source IoT-based SCADA system solution.

4.3 System Description

The proposed low-cost, open source SCADA system is based on the Internet of Things (IoT) SCADA architecture which is the fourth and most recent SCADA architecture [4, 9, 10]. In connecting the hardware components together, two configurations are considered. In the first configuration, the Raspberry Pi is connected to MUN Network via an Ethernet cable so that users on the network with the right authorizations can visualize the acquired data on the Thinger.IO IoT server platform. Also, in this configuration, by opening the Thinger.IO port on MUN network, users can access the stored data over the internet using their private office or home network. In the second configuration, the Raspberry Pi is connected to one of the LAN ports of the local Wi-Fi Router such that only the machines connected to the Wi-Fi network, either wirelessly or via Ethernet cables connected to the LAN ports of the Router, can access the data on Thinger.IO local server IoT platform by using the IP address of the Raspberry Pi. Although the first configuration is more flexible, the second configuration is more secure, as this configuration ensures a kind of industrial network is created, with external internet users, even on MUN network, shut out. In either of the configurations, the ESP32 Thing can connect to the Thinger.IO server over Wi-Fi by using the IP address of the Raspberry Pi. The two configurations are shown below in Figures 4.1 and 4.2 respectively:

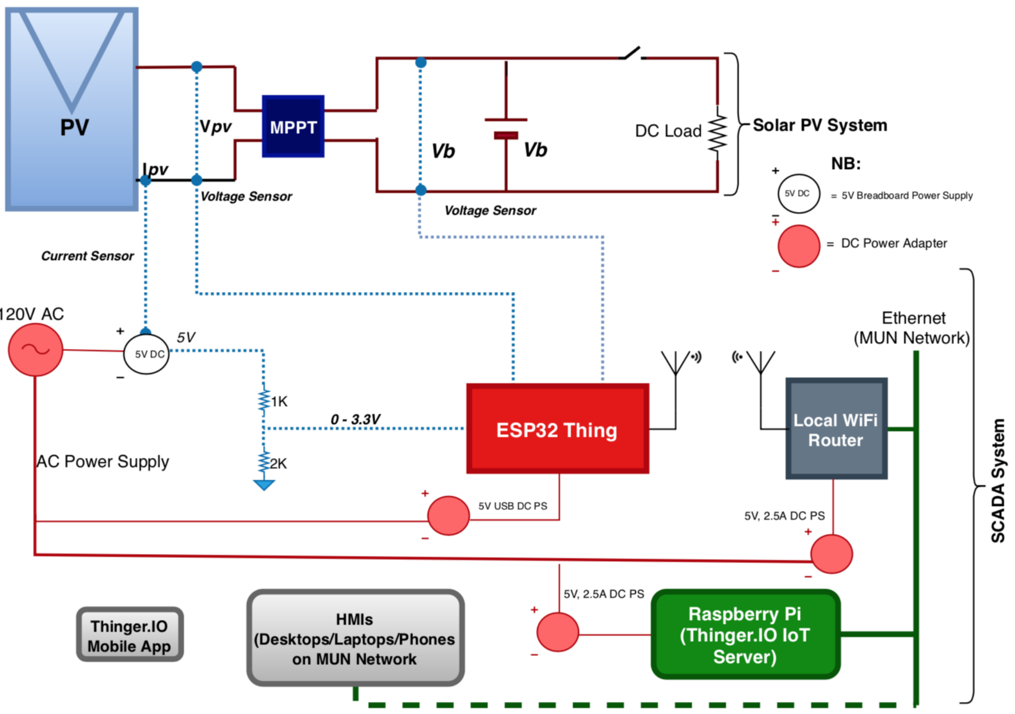


Figure 4.1: The first configuration (A) of the proposed Supervisory Control and Data Acquisition (SCADA) system.

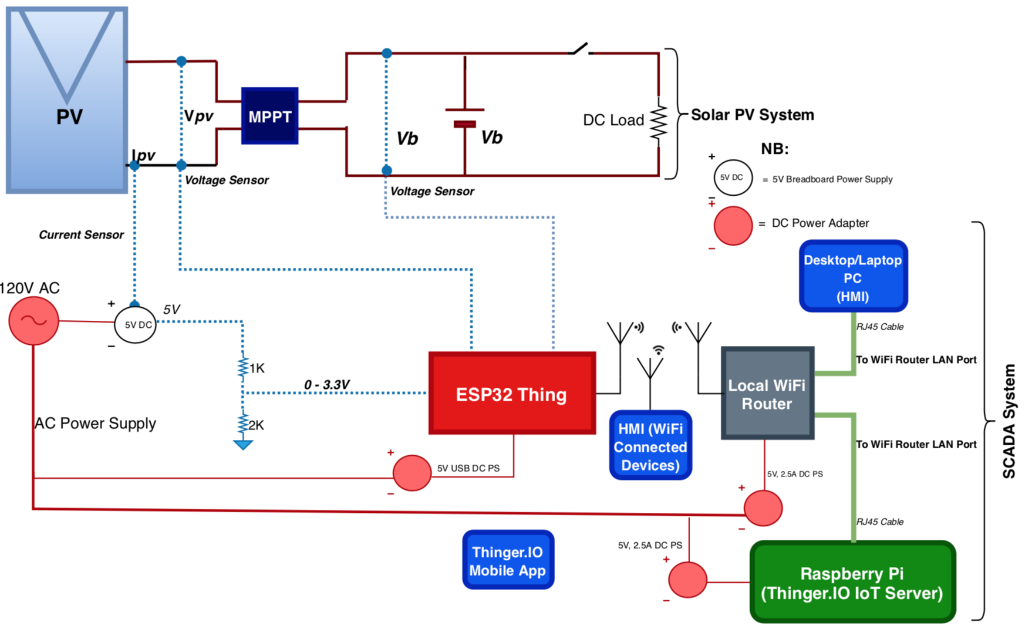


Figure 4.2: The second configuration (B) of the proposed SCADA system.

4.4 Components of the Proposed SCADA System

The SCADA system proposed in this work is made up of analog voltage and current sensors for data acquisition, SparkFun ESP32 Thing micro-controller for receiving, processing and parsing the sensor data, Wi-Fi Router for local Wi-Fi network creation (communication channel), and Thinger.IO local IoT server with graphical user interface (dashboards) created for remote sensor data monitoring and supervisory control. Each of these components is described in details below:

4.4.1 Sensors

Sensors are the Field Instrumentation Devices in the proposed SCADA system as they are connected directly to the PV system being managed to acquire the desired data [1, 34]. Three analog sensors are used in our setup; one ACS 712 Hall Effect Current Sensor, and two MH Electronic Voltage Sensor modules. The operating signal voltage (VCC) of the current sensor is 5 V single supply, and that of voltage sensor is between 3.3 V to 5 V, while that of the ESP32 Thing micro-controller is 0 V to 3.3 V. This means that the current sensor is not suitable for direct connection to the analog-to-digital converter (ADC) Pins of the ESP32 Thing. Therefore, in order to ensure that the sensor matches the 3.3 V signal voltage of the ESP32 Thing, some level shifting is carried out by using a pull-down or step-down resistor arrangement (Figure 4.3). This will ensure the accuracy of the measured sensor value. The properties of these sensors and their usage in this work are described below:

4.4.1.1 ACS 712 Hall Effect Current Sensor

The ACS 712 Hall Effect Current Sensor, manufactured and supplied by Allegro MicroSystems, LLC. is a low-cost, fully integrated, Hall Effect-based linear current sensor IC with

2.1 kVRMS Isolation and a low-resistance current conductor. It has a low-noise analog signal path, 5 V single supply operation, 66 to 185 mV/A output sensitivity, and nearly zero magnetic hysteresis. In its operation, the applied current flowing through the copper conduction path generates a magnetic field which the Hall IC converts into a proportional output voltage [35]. The output voltage is proportional to the AC or DC currents being measured [35]. In this project, the 30 A module is used to measure the DC current from the solar PV system. This module is able to measure current values from 0 A to 30 A. Also, with this module, 0 A corresponds to 2.5 V, while 30 A corresponds to 5 V. These parameters, as well as the parameters of the ESP32 Thing ADC Pins are taken into consideration in writing the ESP32-Arduino code to measure the PV current with the sensor. With respect to the physical connections, the pull-down or step-down resistors arrangement described in “Sensors” above is used to match the 5V signal requirement of the Current Sensor to the 3.3 V signal capability of the ESP32 Thing ADC Pins. The step-down resistors arrangement showing the connection of the sensor to the ESP32 Thing is shown in Figure 4.3, and the voltage divider equation is shown in Equation 4.1. As can be seen, it’s VCC pin is powered with the 5 V supply from the Breadboard, the OUT pin is connected via the pull-down resistors to the Analog pin 32 on the ESP32 Thing micro-controller, and its ground (GND) pin is connected to the GND pin on the Breadboard while the two Input pins are connected in series to the PV system to measure the DC current flowing through the system.

$$V_{out} = \frac{R_2}{(R_1 + R_2)} \times V_{in} \tag{4.1}$$

where V_{out} = ESP32 ADC Voltage (3.3 V), and V_{in} = Sensor Input Voltage from the Breadboard (5 V), while and R_1 and R_2 are calculated to match these voltage values using the voltage divider equation above.

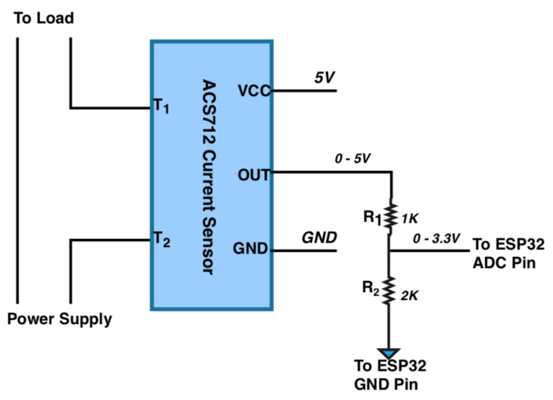


Figure 4.3: ACS712 step-down resistors connection.

4.4.1.2 MH Electronic Voltage Sensor Modules

This is a low-cost analog voltage sensor capable of detecting supply voltages in the range of 0.025 V to 25 V. The sensor uses the concept of voltage divider to measure voltage. This voltage divider is a series connection of a 30 K resistor and a 7.5 K resistor. Its operating voltage range is 3.3 V to 5.0 V, and the voltage analog resolution is 0.000806 V for a 12-bit ADC [36]. In our setup, two voltage sensors are used; one of the voltage sensors is connected in parallel to the PV system to measure the voltage across it while the second one is connected in parallel across the lead acid battery system to measure the storage battery voltage. For the first voltage sensor, PIN S is connected to Analog PIN 34 on the ESP32, PIN—is connected to a GND pin on the ESP32 while its GND and VCC pins are connected in parallel across the PV panel output to measure the voltage across the PV system (PIN + on the sensor is not used). For the second voltage sensor, PIN S is connected to Analog PIN 35 on the ESP32, PIN—is connected to a GND pin on the ESP32 while its GND and VCC pins are connected (after the MPPT module) in parallel across the battery to measure the battery voltage (PIN + on the sensor is not used).

4.4.2 ESP32 Thing Micro-Controller (RTU)

The ESP32 Thing, manufactured and supplied by SparkFun Electronics, is a comprehensive development platform. It is a Wi-Fi compatible micro-controller, it supports Bluetooth Low-Energy (i.e., BLE, BT4.0, Bluetooth Smart), and it has nearly 30 Input/Output (I/O) pins [37]. According to the manufacturer, it is called the "Thing" because it is the perfect foundation for Internet of Things projects [37]. It is one of the most unique low-cost (about $20 CAD), low-power (about 0.5 W) micro-controllers available on the market today. The board can be powered with either a 5 V USB power supply or with a single-cell lithium-polymer (LiPo) battery, and its operating signal voltage range is 2.2 V to 3.6 V. The I/O pins of the ESP32 Thing board are only 3.3 V tolerant, hence the need for the level shifting of the connected 5 V current sensor explained earlier. Figure 4.4 shows a picture of the SparkFun ESP32 board while Figure 4.5 shows a summary of the hardware specifications of the board [37].

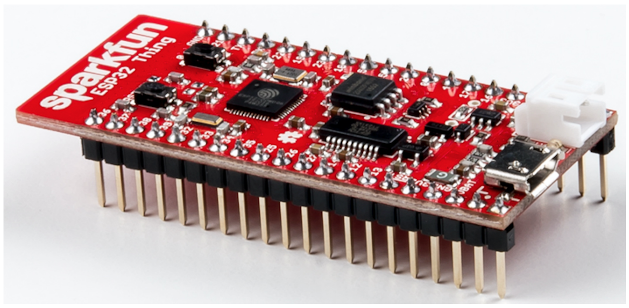
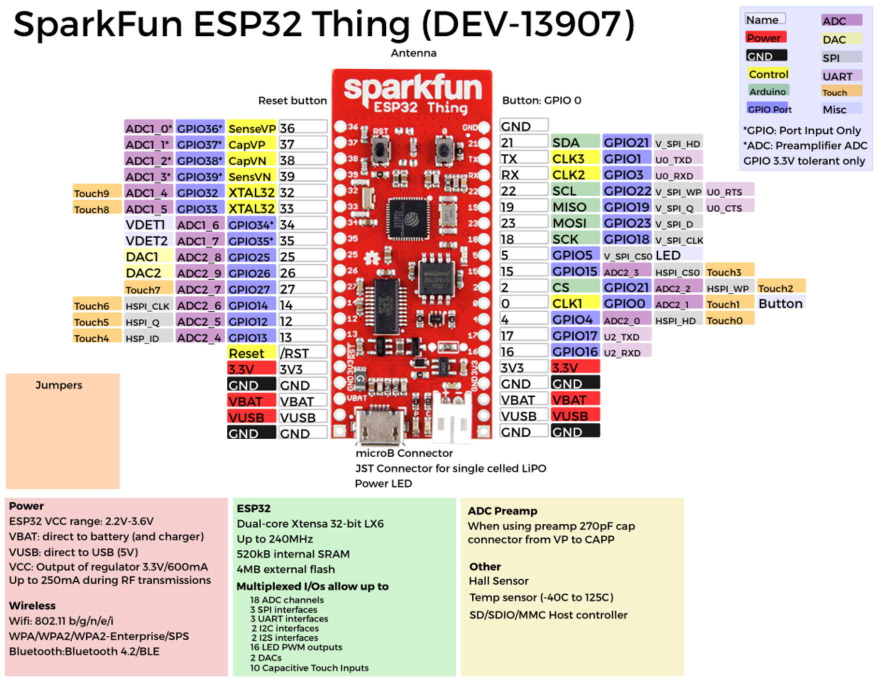


Figure 4.4: Image of the SparkFun ESP32 Thing board [37].

The ESP32 Thing micro-controller is programmed with an Arduino software integrated development environment (IDE). The Arduino IDE allows one to write the desired programs and upload them to the board via a USB cable. Arduino programs are called Sketches, and its language is merely a set of C/C++ functions [37]. In this project, the ESP32 Thing is hooked to a Breadboard, and the current and voltage sensors are connected to it as described in the "Sensors" section above. First, an Arduino sketch to measure the voltage and

DC current from the PV system, and calculate the PV power output from the voltage and current values, as well as to separately measure the storage battery voltage via the sensors is written in the Arduino IDE and uploaded to the board. The measured and calculated values are displayed on the Serial Monitor of the Arduino IDE using the specified Baud Rate. Secondly, having uploaded the program (sketch) into the ESP32 Thing board, the board is powered with a 5 V USB power cable.



Power
ESP32 VCC range: 2.2V-3.6V
VBAT: direct to battery (and charger)
VUSB: direct to USB (5V)
VCC: Output of regulator 3.3V/600mA
Up to 250mA during RF transmissions

Wireless
Wifi: 802.11 b/g/n/e/i
WPA/WPA2/WPA2-Enterprise/SPS
Bluetooth:Bluetooth 4.2/BLE

ESP32
Dual-core Xtensa 32-bit LX6
Up to 240MHz
520kB internal SRAM
4MB external flash
Multiplexed I/Os allow up to
18 ADC channels
3 SPI interfaces
3 UART interfaces
2 I2C interfaces
2 I2S interfaces
16 LED PWM outputs
2 DACs
10 Capacitive Touch Inputs

ADC Preamp
When using preamp 270pF cap connector from VP to CAPP

Other
Hall Sensor
Temp sensor (-40C to 125C)
SD/SDIO/MMC Host controller

Figure 4.5: Hardware and peripherals specification summary of the ESP32 Thing [37].

4.4.3 Raspberry Pi Micro-Controller

The Raspberry Pi 2 model B used in this project is a 85 × 56 mm single board computer (micro-computer) device with BCM2836 quad core (4 processors in one chip) ARMv7 processor. It is a low-cost chip and it has the following properties which make it robust and suitable for the proposed SCADA system design [38, 39]:

- A 900MHz quad-core ARM Cortex-A7 CPU

- 1GB RAM
- One hundred Base Ethernet
- Four USB ports
- Forty GPIO pins
- Full HDMI port
- Combined 3.5 mm audio jack and composite video
- Camera interface (CSI)
- Display interface (DSI)
- Micro SD card slot
- VideoCore IV 3D graphics core.

In this work, the Thinger.IO IoT Server is installed and configured on the Raspberry Pi and the Raspberry Pi is connected to the other components in either of the two configurations described earlier.

Wi-Fi Router (Communication Channel)

In the proposed SCADA system, Wi-Fi serves as the communication channel between the ESP32 Thing (RTU), and the Thinger.IO IoT Server (MTU). This local Wi-Fi network is created using a D-Link Router (DI-524 Airplus G). It is a high speed router with 54 Mbps data transfer rate, 802.11b/g wireless protocol, and it is IEEE 802.11 standards compliant. The router has one WAN port and four LAN ports, and its operating frequency band is 2.4 GHz. Since the ESP32 Thing can implement TCP/IP, full 802.11b/g/e/i WLAN MAC protocol and Wi-Fi direct, the router is configured to setup the needed local Wi-Fi network for transmitting the sensor data from the ESP32 Thing to the Thinger.IO IoT Server by using the server IP address to identify the platform. For the Wi-Fi access control and security purposes, the ESP32 Thing connects to the router using the Wi-Fi network name (SSID) and the assigned password.

4.4.4 Thinger.IO Local Server IoT Platform

Thinger.IO is a powerful open source platform for the Internet of Things (IoT). It supports Representational State Transfer (REST) Application Programming Interface (API) which enables controlling and reading of smart devices [40]. Representational State Transfer (REST) is an architecture based on web standards which uses HTTP protocol for communication. This protocol enables interoperability among the different machines on the internet by treating each and every component as a resource, such that each resource can be accessed by a common interface utilizing the general HTTP methods like OPTIONS, GET, PUT, POST, and DELETE, etc., [22–24, 40]. The specific response of each resource is gotten in JSON/XML format [40]. Some of the important features of the protocol which make it possible to connect and manage IoT devices are automatic discovery of API, and bandwidth savings [24]. Thinger.IO is wholly supported by GitHub (the popular open source development platform) [40].

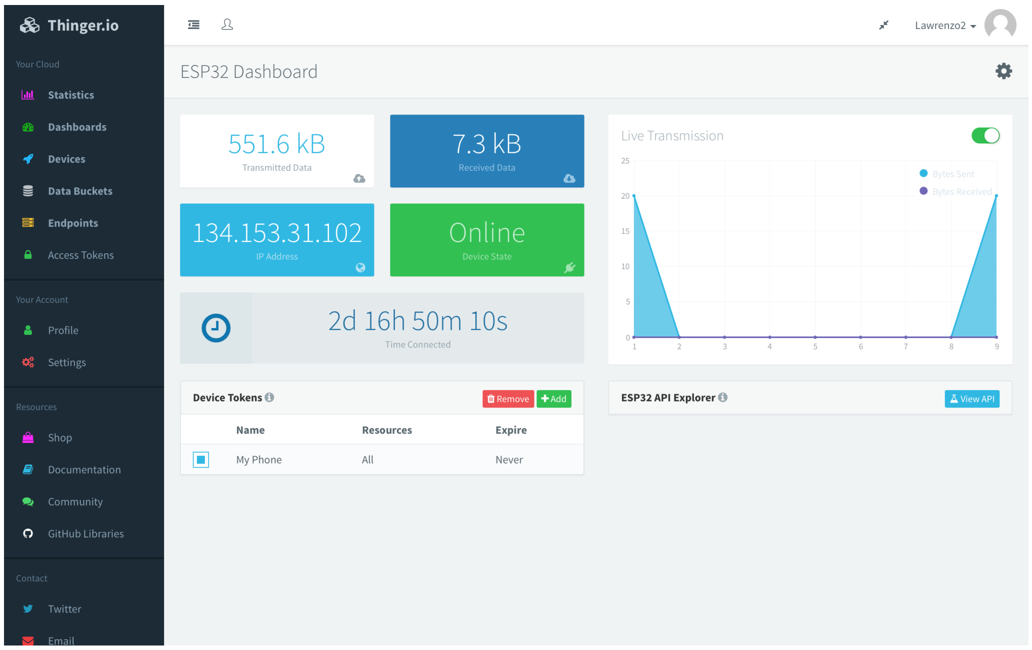
Thinger.IO IoT platform supports the integration of Arduino compatible hardware (any board that can be programmed with Arduino IDE, such as Arduino + Ethernet, Arduino + Wi-Fi, ESP32/8266/13, NodeMCU, TC CC320, etc.), Linux-powered devices like the Raspberry Pi, Intel Edison or any other Linux computer running Ubuntu or MacOS, and the ARM Mbed platform and compatible devices. The IoT platform has a Cloud Console with a beautifully designed front-end where a user can manage the connected devices and visualize the device information in the cloud [40]. To start an IoT project in Thinger.IO, the first step is to create devices by adding the device parameters which will grant access to connect the devices to the Thinger.IO account. Any device on the platform must be registered to have access to the cloud, and each device is identified by its unique identifier and credentials, such that an infinite number of devices can be added to the cloud platform without one device interfering with the other (Figure 4.7). Once a user creates an account on the Thinger.IO cloud, access token is obtained from the user's Username and Password, and this access token grants authorization access to the account resources of the connected devices. On the Cloud Console is a Statistics section where a user can see some basic information about the account such as the number of connected devices, endpoints, data buckets, statistics about device consumption in terms of sent and received data, as well as a Google Map of the approximate current locations of the connected devices (Figure 4.12). In the Cloud Console, an operator can add or remove devices, create real-time dashboards, access the device API, and perform other device and data management operations [22–24, 40]. Also, the left side of the Statistics screen has a main menu with all the platform features needed to build IoT projects (Figure 4.6) [40].

One unique feature of the Thinger.IO IoT platform is that it allows an operator to discover the resources defined in the connected devices. A resource, in this case, can be a sensor reading like current, voltage, temperature, humidity, pressure, or any actionable element like a light, a relay, a motor, etc. Once a device is connected to an account, an operator can access its resources and explore the API REST endpoints using the API Explorer which is accessible over the Device Dashboard by clicking on a small blue button called Device API (Figure 4.6). Essentially, any device resource is like a callback function that can be called (on demand) through a REST API. On the Thinger.IO platform, four different types of resources can be defined, one for input (sending data to the device), one for output (sending data or information from the device), one for input/output (sending and receiving information in one call), and lastly, a callback resource which can be executed without sending or receiving information [40]. From the API perspective, the input and output data can be any JavaScript Object Notation (JSON) document [40].

Thinger.IO has a Local Server option where a user can purchase (one-off) the hardware or hardware installation ISO image and install it on a standalone or networked machine for proper management. It also has a web-based server option which can be accessed using its URL just like every other web-application [40]. For example, the authors in [22–24] used the web-based server option. Both the web-based and local server options have IoT capability as the data stored in them can be accessed remotely with an internet enabled computer or with an internet enabled phone via Thinger.IO mobile app or phone browser. However, the locally-installed server option is more secure as the user has a better control of the server and stored data for security purposes [40]. In this paper, the local server option is used. The low-cost Thinger.IO Raspberry Pi ISO Image (about $15.00 CAD) has been purchased, installed and configured on a Raspberry Pi machine.

Thinger.IO IoT platform allows a user to create all kinds of real-time visualization dashboards and charts for remote monitoring, as well as supports monitoring and control via emails, HTTP requests, etc., using endpoints. The platform also has free Android and iOS Apps that can be downloaded from Google Play Store and Apple Store respectively. Any of these Apps can be connected to a registered device in the cloud by scanning the QR barcode of the device. For example, the Thinger.IO Mobile App on my iPhone is connected to the ESP32 device on the local server by scanning the QR barcode of the device in the cloud as shown in Figure 4.6. This means that in addition to the cloud console monitoring and control features provided by the platform, an operator can also check the status of the connected devices, visualize and update output resources, edit and post input resources, as well as run resources anywhere in the world by using the Mobile Apps [40].

In this work, the Thinger.IO local server receives the PV voltage, PV current, measured PV power, and storage battery voltage from the connected ESP32 device at the Cloud Console, and automatically logs the data to the created Dashboards and Data Buckets at the specified data transfer rates. This means that an operator can either remotely visualize (monitor) the received data at the Cloud Console by clicking on the Device API, or by checking the Dashboards and Data Buckets. An operator can also initiate Supervisory Control actions by setting up and using the endpoint features of the platform. Here, an endpoint is defined as a target destination that can be called by the connected devices to perform any action, such as sending an email, sending SMS, calling a REST API, interacting with IFTTT (If This Then That), calling a device from a different account, or calling any other HTTP endpoint [24,40]. Figures 4.6 and 4.7 show a visual of the Thinger.IO Cloud Console and Console Dashboards respectively.



551.6 kB Transmitted Data

7.3 kB Received Data

134.153.31.102 IP Address

Online Device State

2d 16h 50m 10s Time Connected

Device Tokens

Name	Resources	Expire
My Phone	All	Never

Figure 4.6: Thinger.IO Cloud Console.

4.4.5 MUN ECE Laboratory PV System Overview

The Memorial University Electrical and Computer Engineering Laboratory photovoltaic system is made up of 12 Solar Panels covering a total area of 14 square meter on the roof of the building and producing about 130 W and 7.6 Amps each. Two modules are connected

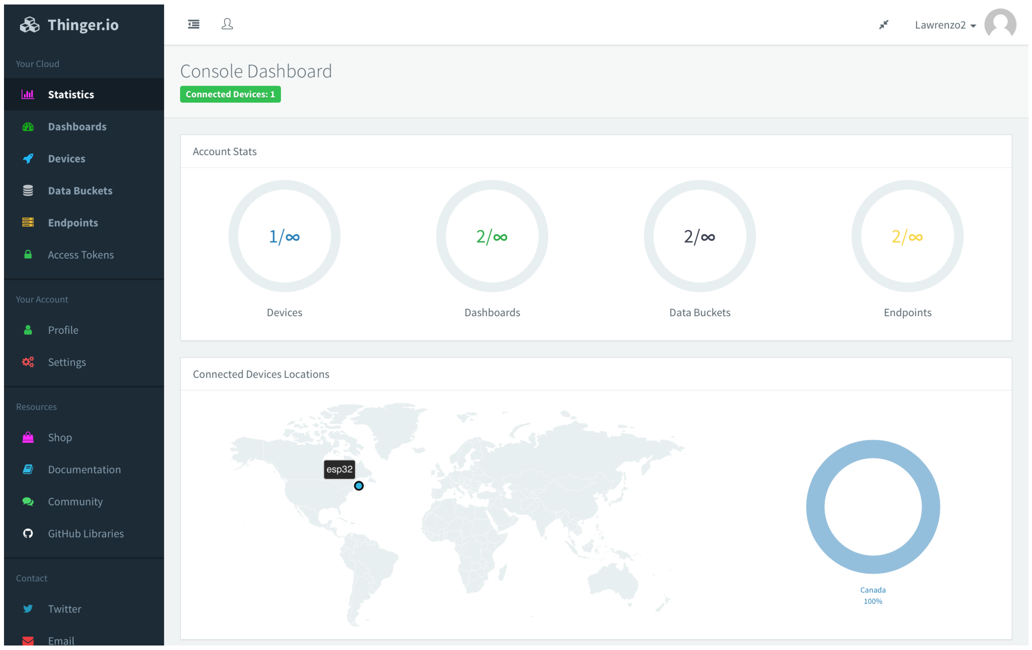


Figure 4.7: Thinger.IO Console Dashboard.

in parallel such that it contains six sets of 260 W, and 14 A each. It has Maximum Power Point Tracking (MPPT) system to ensure that maximum power is captured from the solar panels under all operating conditions, and lead acid electrical battery system is connected to the MPPT to store the energy from the solar panels for use during prolonged extreme weather conditions.

In this project, the SCADA system is set up to acquire the PV voltage, PV current, the measured PV power from the voltage and current values, as well as the storage battery voltage, for remote monitoring and supervisory control. Here, only one set of the modules (about 260 W, and 14 A output) is used for testing purposes.

4.5 Implementation Methodology

In implementing the proposed low-cost, open source SCADA solution, the analog sensors are connected to the Solar PV System to collect the required data from the system, and the

Sparkfun ESP32 Thing micro-controller is programmed with Arduino IDE to receive these sensor data, display them on the Arduino IDE Serial Monitor, and then send them via the locally configured Wi-Fi network to the locally installed Thinger.IO IoT server platform for remote monitoring and supervisory control. On the Thinger.IO Cloud Console, HMI Dashboards (Graphical User Interface, GUI), are created by an operator for data visualization, remote monitoring and supervisory control. The pseudocode for the implementation methodology is shown in Algorithm 1 below, and the appearance of the received data on the Thinger.IO server which is the JSON format described earlier (Name: Value) is shown in Figure 4.8.

Algorithm 1: Data Logging Algorithm:

```
Initialization;
1. Read Sensor Values on Analog Pins 32, 34 and 35, and Calculate Values for Pins
   32 × 34;
2. Display the above Values on Arduino IDE Serial Monitor;
3. Connect to Local Wi-Fi Network with Wi-Fi Name and Password;
4. Connect to Thinger.IO Local Server IP Address;
5. Identify the specified Thinger.IO Account Name, Device ID and Credentials;
6. Post Sensor Data to the specified Thinger.IO Device;
while Thinger.IO Server Acknowledges Data Receipt do
    7. Display Sensor Data on Thinger.IO Cloud Console, and;
    8. Display "Ok" on Arduino IDE Serial Monitor;
    if No Data Receipt Acknowledgement from Thinger.IO Server then
        9. Display Debug/Error Message on Arduino IDE Serial Monitor;
    else
        10. Go to Step 1;
    end
end
```

4.6 Prototype Design

Using the described hardware components and the operational principles of each of the components, the proposed SCADA system is designed and implemented as shown in Figure

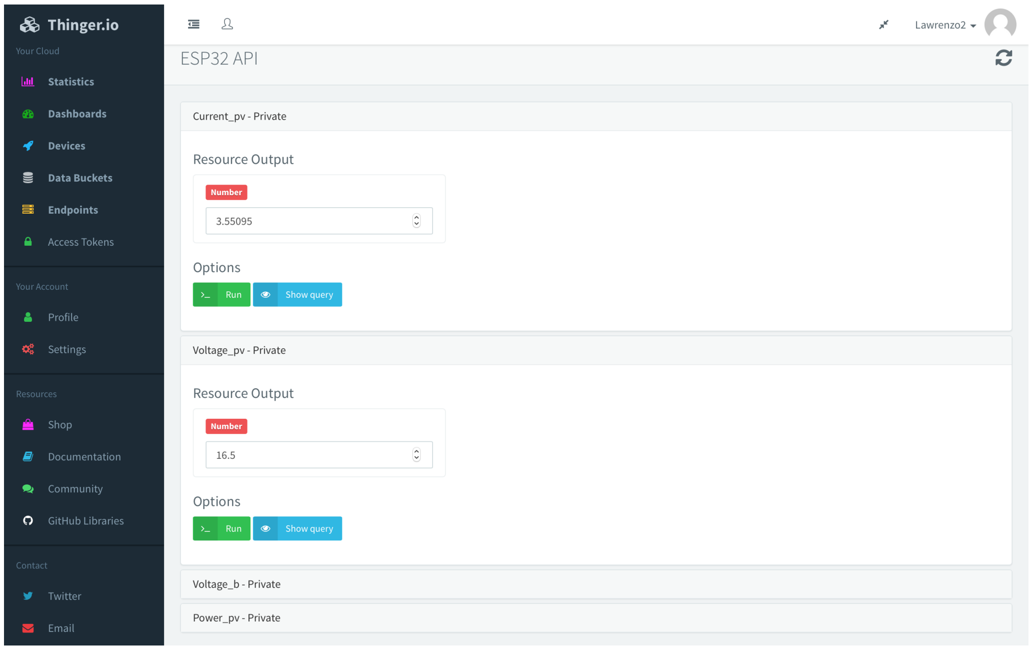


Figure 4.8: Thinger.IO received data page.

4.9. As shown in the figure, the analog sensors, the pull-down resistors arrangement, and the ESP32 Thing micro-controller are connected together on a Breadboard. The 3.3 V voltage signal needed for the current sensor to match the 3.3 V requirement of the ESP32 ADC pins is acquired from the Breadboard with the pull-down resistors arrangement shown while the 5 V power supply for the ESP32 Thing board is provided using a 5 V USB power supply. The Wi-Fi Router and the Raspberry Pi-hosted Thinger.IO local server IoT platform are both placed in the building, and integrated into the system in two different configurations. For the first configuration, the Raspberry Pi is placed at a different office in the building and connected to MUN network via an RJ45 Ethernet cable. However, for the second configuration, the Raspberry Pi is placed close to the setup and connected to one of the LAN ports of the Wi-Fi Router.

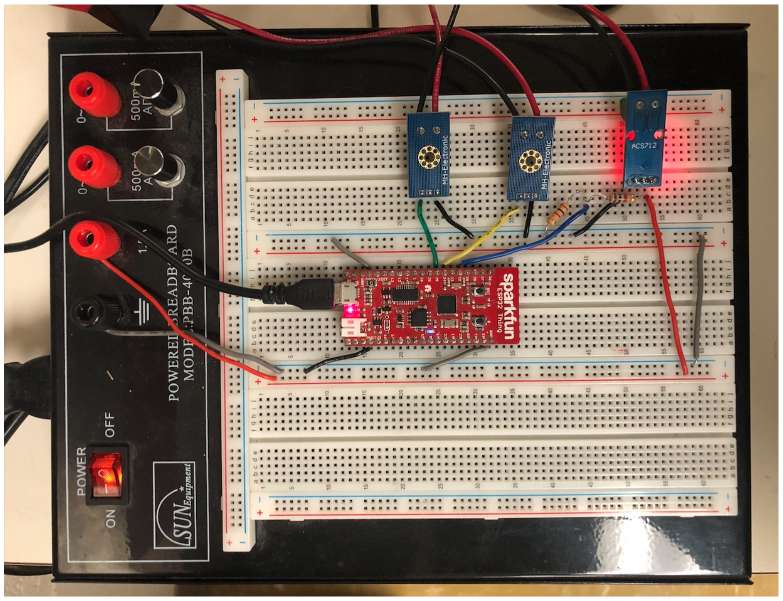


Figure 4.9: Hardware implementation of the proposed SCADA system.

4.7 Experimental Setup of the Proposed SCADA System

In order to test the proposed SCADA system solution, the implemented hardware for each of the two configurations is setup in MUN ECE Laboratory as shown in Figure 4.10. The inputs of the current and voltage sensors are connected to the PV and battery systems to acquire the PV data using electrical cables, and the sensor outputs are connected via cables to the ESP32 Thing to capture and parse the acquired data to the Thinger.IO IoT Server.

4.8 Testing and Results

As described above, each of the two configurations of the proposed low-cost, open source SCADA system solution was setup in the MUN ECE Laboratory to acquire the PV system data, and to parse the acquired data to Thinger.Io local server IoT platform for remote monitoring and supervisory control. A flow chart of the data acquisition, processing, visualization and supervisory control process from the sensors to the Thinger.IO server platform is shown in Figure 4.11.

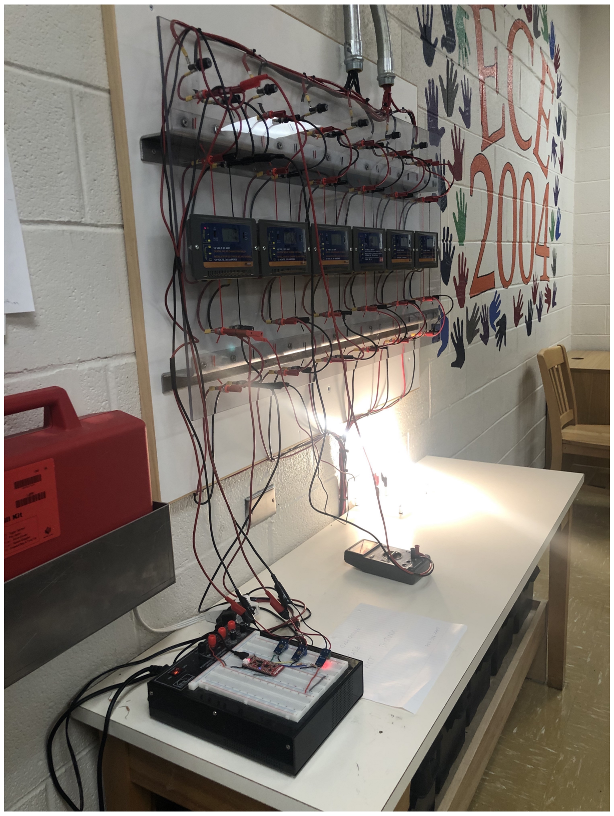


Figure 4.10: Experimental setup of the proposed SCADA system.

Results

The Thinger.IO local server IoT platform was configured, and using both hardware configurations A and B described earlier and the developed ESP32-Thinger.IO program (Pseudocode shown in Algorithm 1), the acquired sensor data were posted to the Thinger.IO server platform, and received at the Cloud Console in JSON format (Name: Value), and through the “View API” menu, an operator could view the received data directly on the Cloud Console. Having received the PV data at the cloud console, dashboards and data buckets were created and configured such that the received data were automatically logged to both the dashboards and data buckets for remote monitoring and supervisory control via computers and mobile devices.

In the first configuration (A), authorized users on MUN Network can view the data on

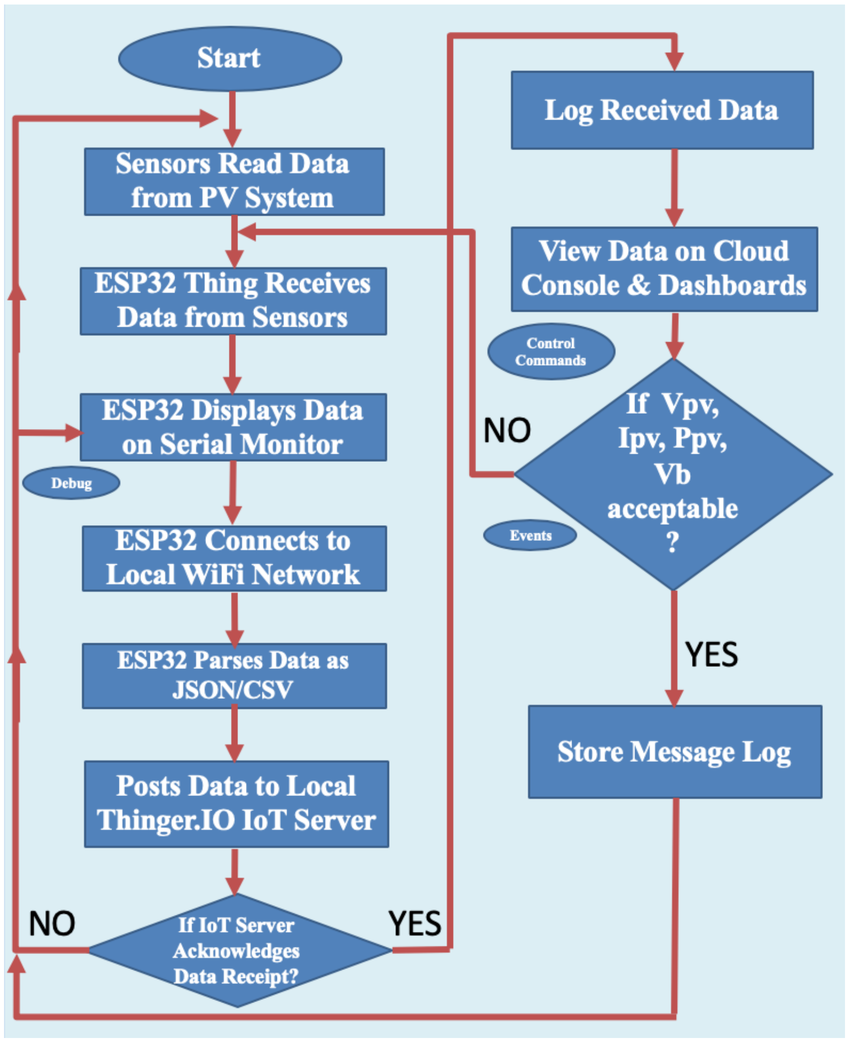
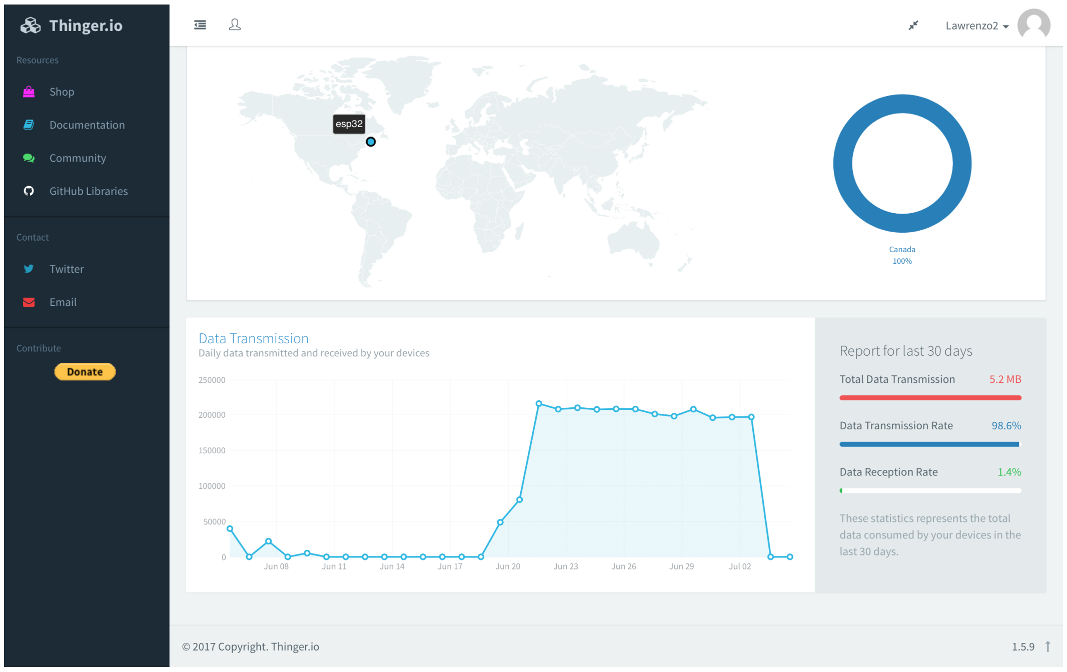

Start
Sensors Read Data from PV System
ESP32 Thing Receives Data from Sensors
ESP32 Displays Data on Serial Monitor
Debug
ESP32 Connects to Local WiFi Network
ESP32 Parses Data as JSON/CSV
Posts Data to Local Thinger.IO IoT Server
If IoT Server Acknowledges Data Receipt?
NO
YES
Log Received Data
View Data on Cloud Console & Dashboards
Control Commands
If Vpv, Ipv, Ppv, Vb acceptable ?
NO
Events
YES
Store Message Log

Figure 4.11: Flow chart of the SCADA system solution.

Thinger.IO platform using desktops, laptops and mobile browsers pointed to Thinger.IO local server IP Address. Authorized internet users outside MUN Network can also view the data on the platform if the Thinger.IO port is left open on MUN network. In the second configuration (B), only the authorized users connected to the Local Wi-Fi Network can view the data on the Thinger.IO platform using Wi-Fi enabled machines and the IP address of the server. Also, in both configurations, authorized personnel can view the stored data on the platform using the Thinger.IO Mobile App by scanning the QR barcode of the device on the platform. However, only the users connected to either of the networks can view the real-time data on the Mobile App. While the system was being tested, a digital multimeter was connected to each of the points of interest to measure the desired values. In both configurations, the acquired sensor data matched the values measured locally using the digital multimeter, with minor measurement errors. The system was tested for about a month, disconnected and reconnected on different days during this testing period to test its robustness as shown on the Data History window in Figure 4.12. Also, during testing, a load (an electric bulb) was connected to the battery to discharge it so that a significant amount of current can flow from the PV system across the MPPT to recharge the battery. Various dashboards were created on the Thinger.IO Server IoT platform to log the real-time PV data for remote monitoring and supervisory control, and from the dashboards, variations in the acquired sensor values were seen depending on the prevalent weather conditions affecting the PV system at the time of testing. As shown in Figures 4.13 and 4.14, the vibrations in the real-time values were due to the frequent changes in the weather conditions in St. John's during the testing. Furthermore, by clicking on the GPS at the bottom of Figures 4.13 and 4.14 (dashboards) on the cloud platform, the exact location of the connected devices can be seen. Aside from these two dashboards presented, the Thinger.IO Mobile App installed on an iPhone was connected to the local server by scanning the QR Barcode of the device for real-time monitoring.

In each of the two configurations, the received data are essentially the same, and only affected by the prevalent environmental conditions affecting the PV system (process plant). The major difference between the two configurations is the manner in which the received data can be accessed. In the first configuration, the real-time and stored data can be accessed with the server IP address as long as the user is connected to MUN network or if the Thinger.IO port is open for access via the user's private office or home internet connection. In the second configuration, only the users connected to the local Wi-Fi network, either wirelessly or via network cables connected to the LAN ports of the Wi-Fi Router, can view



Report for last 30 days

Total Data Transmission 5.2 MB

Data Transmission Rate 98.6%

Data Reception Rate 1.4%

These statistics represents the total data consumed by your devices in the last 30 days.

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1.5.9

Figure 4.12: Logged data history on Thinger.IO Server.

the real-time and stored data. Although the first configuration is more flexible, the second configuration is more secure, and the decision to implement either configurations rests solely with the user. In addition, even though the Wi-Fi coverage distance was limited to the building where the tests were carried out in our system, the Wi-Fi range can be extended in other applications requiring wider coverage distance by using a Wi-Fi repeater.

4.9 Discussion

Some of the key features of the designed low-cost, open source SCADA system are enumerated below:

- **Internet of Things-based SCADA System:** It is based on the Internet of Things SCADA architecture (the fourth, and most recent SCADA architecture), and it has the four basic elements of a SCADA system listed earlier in this paper. The PV System is the Process Facility (Plant) being managed, the Current and Voltage Sensors

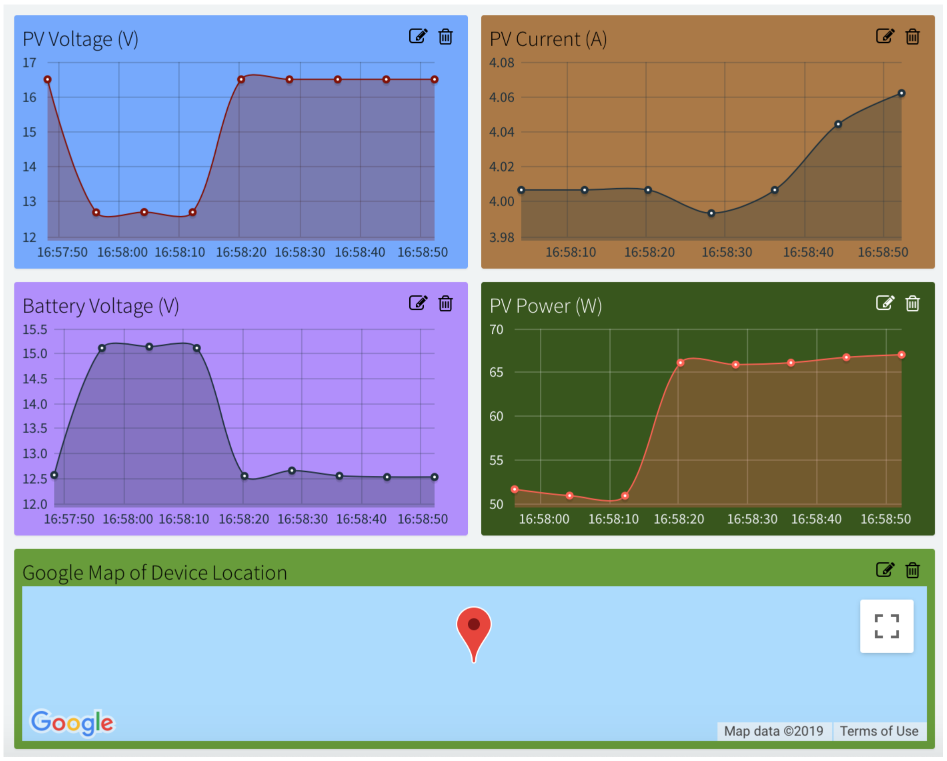

Figure 4.13: Created Dashboard (A) showing real-time data.

are the Field Instrumentation Devices as they acquire the desired data from the PV system, the ESP32 Thing micro-controller acts as the Remote Terminal Unit (RTU) as it helps to receive and parse the acquired sensor data, and the Thinger.IO Local Server IoT Platform serves as the Master Terminal Unit (MTU) as it provides means of handling data processing and human machine interactions. The SCADA Communication Channel between the RTU and the MTU is Wi-Fi which is created using a Wireless Router.

- **Low-Cost and Open Source:** All the components of the proposed SCADA system are manufactured and supplied by different manufacturers (mix and match), they are readily available and are cheap. The components are also compatible with related process facilities and components from various vendors. Therefore, the consumer is not beholden to a single manufacturer/supplier which is one of the key features of

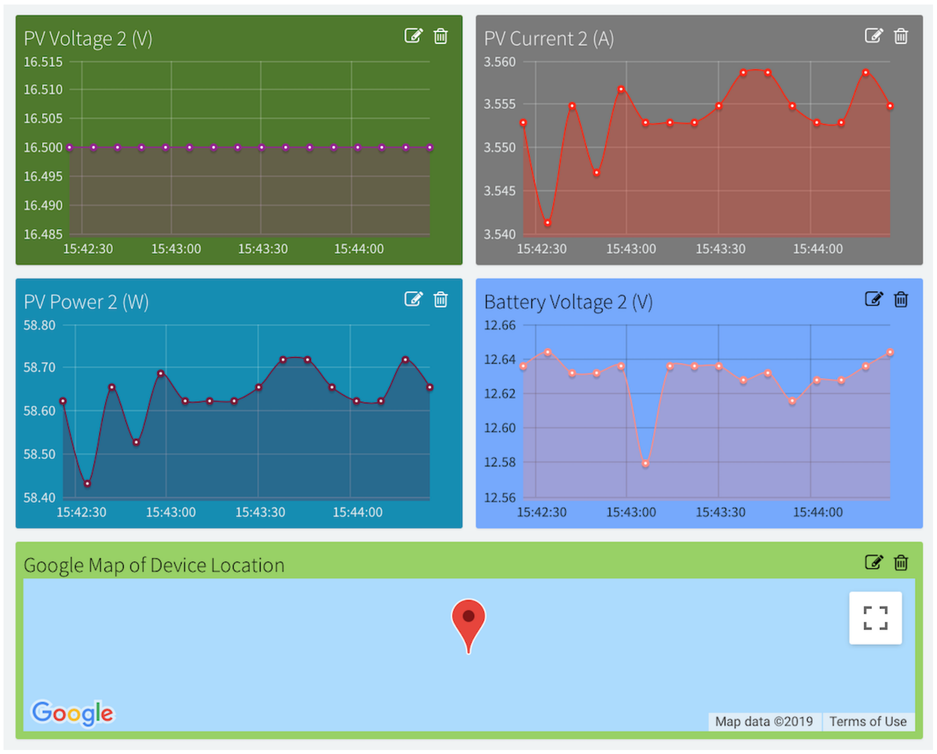

Figure 4.14: Created Dashboard (B) showing real-time data.

an open source system [4, 12, 13]. Table 4.1 below shows the cost of each of the components and the overall cost of the designed SCADA system. As can be seen, the overall cost is just under \$300 CAD. It is indeed a low-cost SCADA system solution compared to the available commercial SCADA system solutions which are in thousands of dollars [3, 11].

- **Data Acquisition and Historic Storage:** The SCADA system stores the received data and maintains data history [41] (Figure 4.12).

- **Low-Power:** The system uses low-power components. For example, the two major components of the system (Raspberry Pi (Thinger.IO Local Server) and ESP32 Thing) consume a combined total of 2.2 W while in operation, which is low. It should be noted that the power consumption values for all the components shown in Table 4.2 were measured simultaneously while the system was running. As shown in

Table 4.1: Bill of Materials.

S/N	COMPONENT	QTY	PRICE (CAD)
1	Thinger.IO RPi ISO Image	1	15.62
2	Raspberry Pi 2 B	1	45.95
3	ESP32 Thing	1	31.90
4	Current Sensor	1	5.25
5	Voltage Sensor	2	11.98
6	D-Link D1-524 Wireless Router	1	98.51
7	8GB SD Card	1	12.66
8	Miscellaneous (Breadboard, Resistors, Wires, Boxes, etc.)	1	70.00
	Grand Total:		**$ 291.87 CAD**

Table 4.2, the overall power consumption of the designed system while in operation is under 10 W. This power can further be reduced by eliminating the D-Link Wi-Fi Router and configuring the Raspberry Pi as a Wireless Access Point, and using a less power demanding breadboard as the breadboard only provides 5 V power supply to the VCC pin of the current sensor in this current setup.

Table 4.2: Power consumption of hardware components.

S/N	HARDWARE	POWER (W)
1	Raspberry Pi 2 B	1.7
2	ESP32 Thing (alone)	0.5
3	Breadboard (with Sensors, ESP32, Resistors, etc. connected)	3.3
4	D-Link D1-524 Wireless Router	4.4
	Total Power Consumption (less ESP32 alone):	**9.4 W**

- **Monitoring:** The system provides Dashboards for events and data monitoring via the Thinger.IO Cloud Console on web browsers and Thinger.IO Mobile Apps [42].

- **Supervisory Control:** The system enables an administrator to issue supervisory control commands to a local operator for critical actions in the events where the received data do not correspond to a predetermined value or expected range. The administrator also has the option of creating Endpoints on the platform for more supervisory control options.

- **Reporting:** The system presents reports to the administrator and key decision makers in the form of charts, data logs, and alarms (local, email, web, and mobile app).

- **Security:** Because the proposed solution here involves the use of a locally hosted cloud server on MUN network, data integrity and security measures such as access control, whitelists, authentication, authorization, firewalls, regular risk assessment, continuous monitoring and log analysis, updating and patching regularly, etc., can easily be taken by the administrator. Also, for more critical infrastructure monitoring and control such as traffic light system or oil and gas facilities monitoring applications, additional security measures such as hardware protection and data encryption on the SCADA communication channel might be necessary [29, 30, 43].

- **Reliability and Availability:** Although system reliability calculation is beyond the scope of this work, research has shown that SCADA system reliability and availability are affected by delayed or wrong operator decisions [31]. In this project, because the components are completely open source and readily available, and the fact that the main cloud server is locally installed and self-managed, it is easy for an operator or administrator to manage the system to ensure its continuous reliability and availability. However, this might not be the case in a proprietary SCADA system where the customer is beholden to a single vendor, and as such there could be time-lags in responding to customer's complaints since having a trained operator on stand-by 24/7 on the customer's site might not be feasible.

- **Ease of Use:** The designed SCADA system solution is easy to use as the Thinger.IO IoT Platform is very user-friendly.

4.10 Conclusions

In most industries all over the world, like the energy industry, critical assets are distributed over large geographical areas, sometimes in harsh environments such as deep offshore and swamps. While it may be necessary to have local means of managing the operations of these critical assets, it is equally important to have a reliable, flexible, cost-effective and sophisticated coordinated monitoring and control. Although SCADA systems have revolutionized the way these critical, complex and geographically distributed industrial systems are monitored and controlled, SCADA system designs and implementations have largely remained proprietary. However in many applications, for example in power systems, the energy storage systems such as inverters and batteries, power electronic converters, and other devices connected to the grid are from various manufacturers or vendors, which often result in compatibility issues between these existing infrastructures and the proprietary SCADA system solutions. Therefore, an open source SCADA system solution represents the most flexible SCADA solution as it allows a user to "mix and match" components and choose the most appropriate from several manufacturers and suppliers. Furthermore, proprietary SCADA system solutions are largely expensive, and while it may be affordable for big companies like most oil and gas producing companies, it is pricey for smaller companies with no enormous financial resources like most small power companies, especially power companies into renewable generation systems. Therefore, an open source SCADA solution represents the most cost effective solution as the user is not beholden to a single vendor.

In this paper, a low-cost, open source SCADA system solution based on the Internet of Things (IoT) SCADA architecture, which is the most recent SCADA architecture, has been presented. The hardware design of the proposed SCADA system solution has been carried out, and the implemented system has the four basic elements needed in a SCADA system, including Field Instrumentation Devices (Current and Voltage Sensors), Remote Terminal Units (ESP32 Thing micro-controller), Master Terminal Units (Thinger.IO IoT Server Platform), and SCADA Communication Channel (Local Wi-Fi Network). In order to validate the functionalities of the designed SCADA system, it was setup and tested at the Memorial University Electrical and Computer Engineering Laboratory to acquire and remotely monitor a 260 W, 12 V Solar PV System data, as well as to initiate supervisory control activities whenever necessary. From the tests, the system was found to be capable of carrying out the desired functions of a SCADA system which include Data Acquisition, Networked Data Communication, Data Presentation, and Remote Monitoring and Supervisory Control. The power consumption of each of the components was measured while the system was in operation and the entire system was found to require low power for operation, less than 10 W. The overall cost of the system was also found to be below $300 CAD which is extremely low for such a critical solution. Furthermore, the acquired real-time PV data visualized at the Thinger.IO IoT Server Cloud Console and Dashboards were found to be within the same range as the data locally measured using the conventional digital multimeter. From information security and system reliability points of view, because the main cloud server is privately hosted and self-managed on own network, data security measures such as access control, authorization, authentication, whitelisting, firewalls, log analysis, etc., are easily implemented, and since the system is self-managed, it means that the operator or administrator is readily available to carry out these tasks, thereby ensuring the security, reliability and availability of the proposed system.

Although a PV system has been used as the process plant for testing purposes in this work, the designed SCADA system can also be applied in other industries and fields to remotely monitor and control critical infrastructures such as electric power generation, transmission and distribution systems, buildings, facilities and environments, oil and gas production facilities, mass transit systems, water and sewage systems, and traffic signal systems. However, it should be noted that the designed system for this particular application is not a plug and play turnkey solution or a one-size-fits-all system for the above possible applications as further measures will need to be taken to customize the system for any chosen application in order to guarantee its functionalities, reliability and security, which might increase the overall cost and power consumption presented in this application. For example, for outdoor deployment of the proposed SCADA system, options for boxes and shields will have to be considered for the electronic components to prevent damage due to moisture and wild animals. Also, to increase the security of the proposed SCADA system for very critical applications like oil and gas facilities monitoring and traffic signal control, additional security measures such as data encryption algorithms can be implemented on the ESP32 micro-controller side to encrypt the acquired sensor data before sending them to the Thinger.IO server, and at the server side, data decryption and further security measures can be carried out. These could relatively increase the overall cost and power consumption of the system.

4.11 Future Work

In the future, endpoints can be created on Thinger.IO platform to carry out more supervisory control events like sending an email, sending an SMS, calling a REST API, interacting with IFTTT (If This Then That), calling a device from a different account, or calling any other HTTP endpoint directly from the server to complement the current supervisory control strategy where an administrator has to notify a local operator of any abnormal variations in the received data for necessary actions. Also, to further reduce the overall power consumption which is already low, the D-Link Wi-Fi Router can be eliminated, and the Raspberry Pi configured as a Wireless Access Point to provide the Wi-Fi connection needed for communication between the ESP32 Thing and the Thinger.IO Server. Furthermore, to increase the security of the proposed SCADA system, especially when the system is deployed in very critical applications like oil and gas facilities monitoring and traffic signal control, data encryption algorithms can be implemented on the ESP32 micro-controller side to encrypt the acquired sensor data before sending them to the Thinger.IO server, and on the server side, data decryption and further security measures can be carried out.

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Chapter 5

Low-Cost, IoT-Based Open Source SCADA system using ESP32 with OLED, ThingsBoard and MQTT Protocol*

Preface

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thor, and I carried out most of the research work, performed the literature reviews, carried out the system designs, hardware implementations, experimental setups and analysis of the results. I also prepared the first drafts of the manuscripts and subsequently revised the final manuscripts based on the feedback from the co-author and the peer-review process. The Co-author, Dr. M. Tariq Iqbal, supervised the research, acquired and made available the research funding, provided the research components, reviewed and corrected the manuscript, and contributed research ideas in the actualization of the manuscripts.

Abstract

Distributed assets, such as hybrid power system components, require reliable, timely, and secure coordinated data monitoring and control systems. Supervisory Control and Data Acquisition (SCADA) is a technology for the coordinated monitoring and control of such assets. However, SCADA system designs and implementations have largely been proprietary, mostly pricey and therefore economically unjustifiable for smaller applications. With proprietary SCADA systems, there is also the problem of interoperability with the existing components such as power electronic converters, energy storage systems, and communication systems since these components are usually from multiple vendors. Therefore, an open source SCADA system represents the most flexible and most cost-effective SCADA option for such assets. In this paper, we present the design and implementation of a low-cost, open source SCADA system based on the most recent SCADA architecture, the Internet of Things (IoT). The proposed SCADA system consists of current and voltage sensors for data collection, an ESP32 micro-controller with organic light-emitting diode (OLED) display, for receiving and processing the sensor data, and ThingsBoard IoT server for historic data storage and human machine interactions. For the sensor data transfer from the ESP32 to the ThingsBoard IoT server, Message Queuing Telemetry Transport (MQTT) protocol is implemented for data transfer over a local Wi-Fi connection with the MQTT Client configured on the ESP32, and the ThingsBoard server node serving as the MQTT Broker. The ThingsBoard IoT server is locally installed with PostgreSQL database on a Raspberry Pi single-board computer and hosted locally on MUN Network for data integrity and security. To test the performance of the developed open source SCADA system solution, it was setup to acquire and process the current, voltage and power of a standalone solar photovoltaic system for remote monitoring and supervisory control. The overall system design procedures and testing, as well as the created dashboards and alarms on the ThingsBoard IoT server platform are presented in the paper.

Index Terms: Open Source; SCADA; ThingsBoard; Internet of Things; ESP32 with OLED; Raspberry Pi; MQTT, Automation; Instrumentation and Control.

5.1 Introduction

Energy shortage and Global Warming are some of the major challenges facing the world today, especially with the recent rapid industrial development across the globe. As such, world leaders in collaboration with energy experts continue to search for alternative sources of energy, such as clean and renewable energy, to meet the growing global demand for energy and to save the environment from further degradation, caused by the use of the conventional sources of energy such as fossil fuels over the years. As energy experts continue to capture clean and renewable energy sources for the benefit of mankind, these sources are continuously being injected into today's power systems. These clean and renewable sources are incorporated with the conventional energy generation systems to form Hybrid Power Systems (HPS) [1]. However, due to the intermittent nature of these sustainable (renewable) energy sources such as solar and wind as they are hugely affected by the prevalent environmental conditions, energy storage systems are usually required in the resulting hybrid power systems for system, power grid and supply stability. Energy storage systems help to mitigate supply output fluctuations, as well as help to ensure frequency control and load balancing, amongst other important functions. These hybrid power systems, which are usually made up of the conventional energy generation sources such as fossil fuels, and one or more renewable generation sources such as wind and solar, together with the energy storage systems, power electronic converters such as inverters, as well as other power system devices such as communication systems needed for their successful operations are usually spread over large geographical areas, sometimes in harsh environments such as offshore and swamps. As a result of this distributed nature, the interconnection of these systems to generate and supply energy presents numerous challenges, such as power quality issues, voltage tolerances, frequency control, grid synchronization and metering, data exchange and communications between components, as well as the safety and security of both assets and personnel [2].

In order to overcome these challenges and to ensure seamless power system operations, diverse sensors, micro-controllers, micro-processors (e.g programmable logic controllers), actuators, valves, pumps, etc. are usually connected to various points of interest in the entire HPS to acquire important data such as current, voltage, power, and so on. and for real-time data monitoring, remote and co-ordinated controls. Supervisory Control and Data Acquisition (SCADA) is the perfect solution for these tasks. Since these hybrid power systems and their associated components are located remotely, a SCADA system is needed for their remote monitoring, coordinated control, and data acquisition from the various sensors, actuators, and other field instrumentation devices connected to the various points of interest. The SCADA system would help in the efficient collection of data from these variously distributed sensors, actuators and controllers, real-time remote control of the system, remote monitoring, and maintenance of the produced current, voltage, and power [3].

SCADA refers to the combination of telemetry and data acquisition. It encompasses the collection of information (data) from distributed process facilities, the transfer of these data to a central location, analysis of these data to know the current states of the distributed process facilities, supervisory control of the process facilities, displaying these data on a number of operator screens or displays (Human Machine Interface), and conveying the necessary control actions back to these distributed process facilities for the local operator's actions [4, 5]. It is a closed loop control system. The major functions of a SCADA system include the following [4]:

- Data acquisition
- Data presentation
- Supervisory control
- Networked data communication
- Alarm processing
- Historic data storage, data trending and reporting
- Remote monitoring

The architectural design of a SCADA system is made up of four basic elements; field instrumentation devices such as sensors which collect data from the distributed process facilities being managed, Remote Terminal Units (RTUs) such as single-board computers (PLCs, micro-controllers, etc.) for acquiring, processing and parsing these sensor data, Master Terminal Units (MTUs) such as IoT servers and platforms for data processing and human machine interactions, and finally SCADA communication channels for connecting the RTUs to the MTUs, and for data transfer [6].

SCADA architectures have evolved over the years, starting from the very first generation SCADA systems in the 70s called Monolithic SCADA, through the second generation SCADA systems called distributed SCADA (80s and 90s), and the third generation

SCADA systems called Networked SCADA systems (90s and early 2000s), to the most recent SCADA architecture called the Internet of Things (IoT) SCADA architecture (4^{th} generation) [7]. The SCADA system proposed in this work is based on the Internet of Things SCADA architecture. The Internet of Things concept refers to the interconnection of physical objects, embedded electronics, software and sensors, and so on, to enable real-time data exchange and communication between these devices and an operator over a common network or the web [8, 9]. The IoT-based SCADA system incorporates web or cloud services with the conventional SCADA system for a more robust remote monitoring and control [7].

In general, there are two classes of SCADA systems, and they include Proprietary (Commercial), and Open Source SCADA systems [10]. Automation companies like Siemens and Schneider Electric design and develop proprietary SCADA systems such as Simatic WinCC (Siemens), ClearSCADA (Schneider Electric), Ovation SCADA (Emerson), Micro SCADA (Allen Bradley), etc. and they sell these systems as turn-key solutions to the end users while providing regular or scheduled operational and technical supports both remotely and on site (locally). Aside the high initial capital cost of purchasing these SCADA systems, there are usually some additional subscription charges for maintenance and supports which could be billed monthly or quarterly. Thus, these proprietary SCADA solutions are largely expensive and mostly economically unjustifiable for smaller power system applications. In addition to the cost implications of these commercial SCADA system solutions, there is the problem of interoperability with the existing power system infrastructures. This is because the electromechanical components of the hybrid power system, as well as the energy storage systems, power electric converters, and other interconnected devices and the grid integration devices are usually from multiple manufacturers. Seamless integration of a SCADA system into existing infrastructures and communications facilities is of great importance to avoid incurring additional costs due to modifications and redesigns. For these reasons, an open source SCADA system represents the most flexible SCADA solution [10]. Furthermore, in addition to the cost savings of not having to redesign the communication facilities in integrating an open source SCADA system into the existing infrastructures, an open source system allows an end user to "mix and match" components and choose the most appropriate from various vendors, and as such the end user is not beholden to a single vendor [10]. Therefore, an open source SCADA system represents the most flexible and most cost-effective SCADA system solution.

In this paper, we present the design, development and implementation of a low-cost, open source SCADA system based on the Internet of Things (IoT) SCADA architecture. The SCADA system proposed uses low-cost, low-power, reliable and readily available components to realize the desired functions of a SCADA system. We show that the proposed SCADA system works well by testing it extensively using a standalone renewable power generation source, solar photovoltaic (PV) system, made up of solar panels and battery energy storage system similar to the arrangements in a small hybrid power system.

The organization of the remaining part of this paper is as follows. In Section 5.2, we present the related works, including problem statements, and the proposed SCADA system as a solution to the identified problems. In Section 5.3, we present brief overviews of the major technologies employed in our proposed solution, including Internet of Things (IoT) and Message Queuing Telemetry Transport (MQTT). The proposed SCADA system architectures are presented in Section 5.4, the components of the proposed SCADA system and descriptions of each of the components are presented in Section 5.5, and the implementation methodology used in the data collection, logging and remote monitoring presented in Section 5.6. In Section 5.7, we present the hardware implementation, and we present the experimental setup of the proposed SCADA system in Section 5.8. The testing procedures and the realized results are presented in Section 5.9, and in Section 5.10, we present brief discussions of the key features of the developed SCADA system solution, including cost and power consumption analyses. The paper is concluded in Section 5.11, and future directions of the research presented in Section 5.12.

5.2 Related Works

Numerous attempts have been made to reduce the over-dependence on proprietary (commercial) SCADA systems by designing various forms of low-cost, and open source SCADA systems for different industries and applications. For power system applications for example, a few attempts have been made to develop alternative SCADA systems for critical assets monitoring and remote control. J. Lee et al. [3] have proposed an IoT-based open source SCADA system for the remote monitoring, power control, and distributed data processing of a standalone offshore wave-wind hybrid power generation system based on the IEC61850 standard. In particular, their proposed SCADA system comprised of two control devices; a PLC and an industrial VPN router, and the data acquisition, network communication function, PLC management, and data visualization functions are carried out by the router device. Their proposed solution was tested in a simulation-based testing environment with the power transmission system's operator generating commands. In a similar power system application, S. A. Alavi et al. [11] presented an IoT-based open source data collection and visualization system. In their proposed system, two ESP-12E network modules were configured to acquire the desired micro-grid data, and to parse the data using MQTT protocol over Wi-Fi in one setup, and MQTT protocol over GPRS in another setup, depending on the desired coverage range. The acquired data were transmitted to the web-based ThingsBoard server where dashboards were created for situational-awareness (SA), data visualization and micro-grid management.

Elsewhere, K. Kao et al. [12] developed an IoT-based SCADA system for inverter monitoring and remote control. In their implementation, they divided their solution into four different levels which they called monitor; server; cloud; and client tiers. The monitor tier comprised of sensors, a Wi-Fi data acquisition device, an inverter, and a wireless router. A PC server served as the server tier, a database served as the cloud tier, and a laptop, a tablet, and a smart phone served as the client tier. The inverter data such as voltage and frequency were transmitted via a Wireless Sensor Network (WSN) to the database in the cloud, and Asynchronous JavaScript and XML (AJAX) and Responsive Web Design (RWD) tools were used to develop the human machine interface (HMI) for inverter data visualization. Remote control of the voltage and frequency of the inverter was also implemented via RS-485 connection and Modbus protocol. In another development, authors in [13] proposed a cloud-based SCADA system by integrating JustIoT framework with the conventional open source SCADA architecture. In their solution, the JustIoT structure was bridged to the conventional SCADA for cloud capabilities using Modbus TCP and OPC client. The JustIoT structure comprised of Raspberry Pi3 and Arduino Uno micro-controllers for data transfer via MQTT to an intelligent server consisting of Firebase cloud system, and a cloud-based real-time database where PC and mobile devices could visualize the stored data. Their designed system was applied in offshore wind power monitoring, and for smart house monitoring.

Although there are some studies on the design of SCADA systems in general for standalone or grid connected hybrid power systems, most IoT-based remote monitoring and control systems, especially using the lightweight data transfer protocol for the Internet of Things called MQTT, have focused on other sectors and their related applications such as smart healthcare applications [14–16], home automation applications [17–21], intelligent voting systems [22], infrastructure and transport applications [23–27], industrial manufacturing environments [28, 29], and so on.

The major issue with most of the reviewed IoT-based open source SCADA systems above is that the solutions are rather cumbersome as they involve a lot of technologies, tools and programming. Although remote monitoring and control is a complex issue, it is important for the solutions to be as simple as possible, especially for an open source system where the deployed system might have to be operated by the facilities' owners independently of the system designer. This is important because the facilities' owners might not have the advanced technological and programming knowledge needed to safely and successfully manage a complex system. In addition to the complex nature of the reviewed solutions, most of the authors either used a web-based IoT platform for data visualization, storage, and other human machine interactions such as the AWS used in [22], and the web-based ThingsBoard platforms implemented in [11, 30], or designed a web platform for data visualization and human machine interactions using multiple web technologies like the AJAX and RWD technologies utilized in [12], and the Google Chrome based application in [17, 24]. The major problem with using web-based platforms for data management in a critical SCADA system is that the stored data are highly susceptible to internet attacks since the web-based platforms require the public internet for data access just like every other website out there. However, the importance of data security in a SCADA system cannot be overemphasized. This is because attacks on a SCADA system can compromise the critical infrastructures being managed, which could result in devastating economic and operational setbacks. Data integrity in a SCADA system can be ensured by using several techniques, including securing the data communication channel or network such as data encryption, securing the hardware components, or securing the cloud server where the data are stored [4, 7, 31–33].

In this paper, we implement a combination of private network management and private cloud server management strategies to ensure the security of the proposed IoT-based SCADA system. To achieve this, the ThingsBoard IoT Server for data management, storage and human machine interaction is locally hosted on a Raspberry Pi machine, and a private Wi-Fi network is created with a Wi-Fi router while data transfer is made possible using the

MQTT data transfer protocol over the Wi-Fi network, such that only the users with the right authorizations can have access to the stored data. This also means that the SCADA system operator has full control of the security of the system, unlike when it is being managed over the public internet. On this private network, the operator can take multiple measures to protect the data in the cloud. Such measures include ensuring access control, whitelists, authentication, authorization, firewalls, regular risk assessment, continuous monitoring and log analysis, updating and patching regularly, etc. In addition to taking these measures to ensure the security of the proposed SCADA system, we implement the lightweight ISO standard data transfer protocol for the Internet of Things, the Message Queueing Telemetry Transport (MQTT) protocol, for the sensor data transfer from the MQTT client (ESP32 device) to the Raspberry Pi-installed ThingsBoard IoT Server platform which serves as the MQTT broker.

In our proposed SCADA system design solution, very low-cost, low-power, and completely open source components are used as the elements of the SCADA system. A locally installed ThingsBoard IoT server on a Raspberry Pi machine serves as the Master Terminal Unit (MTU) for data storage, data visualization and human machine interactions; ESP32 micro-controller, with OLED display, serves as the Remote Terminal Unit (RTU) for receiving and parsing the sensor data from the Field Instrumentation Devices (Current and Voltage Sensors); and a local Wi-Fi network created with a Wi-Fi router serves as the SCADA Communication Channel between the MTU and the RTU, and over which MQTT data transfer protocol is used for data transfer from the RTU (client) to the MTU (broker). The entire system forms a kind of secure industrial network as implemented by the commercial SCADA manufacturers in various industrial domains all over the world [34]. To the best of our knowledge, we have not found a single literature where a locally installed ThingsBoard IoT Server has been used as the MTU in an IoT-based SCADA system design. Furthermore, with the organic light-emitting diode (OLED) display of the ESP32 device (RTU) used in our design, we ensure that a local operator is able to visualize the current state of the process plant being managed by seeing the data values on the OLED screen, in addition to receiving updates from the remote SCADA operator at the server side. This is also an additional SCADA feature considered in this work.

5.3 Overview of Technologies

In this section, we present a brief description of each of the major technologies employed in the design of our proposed open source SCADA system solution as they relate to the subject matter at hand. These technologies include Internet of Things (IoT), a technology upon which the SCADA architecture considered is built; and Message Queuing Telemetry Transport (MQTT), a lightweight data transfer protocol for the IoT domain.

5.3.0.1 Internet of Things (IoT)

The Internet of Things (IoT) is a technology that enables the interconnection of physical devices such as buildings, vehicles, etc. with embedded electronics, sensors, softwares, and network connectivity such that the devices can collect and exchange real-time data between themselves and an operator over a common platform, the web or network [8, 9, 35]. The IoT brings together mechanical (physical) objects, computing devices, mechanical and digital machines, living beings, user interfaces, and analytics that are all interconnected over a common internet-based infrastructure. The IoT concept is made possible by the exploitation of existing technologies and concepts such as pervasive and ubiquitous computing, embedded devices, communication technologies, internet protocols and applications, and sensor networks which help in the transformation of these physical devices from their traditional forms into smart devices [8]. In the last few years, the IoT concept has been exploited in homes, schools, businesses and industrial domains to bring about smart cities, smart homes, smart healthcare systems, smart energy management systems, smart transportation, smart manufacturing systems, industrial automation systems, smart emergency response systems, and so on [8, 35].

Even though the IoT technology has been around for sometime now, the subject matter experts have not fully agreed on a standard IoT architecture. Different researchers have proposed various architectures [8, 9]. However, the most common architectures are the three-layer and the five-layer architectures. The three-layer architecture comprises of the perception, network, and application layers, while the five-layer architecture consists of the perception, transport, processing, application, and business layers [8, 9]. These are extensively discussed in [8, 9]. Whichever IoT architecture is implemented, a reliable communication is necessary in an IoT-based system as the IoT devices are usually dispersed over large geographical areas. IoT technologies make use of the four layers of the general TCP/IP model. The relationship between the TCP/IP model and the IoT protocols is shown in Figure 5.1 [35, 36].

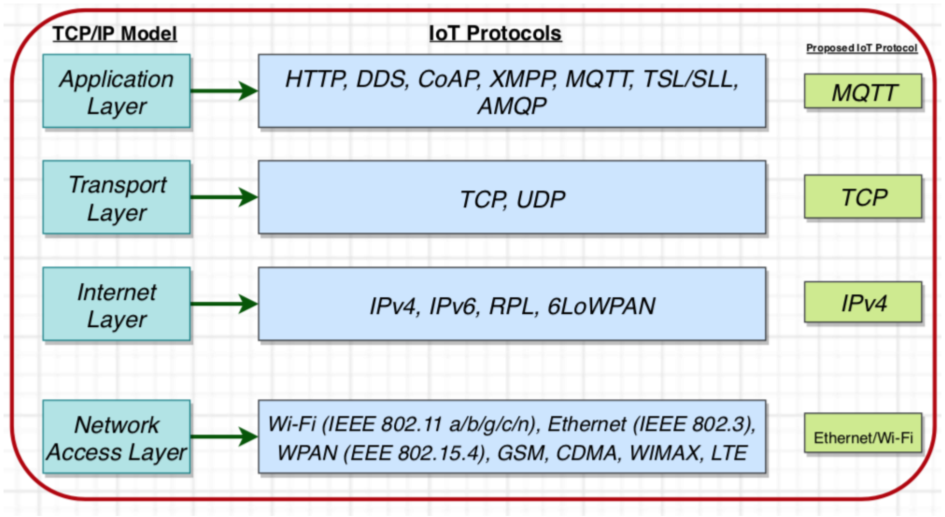


Figure 5.1: TCP/IP model vs Internet of Things (IoT) protocols.

The SCADA system proposed in this work is based on the IoT-SCADA architecture in which IoT features are incorporated into the conventional SCADA system for more robust data acquisition, remote monitoring and supervisory control. This means that IoT protocols are involved in the IoT-based SCADA system design. Research has shown that the most critical design alternatives for developing IoT-based real-time applications such as SCADA, are communication protocols, message encoding format, and the web or IoT platform [35,36]. Therefore, in each of the IoT protocol layers shown in Figure 5.1, it is critical to pick the right protocol for a particular IoT-based application. For instance, in the Application Layer, one has to make the hard choice between HTTP, MQTT, CoAP, and so on, as well as pick the right protocol in the Transport, Internet, and Network Access Layers. The properties, advantages and disadvantages of the different Application Layer IoT protocols such as MQTT, CoAP, HTTP, and AMQP are extensively discussed in [8, 35, 37]. In this work, after so much research, testing and consultations, we have chosen to go with MQTT, TCP, IPv4, and IEEE 802.11 (Wi-Fi)/Ethernet in the respective Layers. In our proposed system, MQTT data transfer protocol is implemented over TCP/IP Wireless connectivity. ThingsBoard has also been chosen as the preferred IoT platform after researching the alternatives [38], and for security reasons, the ThingsBoard IoT server platform is locally installed and hosted on own private machine (Raspberry Pi), and own network (Memorial University (MUN) Network) rather than using the ThingsBoard web platform as is commonly implemented in literatures. One of the reasons for choosing ThingsBoard is that it supports MQTT protocol over wireless connectivity. When implemented, the ThingsBoard server API serves as MQTT Broker [39]. MQTT is discussed in the next section.

5.3.0.2 Message Queuing Telemetry Transport (MQTT) protocol

Message Queuing Telemetry Transport (MQTT) is a lightweight machine-to-machine data communication protocol [8]. The MQTT, with a 2 byte fixed header, is especially suited for IoT applications as it supports applications with limited resources such as low bandwidths, low computational power, low memory, battery, etc. which is typical in an IoT domain [17, 22, 24]. MQTT runs on TCP/IP connection, and can be implemented on various networks such as Wired (Ethernet) and Wireless Local Area Networks [26, 40]. Originally invented in 1999 by Andy Stanford-Clark of IBM, and Arlen Nipper of Arcom (now Eurotech), MQTT is now recognized as an open standard by the Organization for the Advancement of Structured Information Standards (OASIS) [27].

Figure 5.2 shows the general architecture of the MQTT protocol. Essentially, MQTT uses a Publish-Subscribe messaging mechanism, and it is made up of a Broker (Server), and Clients. The MQTT Broker is usually a server running in the cloud or on the internet, and is responsible for storing the published data based on different Topics, and releasing the message (data) to the rightful Subscribers. The MQTT Client is any piece of hardware, software, or a combination of both hardware and software, which connects to the Broker for the purpose of exchanging data. When a connected device or Client downloads data from the Broker (server), the process is called Subscribing, and that particular Client is known as a Subscriber. On the other hand, when a connected device (Client) sends data to a Broker (server), the Client is referred to as the Publisher, and the process is called Publishing. Hence, the term, "Publish-Subscribe" mechanism upon which the MQTT protocol is based. It is worth noting that a Broker can serve several Subscribers and Publishers, depending on the capability of the machine running the Broker. A Client can also act as both a Publisher and a Subscriber. When a Client publishes data, it assigns a specific Topic to the data, with each Topic separated by a forward slash. For each Topic, there is a Topic name, and Topic level associated with it, and wildcard characters are used to match multiple levels to a Topic [8, 17, 26].

MQTT protocol uses three levels of Quality of Service (QoS) for message delivery: QoS 0, QoS 1, and QoS 2. In QoS 0, the receiver does not acknowledge message receipt, and the sender does not re-transmit the message. Here, message delivery is based on the guarantee that there is a reliable connection between the Client(s) and the Broker (server).

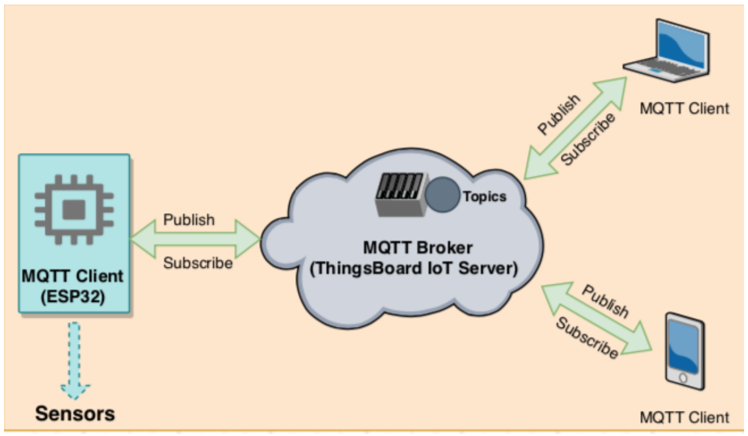


Figure 5.2: MQTT architecture.

In QoS 1, a packet identifier is assigned to the message by the sender, and the receiver replies with an acknowledgement if it receives and accepts the message, while the unacknowledged messages are re-transmitted by the sender. Although this process could lead to message duplication, this system is implemented to ensure that the transmitted message is actually received by the MQTT Broker. When QoS 2 is used, multiple messages are exchanged between the MQTT Client and the Broker so that the information is transmitted exactly one time, as such prevent the loss and duplication of data at the cost of extra overheads. Hence, there is a trade-off between message overhead cost and reliability. There is also a two step acknowledgement process to publish the message in this QoS. Depending on the QoS associated with a message, control packets are exchanged before transmitting the message [17,22]. An MQTT control packet comprises of a fixed header, a variable header, and payload. Some of the MQTT control packets exchanged between the MQTT Clients and Broker include CONNECT, CONNACK, PUBLISH, PUBACK, PUBREC, PUBREL, SUBSCRIBE, SUBACK, etc [17,22,26]. For instance, upon receiving the sent message, the receiver sends a PUBREC to acknowledge the packet receipt, and a PUBREL is transmitted by the message publisher to indicate the release of a published message, and then PUBCOMP is transmitted by the receiver to indicate the completion of the publication.

Furthermore, MQTT has a queuing system where the Broker buffers all the messages if the Client is offline, and delivers them to the Client when the Client is back online. In this case, the Client and the Broker store the current state of the session, and the Broker delivers the queued messages once the Client has an active session. Thus, MQTT protocol is reliable and suitable for IoT applications where there are usually limited resources such as low bandwidth, low memory, low power, etc [8, 17, 22, 26]. This is why MQTT is preferred to other data transfer protocols like CoAP, HTTP, REST API, etc [8, 35]. MQTT also runs on TCP/IP connection unlike CoAP which runs on UDP [8, 35]. The detailed advantages of MQTT over other data transport protocols are presented in literatures [8, 35, 37]. Because of these valuable features of the MQTT protocol, numerous applications already use it. For example, Facebook messaging, smart home monitoring, healthcare, transport, energy metering, parking, industrial robots, manufacturing, and intelligent monitoring systems have been implemented with MQTT protocols over various TCP/IP connections [14–29].

In this project, MQTT protocol is implemented for PV data transfer from the MQTT Client (ESP32 micro-controller) to the MQTT Broker (ThingsBoard IoT server), while personal computers and mobile devices can subscribe to visualize the published data on the server. ThingsBoard server node acts as an MQTT Broker, and it supports QoS levels 0 (at most once) and 1 (at least once), and a set of predefined Topics [39]. This ThingsBoard IoT server together with PostgresSQL Database is built on a Raspberry Pi 2 micro-controller, and the MQTT Client Library (Arduino PubSubClient) is implemented with Arduino IDE Software on an ESP32 OLED micro-controller board to collect the sensor data and publish them to the ThingsBoard IoT server (MQTT Broker).

5.4 Proposed SCADA System Architecture

In this section, we describe the hardware and network structures of the proposed IoT-based open source SCADA system solution. In configuration A (Figure 5.3), the Raspberry Pi 2 micro-controller hosting the ThingsBoard IoT server (MQTT Broker) where the received PV data are processed and stored is connected through an Ethernet cable to MUN network. As a result of this connection, authorized users on MUN network can access the stored PV data and visualize the created dashboards and alarms on the ThingsBoard IoT server. In addition, authorized personnel can also have access to the stored data via the internet by using their private home or office network as long as the ThingsBoard IoT server port is opened only on the MUN network. Although this configuration presents a great deal of flexibility as it provides many options for the stored data access, it poses security risks to the stored data since external internet users can access the stored data remotely. In configuration B (Figure 5.4), the public internet is not used, and the Wi-Fi Router is used to create a form of industrial network such that only the authorized users nearby can access the stored PV data on the ThingsBoard IoT server platform. This is done by connecting the Raspberry Pi machine hosting the ThingsBoard IoT server to one of the LAN ports of the Wi-Fi Router. In this configuration, only the connected and authorized users on the local Wi-Fi network created with the Router can access the data on the ThingsBoard IoT server by pointing to the IP address of the Raspberry Pi on their browsers. This configuration also ensures that even the users on the general MUN network cannot access the stored data in the cloud, thereby guaranteeing the security of the stored data. Firewall, and authentications are setup on the Router to guarantee the security of the system. In both configurations, the MQTT Client (ESP32 OLED device) processes and publishes the sensor data to the MQTT Broker (ThingsBoard server) using MQTT protocol on the TCP/IP Wi-Fi connection established with the Router.

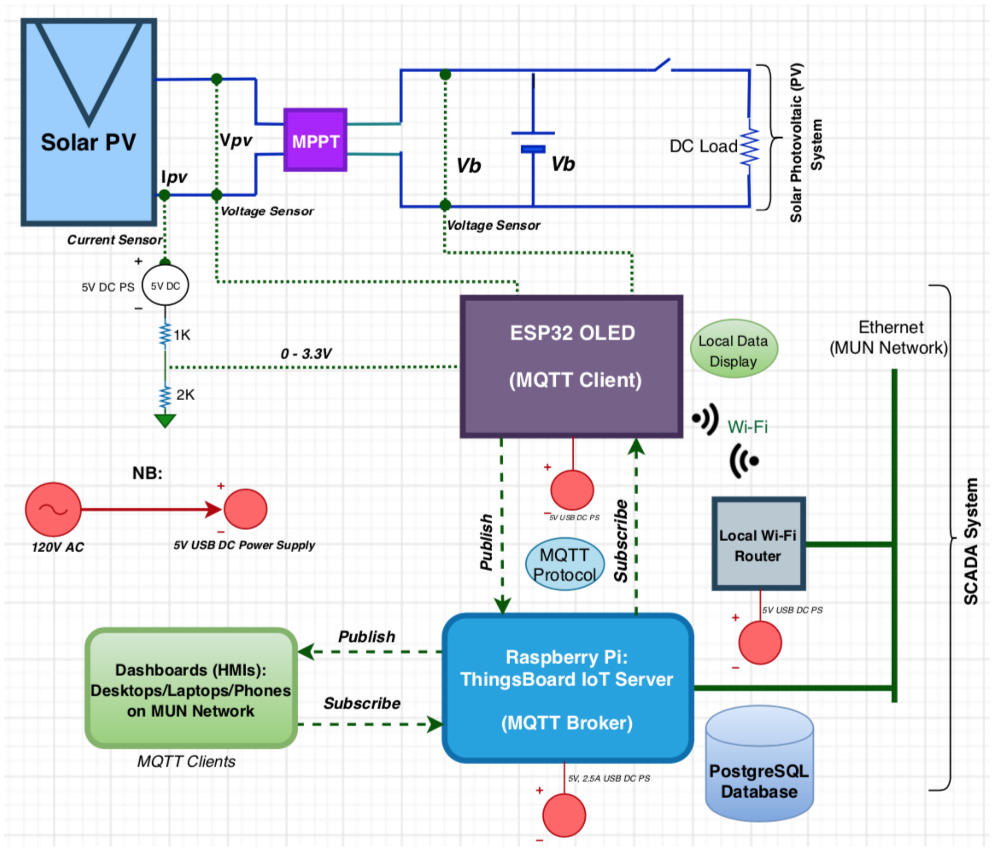


Figure 5.3: The proposed SCADA system configuration A.

5.5 Proposed SCADA System Components

Here, we present a brief description of each of the low-cost hardware and software components used in the realization of the proposed open source SCADA system design. These components include the Hall Effect Current and Voltage Sensors which serve as the field instrumentation devices to acquire the PV system data, the versatile ESP32 micro-controller, with OLED display, which is the remote terminal unit, and is configured as the MQTT Client to process and publish the sensor data using MQTT protocol, a Raspberry Pi2 single-board computer upon which the ThingsBoard IoT server, which is the master terminal unit, and is configured as the MQTT Broker, is built for human machine interactions, data storage, dashboards, alarms, data publishing and subscription, and finally, a Wi-Fi Router for

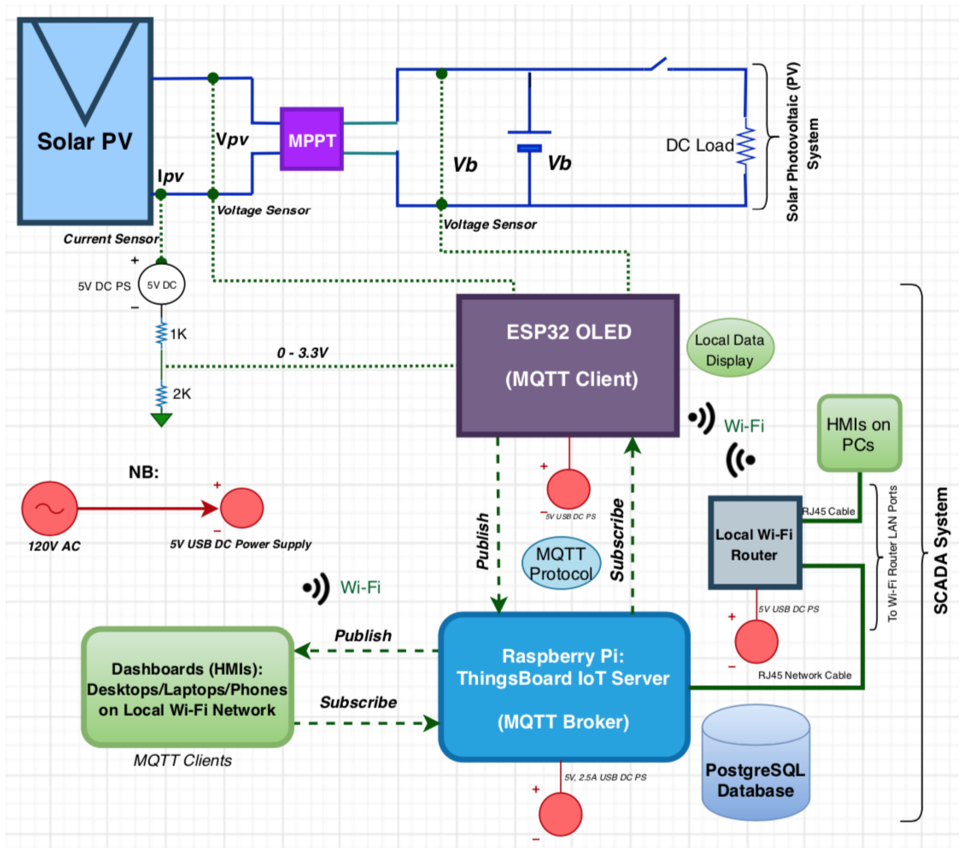


Figure 5.4: The proposed SCADA system configuration B.

creating the TCP/IP Wi-Fi connection for the MQTT protocol implementation.

5.5.1 Sensors (Field Instrumentation Devices)

Three low-cost, and readily available analog sensors are used in this work, including two MH Electronic Voltage Sensor modules, and one ACS 712 Hall Effect Current Sensor. The most important properties of these sensors, as well as their usage in the proposed SCADA system design are described in the next sub-sections.

5.5.1.1 MH Electronic Voltage Sensors

This low-cost analog voltage sensor uses the concept of voltage divider to measure voltage with its in-built series connection of a 7.5 K resistor and a 30 K resistor. Its operating voltage range is 3.3 V to 5.0 V, and it is capable of detecting supply voltages in the range of 0.025 V to 25 V using a 12-bit ADC [41]. Because the operating signal voltage of this sensor is between 3.3 V and 5.0 V, it is suitable for direct connection to the ESP32 OLED micro-controller device with operating voltage of 0 V to 3.3 V. The two voltage sensors used in this project are connected as follows: One of the sensors is connected in parallel across the solar PV system to measure the PV Voltage, while the second sensor is connected in parallel across the lead acid storage battery system (after the MPTT module) to measure the storage battery voltage. The outputs of the sensors are connected to the ESP32 OLED micro-controller as follows: For the first voltage sensor, PIN S is connected to Analog PIN 34 on the ESP32, and PIN – is connected to a GND pin on the ESP32 while its GND and VCC pins are connected in parallel across the PV panel (PIN + of the sensor is not used). For the second voltage sensor, PIN S is connected to Analog PIN 35 on the ESP32, and PIN – is connected to a GND pin on the ESP32 while its GND and VCC pins are connected (after the MPPT module) in parallel across the storage battery (PIN + of the sensor is not used) [41].

5.5.1.2 ACS 712 Hall Effect Current Sensor

This low-cost, fully integrated current sensor is manufactured and supplied by Allegro MicroSystems, LLC. The sensor is based on the principle of Hall Effect. First described by Dr. Edwin Hall in 1879, Hall Effect is a concept whereby a current-carrying conductor placed in a magnetic field generates a voltage perpendicular to both the current and the magnetic field. This Hall Effect is made possible by the unique properties of this sensor. The sensor has a low-noise resistance current conductor, low-noise analog signal path, and close to zero magnetic hysteresis. The 30 A DC module used in this work has 66 to 185 mV/A output sensitivity, and it operates on a 5 V single supply voltage. When this 5 V supply voltage is applied, the current flowing through the copper conduction path generates a magnetic field which the Hall IC then converts to a proportional output voltage. Using the sensor sensitivity, the signal voltage, and the ADC resolution of the ESP32 micro-controller, the equivalent output current is calculated from this output voltage using the Arduino IDE software. Using this system, 0 A corresponds to 2.5 V, and 30 A corresponds to 5 V on the 30 A DC module used in this setup. However, because the signal voltage of the current sensor is 5 V, it is not suitable for direct connection to the ADC pins of the ESP32 micro-controller as the ADC pins operate between 0 V to 3.3 V. Therefore, to ensure the accuracy of the measured values, a pull-down or step-down resistors arrangement is used to match the 5 V signal requirement of the current sensor to the 3.3 V signal capability of the ESP32 ADC pins. This is done using a voltage divider equation. The voltage divider equation used for this task is shown in Equation 5.1, and the step-down resistors circuit connection is shown in Figure 5.5. With the help of this step-down resistors connection, the current sensor is connected to the ESP32 micro-controller as follows: Its OUT pin is connected through the pull-down resistors to the Analog pin 32 on the ESP32, its GND pin is connected to a GND pin on the ESP32, and its VCC pin is powered with a 5 V supply. In order for the sensor to measure the current flowing through the PV panel, its input pins are connected in series to the PV panel [41].

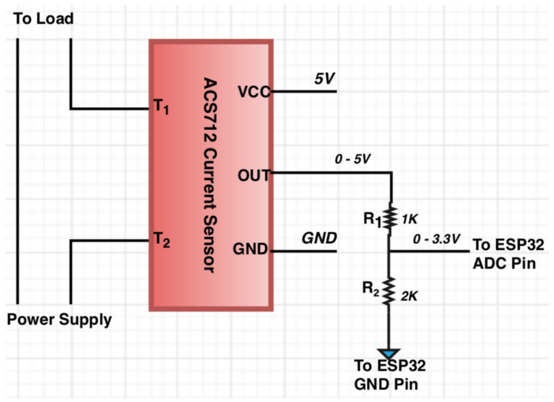


Figure 5.5: ACS712 step-down resistors connection.

$$V_{out} = \frac{R_2}{(R_1 + R_2)} \times V_{in} \tag{5.1}$$

where; V_{out} = ESP32 ADC Voltage (3.3 V), and V_{in} = Sensor Input Voltage (5 V), while R_1 and R_2 are calculated to match these voltage values using the voltage divider equation.

5.5.2 TTGO ESP32 LoRa32 OLED Micro-controller (RTU)

The TTGO ESP32 LoRa32 micro-controller board with 0.96 inch organic light-emitting diode (OLED) display used in this work is a low-cost (about $20 CAD), low-power ((about 0.9 W), and completely open source ESP32 development board. Its physical construction is based on the ESP32-DOWDQ6 ESP chip, and it has a built-in heat sink at the back. The most important specifications of the board include the following [42];

- IEEE 802.11 b/g/n Standards HT40 Wi-Fi Transceiver.
- Dual Core Processor, clocked at 240 MHZ.
- 520 KB Static RAM (SRAM).
- Baseband and Lightweight TCP/IP (LwIP) stack.
- Bluetooth dual mode integrated traditional and BLE low-power Bluetooth support.
- 4 MB on-board Flash, and Wi-Fi and Bluetooth Antenna.
- 18 ADC pins and over 30 GPIO pins (I/O Pins).
- 0.96 inch white OLED display.
- 5 V single power supply, and support for a single-cell lithium-polymer (LiPo) battery.
- Support for CP2102 USB to Serial (UART) chip.

- Computing capacity of up to 600 DMIPS (Dhrystone Million Instructions per Second).
- Operating ADC signal voltage range of 1.8 V - 3.7 V.

With these specifications, especially with the 520 KB SRAM and 4 MB Flash, the board supports debugging, as well as programming the firmware after the development of an application. Also, with the Wi-Fi support, the board can implement HTTP and MQTT. These properties also make the board perfect for Arduino development environment. Although the board is capable of implementing LoRa, its LoRa features have not been considered in this work. Since the ADC pins of the ESP32 board are only 3.3 V tolerant, there is the need for the level shifting of the connected 5 V current sensor as explained earlier. An image of the TTGO ESP32 LoRa32 OLED V1.0 board used in this work is shown in Figure 5.6, and its Pinout arrangement showing the GPIO and ADC pins, power supply interface, SPI, etc. is shown in Figure 5.7 [42].

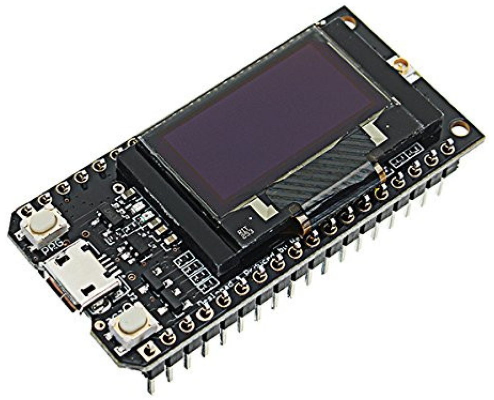


Figure 5.6: Image of the TTGO ESP32 LoRa32 OLED micro-controller [42].

The ESP32 board can be programmed with either PlatformIO integrated development environment (IDE) or Arduino IDE. In this project, the Arduino IDE is used to program the board. With the Arduino IDE, one can write any desired programs and upload them to the board either via USB or using its USB to Serial (UART) interface. The Arduino

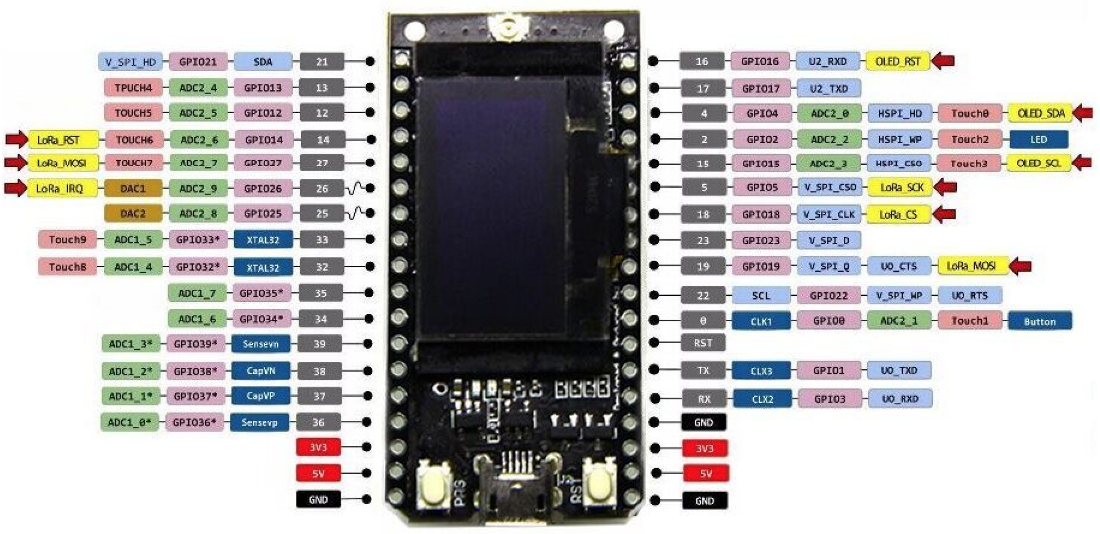

V_SPI_HD GPIO21 SDA 21
TPUCH4 ADC2_4 GPIO13 13
TOUCH5 ADC2_5 GPIO12 12
LoRa_RST TOUCH6 ADC2_6 GPIO14 14
LoRa_MOSI TOUCH7 ADC2_7 GPIO27 27
LoRa_IRQ DAC1 ADC2_9 GPIO26 26
DAC2 ADC2_8 GPIO25 25
Touch9 ADC1_5 GPIO33* XTAL32 33
Touch8 ADC1_4 GPIO32* XTAL32 32
ADC1_7 GPIO35* 35
ADC1_6 GPIO34* 34
ADC1_3* GPIO39* Sensevn 39
ADC1_2* GPIO38* CapVN 38
ADC1_1* GPIO37* CapVP 37
ADC1_0* GPIO36* Sensevp 36
3V3
5V
GND
16 GPIO16 U2_RXD OLED_RST
17 GPIO17 U2_TXD
4 GPIO4 ADC2_0 HSPI_HD Touch0 OLED_SDA
2 GPIO2 ADC2_2 HSPI_WP Touch2 LED
15 GPIO15 ADC2_3 HSPI_CS0 Touch3 OLED_SCL
5 GPIO5 V_SPI_CS0 LoRa_SCK
18 GPIO18 V_SPI_CLK LoRa_CS
23 GPIO23 V_SPI_D
19 GPIO19 V_SPI_Q U0_CTS LoRa_MOSI
22 SCL GPIO22 V_SPI_WP U0_RTS
0 CLK1 GPIO0 ADC2_1 Touch1 Button
RST
TX CLX3 GPIO1 U0_TXD
RX CLX2 GPIO3 U0_RXD
GND
3V3
5V
GND
PRG
RST

Figure 5.7: Pinout of the TTGO ESP32 LoRa32 OLED micro-controller [42].

programs, called Sketches, are written using a set of C/C++ functions. In this work, the ESP32 micro-controller is programmed as an MQTT Client using the Arduino IDE software and the MQTT Client Library called PubSubClient. The program is such that the board acquires the measured real-time PV voltage and current values, battery voltage values, and the calculated PV power values from the sensors, displays the values on both the Arduino IDE Serial Monitor and its OLED display screen, and continuously publishes the real-time data to the MQTT Broker, the ThingsBoard local server IoT platform, using MQTT protocol over the TCP/IP Wi-Fi connectivity. The ESP32 board represents the Remote Terminal Unit (RTU) in the proposed IoT-based SCADA system, and the MQTT protocol implemented on the board helps in realizing the basic functions of the RTU: to acquire and process the sensor data, and parse them to the Master Terminal Unit, ThingsBoard Server in this case. The OLED display screen of the board provides the extra SCADA monitoring function of giving the local plant operator an interface to view the most recent data of the facility being managed. Although the local plant operator is unable to see the data trends on the OLED display as is on the HMI on the Master Terminal Unit (SCADA server), being able to see the most recent data could be critical in the event that the remote SCADA operator is unavailable to provide supervisory control actions. This extra SCADA feature implemented in this work is one of the contributions of this work as we have not found any IoT-based open source SCADA system design solution where such extra plant monitoring feature is implemented.

5.5.3 Raspberry Pi Single-board Computer

The Raspberry Pi 2 model B device used in this work is a low-cost, single-board computer developed in the United Kingdom by the Raspberry Pi Foundation [43]. It is a portable credit card-sized single-board computer (about 85*56 mm) featuring the BCM2836 quad core (4 processors in one chip) ARMv7 processor, and it is completely open source. The Raspberry Pi machine primarily runs on Raspbian operating system (OS) which is a Debian-based Linux distribution specifically for the Raspberry Pi [43]. The most important hardware specifications of the specific Raspberry Pi 2 model B used in this project include the following [43];

- 32-bit 900 MHz quad-core ARM Cortex-A7 CPU
- 1 GB RAM
- 100 Base Ethernet support
- 4 USB ports
- 40 GPIO pins
- Full HDMI port
- Combined 3.5 mm audio jack and composite video
- Camera interface (CSI)

- Display interface (DSI)
- Micro SD card slot.
- VideoCore IV 3D graphics core.

In the proposed SCADA system design, the ThingsBoard IoT server which is the MQTT Broker, as well as the Master Terminal Unit for human machine interactions and data processing, is installed on the Raspberry Pi computer. This is done by building the ThingsBoard server alongside the required third-party components and services on the Raspberry Pi operating system. To realize this, the Raspbian Buster OS was installed on a micro-SD card and inserted into the Raspberry Pi's micro-SD card slot. Following the available ThingsBoard installation documentation [44], and the open source ThingsBoard server repository on GitHub, several installation codes were run on the Raspberry Pi Terminal to download and install the ThingsBoard version 2.4 server and its services on the Raspberry Pi computer. The open source PostgreSQL Database was also installed alongside the ThingsBoard server to store the acquired data. After the installation and configuration of the ThingsBoard server and the PostgreSQL Database on the Raspberry Pi, the Raspberry Pi was then connected to the other components of the proposed SCADA system in two different configurations as described earlier, and each configuration was tested.

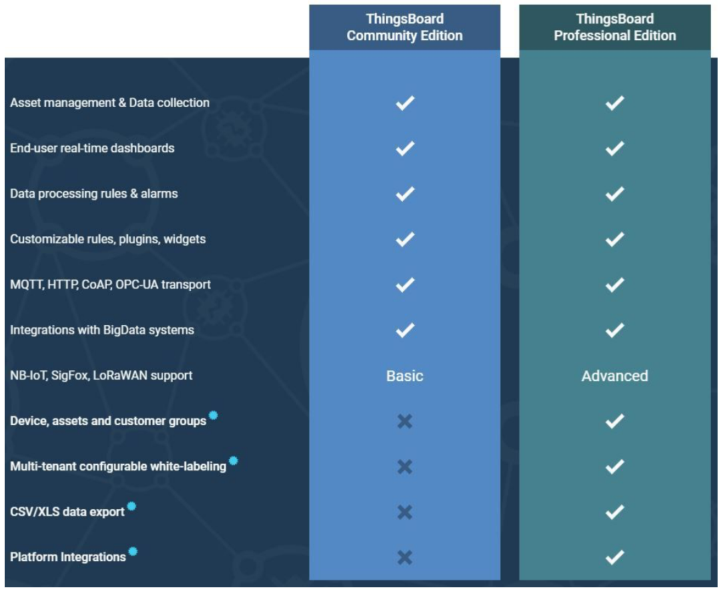
5.5.4 Wi-Fi Router (TCP/IP Wi-Fi Connection)

The D-Link Router (DI-524 Airplus G) is used to create the TCP/IP Wireless network connectivity over which the MQTT protocol is implemented for data transfer from the MQTT Client (ESP32) to the MQTT Broker (ThingsBoard IoT server). The major specifications of the router include 1 WAN port and 4 LAN ports, 2.4 GHz operating frequency band, high speed with 54 Mbps data transfer rate, 802.11 b/g wireless protocol support and IEEE 802.11 standards-compliant, and access control capabilities [41]. Because the ESP32 micro-controller used in this work supports TCP/IP, IEEE 802.11b/g/n Wi-Fi standards, the router is configured to set up the needed local Wi-Fi network connectivity, and the implemented MQTT protocol on the ESP32 (MQTT Client) is used to publish the acquired sensor data over this TCP/IP Wireless connectivity to the ThingsBoard IoT server platform (MQTT Broker). For security and access control purposes, connection to the Wi-Fi network is restricted using the Wi-Fi network name (SSID) and the assigned password, as well as other implemented security measures on the router.

5.5.5 ThingsBoard Local Server IoT Platform

ThingsBoard is an open-source IoT platform for data collection, processing, visualization, and device management [44]. It provides an out-of-the-box IoT cloud or on-premises solution to enable server-side infrastructure for various IoT applications [44]. Built on Java 8 platform, ThingsBoard provides 100 percent support for standard IoT protocols for device connectivity, including MQTT, CoAP, and HTTP(S), and it presently supports three different database options: SQL, NoSQL, and Hybrid databases. The ThingsBoard platform uses these databases to store *entities* (such as devices, assets, dashboards, users, alarms, customers, etc.), and *telemetry data* (attributes, time-series sensor readings, statistics, events, etc.). *Telemetries* are time-series of key-value pairs of data associated with a specific device, and ThingsBoard stores its received data as *telemetries*. *Assets* are containers for reorganizing the received data, and could be used to upload the results of the data processing. *Attributes*, on the other hand, usually represent the device features such as firmware version, hardware specifications, etc. which are assigned to registered devices and assets in the form of key-value pairs. The SQL database such as PostgreSQL stores all *entities* and *telemetry* in SQL database, while the NoSQL option such as Cassandra stores all *entities* and *telemetry* in NoSQL database. In the Hybrid database option, all *entities* are stored in SQL database while all *telemetry* are stored in NoSQL database [11, 30, 38, 44]. In this project, the PostgreSQL database is installed on the ThingsBoard server for *entities* and *telemetry* storage.

ThingsBoard has two different editions, the Community Edition, which is free and wholly open source, and the Professional Edition, which has more advanced features. The features of both editions and their major differences are shown in Figure 5.8 [44].



	ThingsBoard Community Edition	ThingsBoard Professional Edition
Asset management & Data collection	✓	✓
End-user real-time dashboards	✓	✓
Data processing rules & alarms	✓	✓
Customizable rules, plugins, widgets	✓	✓
MQTT, HTTP, CoAP, OPC-UA transport	✓	✓
Integrations with BigData systems	✓	✓
NB-IoT, SigFox, LoRaWAN support	Basic	Advanced
Device, assets and customer groups ●	✗	✓
Multi-tenant configurable white-labeling ●	✗	✓
CSV/XLS data export ●	✗	✓
Platform Integrations ●	✗	✓

Figure 5.8: The ThingsBoard Community Edition vs Professional Edition [39, 44].

In this project, the Community Edition is used. This Community Edition is open source, and is available free-of-charge on both the ThingsBoard official website and on GitHub software development platform [44]. With the ThingsBoard back-end written in Java, and some of its micro-services based on Node.js, the ThingsBoard architecture is designed to be scalable, fault-tolerant, robust and efficient, customizable, and durable. The basic ThingsBoard architecture is shown in Figure 5.9 [30, 44].

The key features and functions of the major components of the ThingsBoard architecture are presented as follows;

- **Transport components:** These include MQTT, HTTP, and CoAP-based APIs for device applications and firmware. Being a part of the ThingsBoard "Transport Layer",

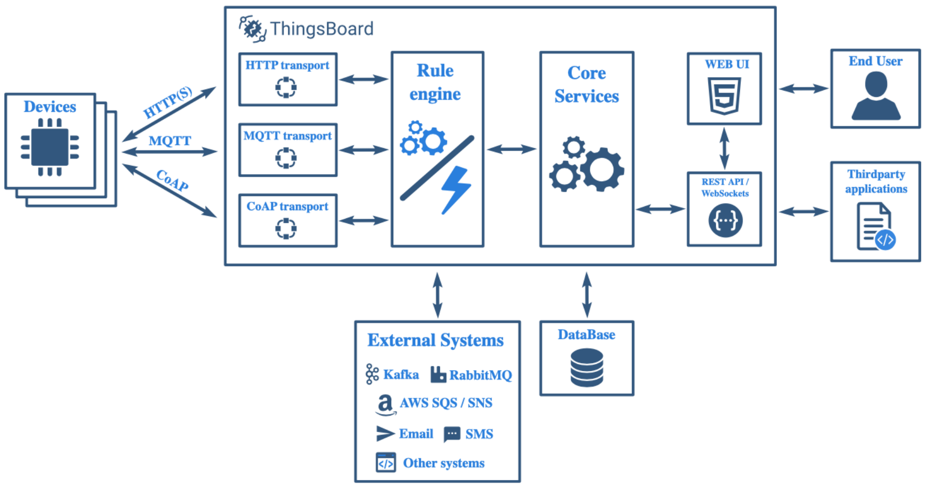


Figure 5.9: The basic ThingsBoard architecture [39, 44].

each of the components here helps to push data to the *Rule Engine*, and could also use *Core Services* to issue requests to the database to validate device credentials [11, 30, 38, 44]. In this project, the MQTT-based device API supported by the MQTT communication protocol is implemented. MQTT is favoured ahead of the HTTP and CoAP because of its unique features like support for constrained resources such as low bandwidth, and it can be implemented over various TCP/IP connectivities. In addition, ThingsBoard server nodes act as an MQTT Broker that supports QoS levels 0 (at most once) and 1 (at least once), and a set of predefined topics which means that an external device can be configured as an MQTT Client to publish data to the server nodes [39]. Here, ESP32 is programmed and configured as that MQTT Client to publish the acquired PV System data to the ThingsBoard server nodes.

- **Rule Engine components:** The ThingsBoard *Rule Engine* helps in processing the incoming messages with user-defined logic and flow. This *Rule Engine*, which comprises of *Rule Node* and *Rule Chain*, is highly customizable and configurable, and can be used for processing complex events [30, 44]. For example, the system administrator is able to filter, enrich, and transform incoming messages sent by IoT devices and related applications, as well as implement and trigger various actions such as alarms, notifications on the state of the connected devices, email alerts, or other communication with external devices using the *Rule Engine* [44]. In this work, the configured *Rule Engines* for the overall system implementation (e.g data transfer), and that for the alarm notifications on the state of the PV system being monitored (Storage Battery Voltage monitoring) are shown in Figures 5.10 and 5.11 respectively.

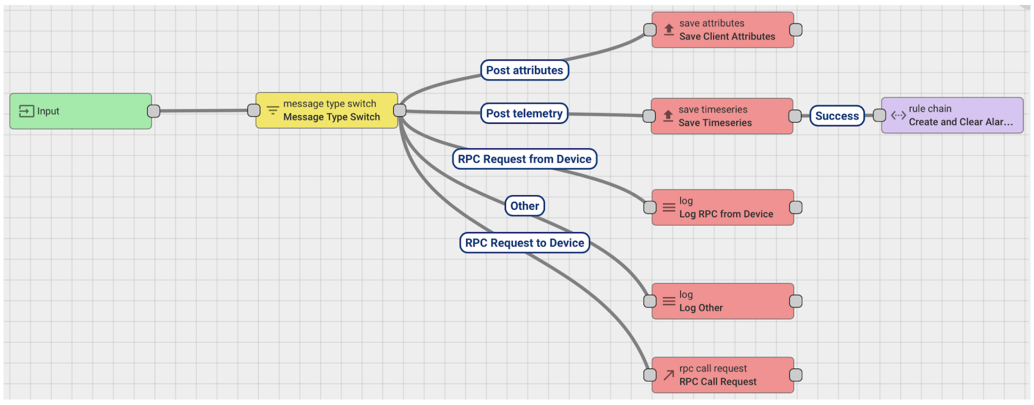


Figure 5.10: System Rule Engine.

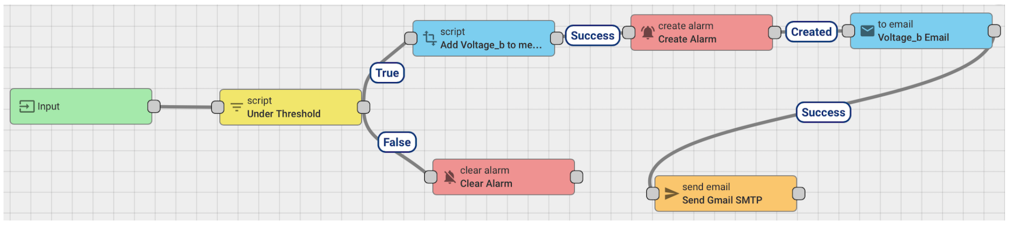


Figure 5.11: Alarm Rule Engine.

- **Core services:** These are responsible for handling REST API calls, monitoring device connectivity states, and WebSocket Subscriptions on entity, telemetry and attribute changes [44].

- **External systems:** Using the Rule Engine, communications can be established between ThingsBoard and external systems. This involves pushing data to external systems, processing the data, and reporting the results of the processed data back to

ThingsBoard server for visualization [30, 44]. Being able to integrate ThingsBoard data processing with external systems in this way ensures a great deal of flexibility in the system, unlike most IoT platforms [38].

ThingsBoard server can either be utilized directly on the *Live Demo* platform, installed on a private machine *On-Premise*, or hosted on a *Cloud Server* such as DigitalOcean, Amazon Web Services (AWS), Google Cloud platform, Microsoft Azure, IMB Cloud, etc [44]. The few literatures found on ThingsBoard have used the Live Demo platform to implement their proposed IoT-based monitoring solutions [11, 30]. This Live Demo platform requires the public internet for data access just like every other web application out there, which could leave the stored data vulnerable to internet attacks. On the other hand, hosting the ThingsBoard server on a Cloud platform such as AWS, requires not just the public internet for data access, it also requires subscriptions which might not be affordable depending on the stored data footprint, which means more cost and the possibility of internet attacks [44]. However, security in a SCADA system is a critical issue as attacks on the SCADA could compromise the important company data stored in the cloud. Therefore, in our proposed IoT-based SCADA system design solution, the on-premise, self-hosted ThingsBoard server option is implemented. Although the ThingsBoard developers have provided installation options and guides for various machines and operating systems, including Windows, Linux (CentOS and Ubuntu), Raspberry Pi, Docker (Linux and MacOS), Docker (Windows), Maven, and Cluster Setup, the ThingsBoard server used in this work is installed on a Raspberry Pi 2 model B machine. This is because the Raspberry Pi is reliable, portable, and consumes relatively low power compared to the other options. This Raspberry Pi option is also completely free as it has been built from scratch on the Raspberry Pi using the installation guides on GitHub and ThingsBoard official website. Keeping the power consumption to the possible minimum is essential since the proposed SCADA system is meant to be in operation 24/7 for effective monitoring and supervisory control.

By installing the ThingsBoard server on the Raspberry Pi machine connected to a private network (MUN Network, and local Wi-Fi Network), it can be operated with and without the public internet, depending on what configuration is chosen based on the desired security and flexibility of the operation. This represents a major contribution of this paper as no related works have been found where such measures were considered.

ThingsBoard currently supports various hardware platforms, including Arduino, ESP32, ESP8266, NodeMCU, Raspberry Pi, and LinkIt One, which makes it perfect for IoT applications [44]. Also, the developers are presently working on supports for more platforms such as Intel Edison, C.H.I.P, Samsung Artik, Tessel, and Gemalto. Any of the chosen hardware can be connected to the ThingsBoard server, and two different authentication options supported by ThingsBoard, including Access Tokens and X.509 Certificates, can be implemented [44]. In this work, the TTGO ESP32 LoRa32 V1.0 hardware with OLED display screen is connected to the installed ThingsBoard server, and the Access Token device authentication option implemented. This means that by registering the ESP32 device on the ThingsBoard server platform, and assigning Access Token to the device, the connected sensor data acquired by the ESP32 device can be published to the server using both the server IP address (Raspberry Pi IP address), and the Access Token to identify the platform. The interface of the installed ThingsBoard server on the Raspberry Pi machine showing the IP address, and the numerous menus such as *Rule Chains, Customers, Assets, Devices*, and so on, for various actions is shown in Figure 5.12.

This locally hosted ThingsBoard server on the Raspberry Pi single-board computer, which is the Master Terminal Unit (MTU) of the proposed SCADA system, serves as the MQTT Broker, and the ESP32 device, programmed and configured as an MQTT Client, publishes the acquired sensor data from the connected PV system to the MQTT Broker using MQTT protocol over the TCP/IP Wireless Network connectivity created with the Wi-Fi router. Since ThingsBoard allows for the creation of customizable real-time dashboards

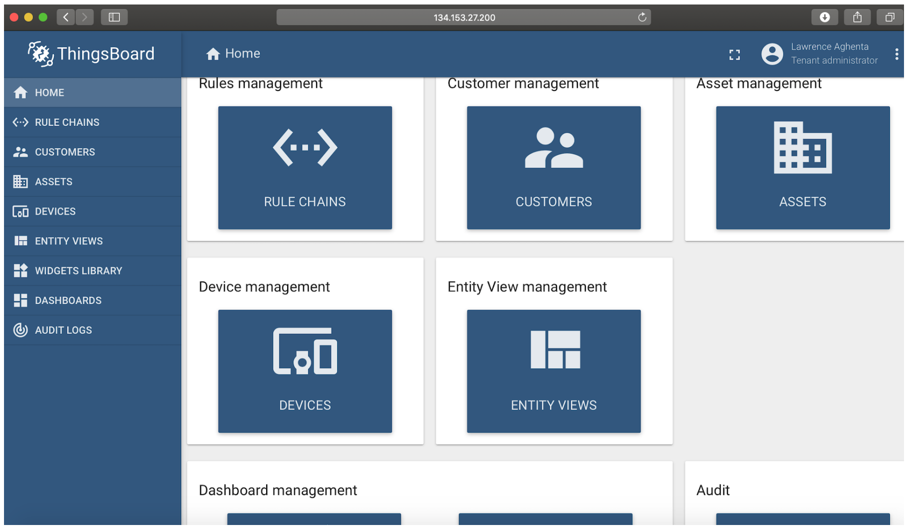
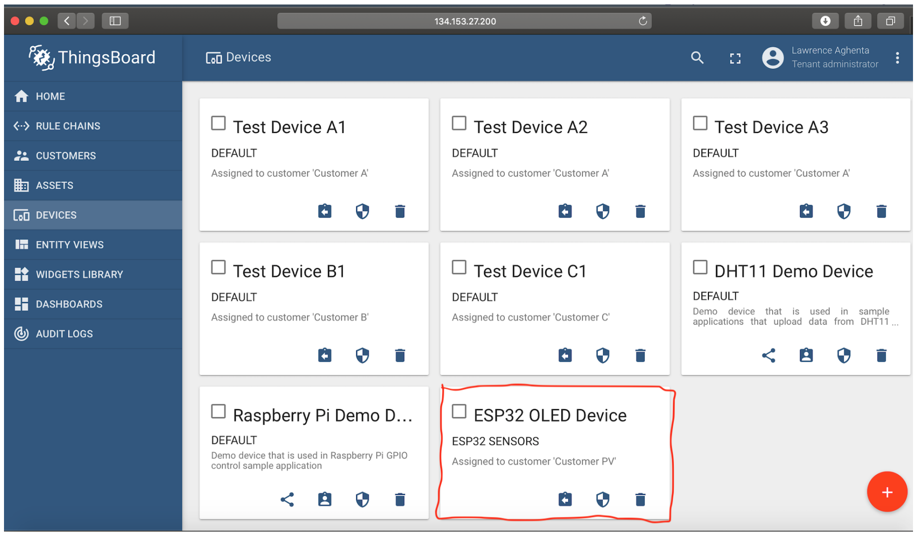


Figure 5.12: Raspberry Pi-installed ThingsBoard server interface.

(HMIs) with more than 30 *Widgets* for data visualization, alarms, notifications, and device managements [30,44], beautiful real-time dashboards are created on the local ThingsBoard server for the PV system data visualization and management. These dashboards (HMIs) which show the states of the PV system being managed can be accessed either via the internet or offline, depending on the chosen configuration deployed. Figure 5.13 shows the connected ESP32 device, while Figure 5.14 shows the sensor data being posted to the ThingsBoard server nodes.

5.5.6 MUN ECE Laboratory PV System Overview

In order to test the functionalities of the designed open source SCADA system, it is setup to acquire the solar photovoltaic (PV) data of the PV system at Memorial University (MUN) Electrical and Computer Engineering Department Laboratory. This PV system is made up of 12 Solar Panels covering a total area of 14 square meter and producing about 130 W and 7.6 A each. Although the proposed SCADA system is connected to just one set of the modules (about 260 W, and 14 A output) for testing purposes, the entire system comprises of two modules connected in parallel such that it contains 6 sets of 260 W, and



Test Device A1
DEFAULT
Assigned to customer 'Customer A'

Test Device A2
DEFAULT
Assigned to customer 'Customer A'

Test Device A3
DEFAULT
Assigned to customer 'Customer A'

Test Device B1
DEFAULT
Assigned to customer 'Customer B'

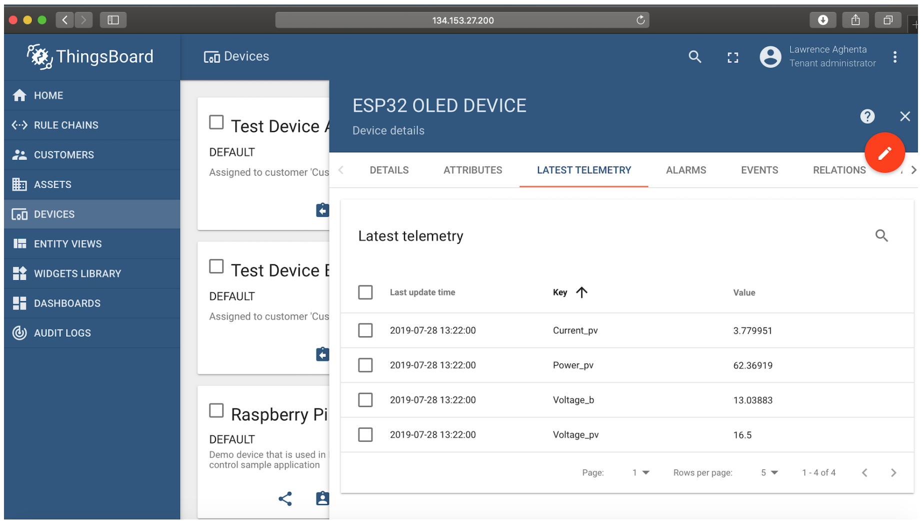
Test Device C1
DEFAULT
Assigned to customer 'Customer C'

DHT11 Demo Device
DEFAULT
Demo device that is used in sample applications that upload data from DHT11 ...

Raspberry Pi Demo D...
DEFAULT
Demo device that is used in Raspberry Pi GPIO control sample application

ESP32 OLED Device
ESP32 SENSORS
Assigned to customer 'Customer PV'

Figure 5.13: The connected ESP32 device.



ESP32 OLED DEVICE
Device details

Latest telemetry

Last update time	Key	Value
2019-07-28 13:22:00	Current_pv	3.779951
2019-07-28 13:22:00	Power_pv	62.36919
2019-07-28 13:22:00	Voltage_b	13.03883
2019-07-28 13:22:00	Voltage_pv	16.5

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Figure 5.14: Sensor data posting.

14 A each. To ensure that maximum power is captured from the solar panels under all operating conditions, Maximum Power Point Tracking (MPPT) system is incorporated into the PV system. Also, to store the energy from the sun for use during prolonged extreme weather conditions, lead acid electrical battery system is connected to the MPPT system. In this work, both the PV system parameters such as power, voltage, and current, and the storage battery voltage are captured and monitored in real-time using the designed open

source SCADA system.

5.6 Implementation Methodology

In the proposed open source SCADA system design, the data and information flows between the solar PV system and the SCADA system are summarized in this section. First, the current, voltage, and power generated by the PV panels, and the storage battery voltage are measured and collected by the analog current and voltage sensors which are physically connected to the PV system using electrical wires. These data measurements and collection are made possible by using the developed Arduino IDE programs written and uploaded into the ESP32 micro-controller. Next, the ESP32 micro-controller, which is programmed and configured as an MQTT Client with the help of the PubSubClient MQTT Library, receives and processes these data from the sensors, and displays them on the Arduino IDE Serial Monitor and its OLED screen. Finally, the acquired PV system data are then published or transmitted via the MQTT Protocol over the locally created TCP/IP Wi-Fi connectivity to the self-hosted ThingsBoard IoT server platform, which is configured as an MQTT Broker. The published PV data received at the ThingsBoard server node are displayed as Telemetry messages. The server node is configured such that these data are automatically made available on the created dashboards and HMIs for remote monitoring and supervisory control actions. With respect to the QoS, data receipt acknowledgements are seen on the Arduino IDE Serial Monitor, and the published data in JSON format (Name: Value) are also displayed on the ESP32 OLED screen for local operator monitoring. The pseudocode describing this data (information) flow process is shown in Algorithm 2 below.

Algorithm 2: Data acquisition and logging algorithm:

```
Initialization;
1. Analog sensors measure and collect PV system data;
2. ESP32 reads sensor values on analog Pins 32, 34 and 35, and calculates values for
   Pins 32×34;
3. ESP32 displays the above values on Arduino IDE Serial Monitor and ESP32
   OLED Screen;
4. ESP32 connects to local TCP/IP Wi-Fi Network with Wi-Fi Name and Password;
5. ESP32 MQTT Client identifies the local ThingsBoard IoT Server (MQTT Broker)
   via the Server IP Address;
6. ESP32 MQTT Client publishes sensor data to MQTT Broker over the TCP/IP
   Wi-Fi connectivity;
7. ThingsBoard Server displays data as Telemetry Messages on the specified Device
   using the Device Name and Access Token;
8. ThingsBoard Server Node logs the Telemetry Messages to Dashboards for data
   visualization;
while ThingsBoard Server acknowledges data receipt do
    9. Display sensor data on ThingsBoard Server Node, Dashboards and ESP32
       OLED Screen, and;
    10. Display "DONE" on Arduino IDE Serial Monitor;
    if No data receipt acknowledgement from ThingsBoard Server Node then
        11. Display "FAILED......retrying in 5 seconds" on Arduino IDE Serial
            Monitor;
    else
        12. Go to step 1;
    end
end
```

5.7 Prototype Design

In this section, we describe the hardware implementation of the proposed IoT-based open source SCADA system solution. As shown in Figure 5.15, the Analog Current and Voltage Sensors are connected (via the pull-down resistors arrangement for the Current Sensor) to the TTGO ESP32 LoRa32 OLED device on a Breadboard using electrical wires. The inputs of the sensors are connected to the points of interest on the PV panel and storage battery system (PV System) using electrical wires such that the sensors measure and acquire the PV voltage, and current, and the storage battery voltage, as well as show the continuously calculated PV power from the PV voltage and current values. The power supplies for each of the components are provided as described in Section 5.5. For instance, the ESP32 micro-controller is powered with a 5 V USB power supply after programming it to acquire and publish the acquired sensor data to the ThingsBoard IoT server. The Wi-Fi Router used to setup the needed Wi-Fi connection, and the Raspberry Pi single-board computer hosting the ThingsBoard IoT server are both placed in the same building and integrated into the other components making up the SCADA system in the two different configurations described earlier.

5.8 Experimental Setup of the Proposed SCADA System

As described in Section 5.7 above, the hardware components were programmed, configured and setup for operation. The setup was then hooked up to the solar PV System in MUN ECE Laboratory. Figure 5.16 shows the analog sensors and ESP32 OLED device connected together and to the PV System, as well as some of the Dashboards created on the ThingsBoard IoT server platform (shown on the Laptop) for real-time data monitoring and supervisory control actions. As shown in the Figure, local operator monitoring of the acquired PV data is an additional feature in the proposed SCADA solution, and this is made

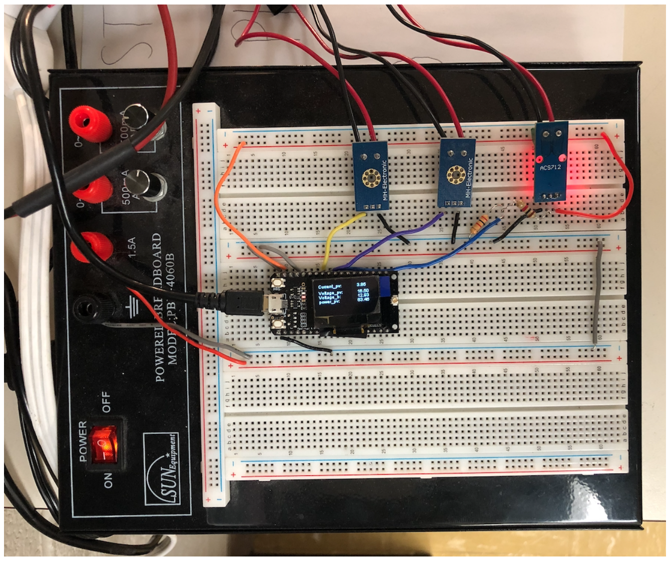


Figure 5.15: Hardware implementation of the proposed SCADA system.

possible using the ESP32 OLED Screen shown.

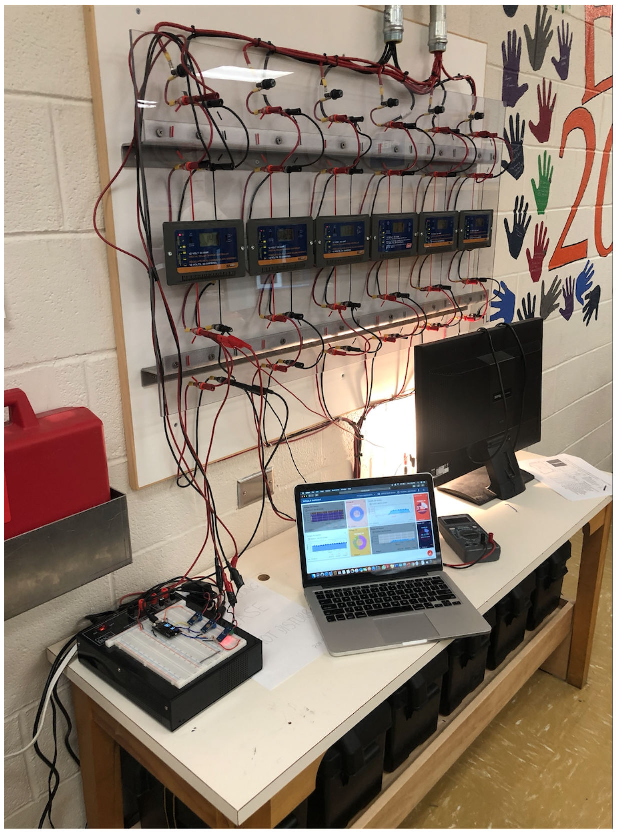


Figure 5.16: Experimental setup of the proposed SCADA system.

5.9 Testing and Results

Having tested the proposed IoT-based open source SCADA system solution extensively by setting up the designed prototype to acquire, process, transmit, remotely monitor and initiate supervisory control actions of the MUN ECE Laboratory PV System data, we present the results and some of the created HMIs (Dashboards) in this section.

5.9.1 Results

Each of the two hardware configurations, A and B (Figures 5.3 and 5.4 respectively) was set up and connected to the standalone solar PV system with the analog current and voltage sensors connected to the points of interest on the PV system to collect the desired data, the PV Current, the PV Voltage, the PV Power, as well as the storage battery Voltage after the MPPT system. The main data server locally installed on the Raspberry Pi machine and hosted on MUN Network, the ThingsBoard IoT server node (the MQTT Broker), was configured to receive the sensor data being collected by the sensors, processed and published by the the ESP32 micro-controller (the MQTT Client). Data transfer was realized using the developed MQTT protocol over the local Wi-Fi network created. The real-time sensor data published as *key:value pairs*, and received as *latest telemetry data* on the *ESP32 OLED Device* are shown in Figure 5.14. The Figure also shows the time stamps of the *latest telemetry data* received.

At the ThingsBoard IoT server platform, dashboards were created for the remote monitoring of the received sensor data, and for easy data trends visualizations. Figure 5.17 shows multiple dashboards for the various PV system variables being acquired, the storage battery Voltage, the PV Current, Voltage and Power, such that the trends of each of the variables can be remotely monitored in one platform. As can be seen, the vibrations of the values of each of the variables were due to the weather conditions in St. John's at the various times of testing as expected since PV system outputs are affected by environmental conditions such as solar irradiance and temperature. At the time of logging these data, a digital multi-meter was also used to locally measure each of the PV system variables so as to validate the accuracy of the acquired data seen on both the OLED display screen and at the ThingsBoard server platform. The acquired sensor values were found to be the same as those measured locally with the multi-meter. Figure 5.18 shows a dashboard created to specifically test configuration A, while Figure 5.19 shows another dashboard specifically created to test configuration B. As seen in the figures, the sudden increase and decrease in the values (especially in Figure 5.18) happened at various times when the storage battery was being discharged with an electric load (a light bulb) connected across it. For example, discharging the storage battery made more current to flow from the PV panels to recharge the battery, thereby increasing the overall PV system outputs, including the current. The opposite effect also happened with the light bulb disconnected, until the PV system reached its stable point where the variables became mostly constant depending on the prevalent environmental conditions at that time. As expected, similar data values were recorded using both configurations A and B, with the values only affected by the prevalent environmental conditions at the time of testing. The major difference between the two configurations is the manner in which the recorded and stored data on the ThingsBoard server platform can be accessed as described earlier.

The proposed SCADA was tested extensively at various times of the day, and left connected to the PV system to continuously log the PV data for about a month so as to confirm the robustness of the designed system, and the results were found to be consistent with the locally measured values using a digital multi-meter, showing that the SCADA system performed optimally and accurately regardless of the environmental conditions and duration of testing. Also, as shown in Figures 5.15 and 5.16, the most recent data values were available for viewing on the ESP32 OLED display screen, thereby providing a local data monitoring interface whenever necessary.

Furthermore, in order to test the supervisory control capabilities of the proposed system, the *Rule Engine* tool of the ThingsBoard IoT server (Figures 5.10 and 5.11), was used to create a test alarm for the storage battery voltage values, and the alarm was configured such that for voltage values above 14 V, the alarm would get triggered to notify the system administrator of the current situation. For instance, the alarm was triggered automatically between 15:00 and 17:00 on the dashboard in Figure 5.20 when the voltage values rose to about 15 V. Also, although not presented here due to space constraint, a data table showing data history was also created at the ThingsBoard IoT server platform for easy data trends analysis.

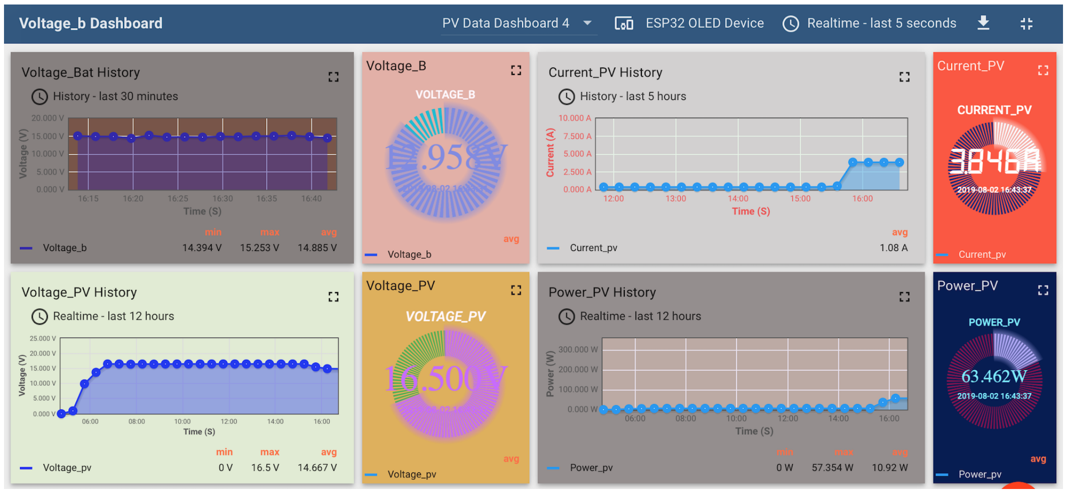
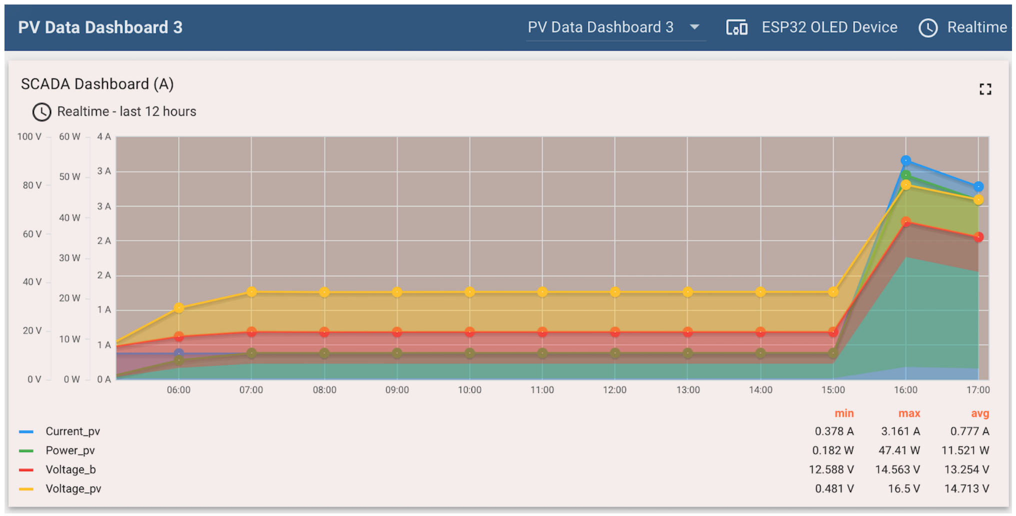


Figure 5.17: Created dashboards showing real-time data.

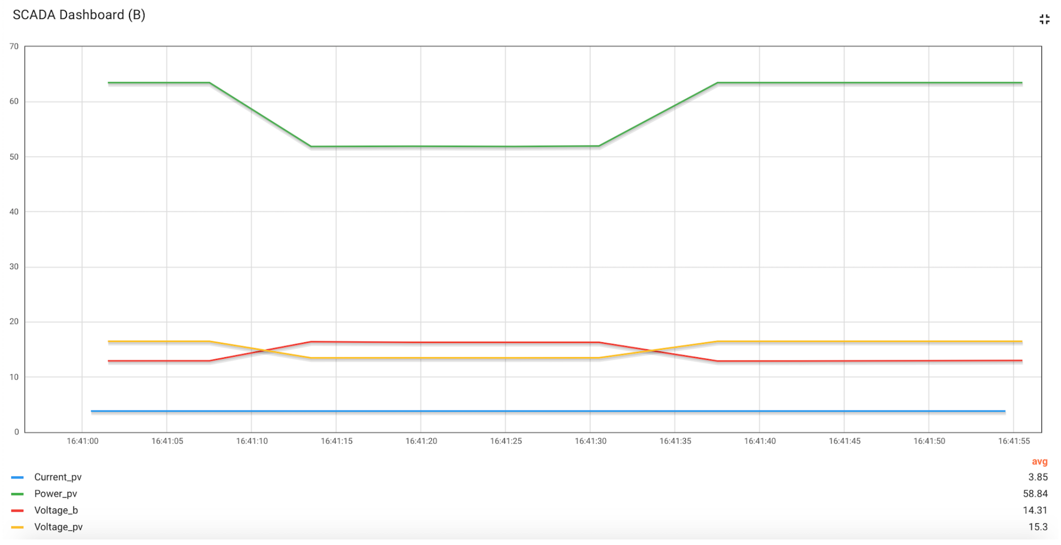
5.10 Discussion

In this section, we briefly describe some of the key features of the designed IoT-based open source SCADA system solution based on the testing and the results realized from the testing:



	min	max	avg
Current_pv	0.378 A	3.161 A	0.777 A
Power_pv	0.182 W	47.41 W	11.521 W
Voltage_b	12.588 V	14.563 V	13.254 V
Voltage_pv	0.481 V	16.5 V	14.713 V

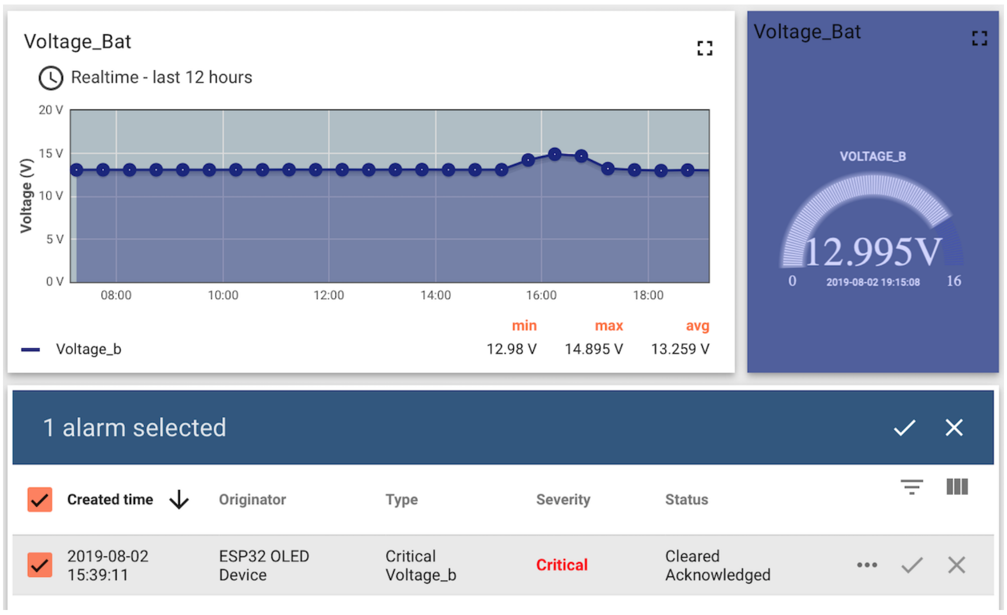
Figure 5.18: Created dashboard (A) showing real-time data.



	avg
Current_pv	3.85
Power_pv	58.84
Voltage_b	14.31
Voltage_pv	15.3

Figure 5.19: Created dashboard (B) showing real-time data.

- **Internet of Things based SCADA system:** The proposed open source SCADA system is based on the most recent SCADA architecture, the Internet of Things. The system features the four essential elements desirable in a SCADA system, including Field Instrumentation Devices (Current and Voltage Sensors), Remote Terminal Unit (TTGO LoRa32 ESP32 OLED Micro-controller), Master Terminal Unit (ThingsBoard IoT Server), and SCADA Communication Channel (MQTT data transfer pro-



	min	max	avg
Voltage_b	12.98 V	14.895 V	13.259 V

12.995V

2019-08-02 19:15:08

1 alarm selected

Created time	Originator	Type	Severity	Status
2019-08-02 15:39:11	ESP32 OLED Device	Critical Voltage_b	Critical	Cleared Acknowledged

Figure 5.20: Test alarm.

tocol over Wi-Fi connectivity).

- **Data acquisition and historic storage:** With the SCADA system solution, data in any process plant of interest can be acquired for remote monitoring and storage. An SQL database, PostgreSQL, is installed with the ThingsBoard IoT server platform on the Raspberry Pi such that data can be stored for future use. As a result of this feature, historic data trends can be viewed on the server platform (e.g: Figure 5.17). Knowing the trends in any data sets could help decision makers to make important business decisions.

- **Remote plant monitoring:** From the created dashboards for human machine interactions on the ThingsBoard IoT server platform, the current state of the process plant being managed can be monitored remotely in terms of data. Examples of such dashboards (HMIs) are presented above.

- **Local operator monitoring:** In the SCADA system solution proposed, local operator interface is considered. This is made possible using the OLED display screen on the ESP32 micro-controller where a local operator can view the most recent sensor data at the plant site simply by looking at the OLED screen. This could be particularly important in the events that the overall system administrator at the server end isn't available to provide system updates.

- **Reporting:** From the data logs, charts, alarms and data trends, reports on the state of the process plant can be generated for critical business decisions. In addition, reports on the states of the created alarms can be sent automatically to *Device Customers* and *System Administrator* either with instant messaging notifications or via emails.

- **Security:** The proposed SCADA system solution is such that the main data server, the ThingsBoard IoT server platform, is locally hosted on MUN network. As such, security measures can be taken by the system administrator to ensure data integrity. Such security measures include access control, firewalls, authorization, regular risk assessment, whitelists, continuous monitoring and log analysis, updating and patching regularly, authentication, and so on.

- **Reliability and availability:** Even though system reliability calculation is outside the scope of this paper, studies have shown that SCADA system reliability and availability are affected by delayed or wrong operator decisions [45]. In the proposed open source SCADA system solution, all the components are open source and readily available. Also, the main cloud server for data processing is locally installed on MUN Network (hosted), and self-managed. Therefore, the system administrator is always available to continuously manage and maintain the system in order to ensure its continuous reliability and availability. However, this is almost impossible in a commercial (proprietary) SCADA system where the customer is beholden to a single vendor, and as such has to contact the vendor in the events of the SCADA system failures which could lead to downtime.

- **Supervisory control:** In the proposed SCADA system solution, by remotely monitoring the data sets of the desired variables in the process plant, the system administrator can send supervisory control commands via emails, alarms or instant messaging notifications to the local operator informing the operator of the problems and requesting immediate actions to correct the problems.

- **Ease of use:** The main data server, ThingsBoard IoT server platform, where data processing and human machine interactions are carried out by the system owner is simple and user-friendly, meaning that it requires less customer training for continuous use. This is usually not the case in most commercial SCADA system solutions as their MTU platforms are complicated, requiring a great deal of training and experience for operation.

- **Open source, and low cost:** In the proposed SCADA system solution, all the components are manufactured and supplied by multiple vendors (mix and match), and are readily available under open source license. The components can easily be interconnected with related components from several vendors. As such, the consumer is not beholden to a single vendor. This is one of the key features of an open source system. In Table 5.1, it can be seen that despite the fact that the proposed SCADA system performs all the basic functions desired in a SCADA system, it is a low-cost solution compared to the available commercial SCADA systems which are in thousands of dollars. The overall system cost is just about \$280 CAD. From the Table, it can be seen that the main data server, the ThingsBoard IoT server installed on the Raspberry Pi, and the database software, PostgreSQL, cost nothing. This is because the server was built from the source code alongside the database using the developers' guides. The MQTT Client Library (PubSubClient) on Arduino IDE is also free.

- **Low power:** For an IoT-based system designed to operate 24/7, power consump-

Table 5.1: Bill of Materials.

S/N	COMPONENT	QTY	PRICE (CAD)
1	ThingsBoard IoT Server	1	00.00
2	PostgreSQL.	1	00.00
3	Raspberry Pi 2 B	1	45.95
4	TTGO LoRa32 ESP32 OLED	1	17.49
5	16GB Memory Card	1	19.99
6	Voltage Sensor	2	11.98
7	Current Sensor	1	5.25
8	D-Link D1-524 Wireless Router	1	98.51
9	Miscellaneous (Boxes, Breadboard, Resistors, Wires, etc.)	1	80.00
	Grand Total:		**$ 279.17 CAD**

tion is a major factor in selecting the individual system components. Hence, power consumption was a major factor considered in choosing the components used in the proposed SCADA system design. The power consumption of the individual components were measured simultaneously using Kilowatt meters while the system was in operation to ascertain the power consumption of the overall SCADA system solution. As can be seen in Table 5.2, the overall power consumption of the system is about 9.3 W. Although this overall power consumption is relatively low, it could still be reduced since the major components, the Raspberry Pi (ThingsBoard IoT server) and ESP32 OLED micro-controller, only consume a combined total of 2.7 W while in operation, which is relatively low. The buck of the overall power consumption value is mostly due to the high power demands of both the D-Link Wi-Fi Router and the Breadboard, which could easily be eliminated or replaced with similar components requiring less power. For instance, the D-Link Wi-Fi Router can be eliminated by configuring the Raspberry Pi as a Wireless Access Point to provide the needed Wi-Fi connectivity, while the breadboard can be replaced with a smaller breadboard requiring less power.

Table 5.2: Power Consumption of Hardware Components.

S/N	HARDWARE	POWER(W)
1	Raspberry Pi 2 B	1.8
2	ESP32 OLED (alone)	0.9
3	D-Link D1-524 Wireless Router	4.2
4	Breadboard (with ESP32 OLED, Sensors, Resistors, etc. connected)	3.3
	Overall System Power Consumption (less ESP32 OLED alone):	**9.3 W**

5.11 Conclusions

With most companies' critical assets spread over large geographical areas, sometimes in harsh environments, especially hybrid power system components comprising of both the conventional generation sources such as fossil fuels, and sustainable (renewable) generation sources such as solar photovoltaic (PV) systems and wind turbines, it is imperative to have a flexible, secure, cost-effective and reliable coordinated means of overseeing the operations of the various generation sources, in addition to a local monitoring interface. Despite the fact that SCADA systems have made such coordinated monitoring and control of these distributed assets possible, SCADA system design solutions, implementations and deployments have largely remained proprietary as these solutions are mostly developed by automation companies across the globe. However, the high costs of these proprietary SCADA systems are hugely unjustifiable for smaller applications. In addition to these high costs, there is also the issue of the SCADA system interoperability with the existing hybrid power system infrastructures which are usually from multiple manufacturers and suppliers. Such infrastructures include energy storage systems, communication systems, power electronic converters, and so on. Therefore, an open source SCADA system represents the most flexible and most cost-effective SCADA system solution, especially for smaller applications. With an open source SCADA solution, the user is not beholden to a single vendor, and is able to combine components from multiple vendors under open source licenses to ensure the system interoperability with existing infrastructures and reduction in the overall system cost.

In this paper, we proposed a low-cost open source SCADA system based on the most recent SCADA architecture, the Internet of Things (IoT). We also demonstrated the hardware implementation of our proposed SCADA system solution using very few low-cost, low-power, open source and readily available components as the essential elements of the SCADA system. In designing our proposed open source SCADA system solution, data security, data integrity, and system reliability were taken into consideration since security in a SCADA system is a critical issue. These considerations were implemented by locally installing the main data server, the ThingsBoard IoT server, on a Raspberry Pi single-board machine. Thus, the data server was locally hosted and self-managed on MUN Network such that data security and data integrity measures like authentication, authorization, access control, whitelisting, log analysis, and firewalls are self-managed by the system administrator to ensure data security, data integrity, and system availability, and thus making sure that the system is reliable. Also, we showed the use of the lightweight IoT application protocol, MQTT protocol, for data transmission in such applications. The overall SCADA system cost was found to be extremely low, about \$280 CAD, and the overall power consumption while in operation was found to be minimal, about 9.3 W. We also demonstrated the performance of our proposed open source SCADA solution by setting it up to collect, log, process, and remotely monitor the current, voltage and power of a standalone 260 W, 12 V solar photovoltaic (PV) system. Supervisory control actions were also considered with alarms created to trigger notifications in the events that the storage battery voltage was above a certain set point. From our testings and results, we showed that the proposed open source SCADA system operates properly and accurately. With the OLED display screen of the ESP32 micro-controller board used, a local real-time data monitoring interface was also incorporated into the proposed SCADA system solution.

Even though the proposed open source SCADA system has only been tested with a standalone solar PV system in this work, the system can also be customized for use in other applications requiring real-time data acquisition, remote monitoring and supervisory control such as traffic signal systems, power transmission and distribution systems, mass transit systems, home energy management systems, and so on.

5.12 Future Work

ThingsBoard IoT server supports other important alarm types. For example, alarms can be configured to notify the system administrator when the process plant being monitored is offline, and alarm notifications can be sent via emails directly to the customers assigned to that particular device and the system administrator. As a future work, we will look at incorporating these alarm types into the system to increase the functionalities of the system. Furthermore, data encryption can be implemented on the communication channel and data transfer protocol for better security.

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Chapter 6

Conclusions and Future Works

6.1 Conclusions

Small renewable power generation systems are becoming increasingly important in today's power systems, especially with the recent increasing quest for a greener environment. With such systems, as well as the energy storage systems, communication systems, power electronic converters and other power system components, spread over large geographical areas, sometimes in harsh environments, it is imperative to have a sophisticated means of monitoring and controlling their operations. Supervisory control and data acquisition (SCADA) system has made this coordinated monitoring and control possible.

However, most of the available SCADA system solutions for these tasks are proprietary (commercial), and they are largely pricey as they require continuous maintenance and support charges in addition to their huge initial purchasing and installation fees. Furthermore, because the renewable power generation components such as energy storage systems, communication systems, power electronic converters and other critical components of the power system are very often from multiple manufacturers, there is also the problem of interoperability of these systems with proprietary SCADA systems, with the entire infrastructure sometimes requiring redesigns and modifications to accommodate the proprietary SCADA system solutions, leading to even more costs and downtime. Thus, these proprietary SCADA system solutions become economically unjustifiable, especially for smaller applications with lower budgets for SCADA system solutions. Therefore, for smaller applications, open source SCADA systems represent the most flexible and the most cost-effective SCADA solution, especially if the open source SCADA systems can be designed to perform similar functions as the available proprietary SCADA systems, but without the high costs and interoperability issues associated with proprietary SCADA systems.

In this thesis, extensive studies have been done to develop various open source SCADA system solutions for small renewable power generation systems so as to solve the problems associated with the available proprietary SCADA system solutions. First, system design and analysis to demonstrate the importance of such systems was shown by designing, dynamically modelling and simulating a hybrid power system with a renewable generation source and energy storage systems using a case study of a house in Nigeria. Next, having carefully studied various proprietary (commercial) SCADA systems such as Ovation SCADA communication server (Emerson), Simatic WinCC (Siemens), Clear SCADA Server (Schneider Electric), and Micro SCADA (Allen Bradley), as well as the available open source SCADA system solutions such as Rapid SCADA, Tango SCADA, Mango, LabView, KingView, etc., three different open source SCADA system options were designed and tested with a small renewable energy generation source comprising of energy storage systems. The designed open source SCADA options were done using the most recent SCADA architecture, the Internet of Things (IoT). This IoT SCADA architecture incorporates IoT capabilities with the traditional SCADA system for a more flexible and more robust monitoring and control. The developed IoT-based open source SCADA system solutions comprised of very few low-cost, low power and readily available components as the elements of the SCADA systems, including master terminal units (IoT server platforms), remote terminal units (micro-controllers), field instrumentation devices (sensors), and data communication protocols.

Furthermore, because security in a SCADA system is a critical issue, security measures were taken into considerations in designing each of the three IoT-based open source SCADA system solutions. These measures were taken by installing the main data cloud server in each of the solutions on self-managed local machines, and then hosting the servers on secure private networks in the form of industrial networks for data security and data integrity. These measures also increased the availability of the SCADA system options as they were less susceptible to internet attacks, and thus more reliable.

In terms of performance, each of the three IoT-based open source SCADA system options was tested extensively. The results showed that the developed open source SCADA systems with similar features and functionalities as the studied proprietary (commercial) SCADA systems performed optimally and accurately. Thus, the systems could serve as viable options for smaller applications such as small renewable generation systems or/and for smaller companies that cannot afford the pricey and inflexible commercial SCADA solutions.

Table 6.1 below shows a comparison of the key similarities and differences between the three IoT-based open source SCADA options in Chapters 3 to 5. The testing and analysis showed that SCADA 1 consumed the least power while in operation, but it is the most expensive of the three options. Also, for SCADA 1, only one configuration which required internet access was considered. Furthermore, this SCADA 1 option doesn't have local operator data monitoring interface. Compared to SCADA 2, SCADA 3 has similar features, but with slightly lower cost and lower power consumption. Both SCADA 2 and 3 have offline configuration options where internet isn't required for data access. However, SCADA 3 has the additional feature of a local operator data monitoring interface which could be crucial in the events that the overall system administrator is unavailable to provide data updates to the local operator. Furthermore, the ThingsBoard IoT server platform is presently more developed than the Thinger.IO IoT server platform. Therefore, the ThingsBoard-based option (SCADA 3) is favored ahead of the other two options.

Table 6.1: Comparison Between The Three IoT-Based Open Source SCADA Systems.

IoT-Based Open Source SCADA Systems			
Key Properties	Emoncms-based SCADA (SCADA 1)	Thinger.IO-based SCADA (SCADA 2)	ThingsBoard-based SCADA (SCADA 3)
IoT Server (MTU)	Emoncms	Thinger.IO	ThingsBoard
RTU	Arduino Uno/Raspberry Pi	ESP32 Thing	ESP32 with OLED
Communication Channel	Node-RED/Ethernet	Wi-Fi/SPI	MQTT/Wi-Fi
FIDs	Sensors	Sensors	Sensors
Security Measure	Local/Self-hosted main data server	Local/Self-hosted main data server	Local/Self-hosted main data server
Reliable from Testing?	Yes	Yes	Yes
Alarm & Notifications	Yes	Yes	Yes
Ease of Use	Yes	Yes	Yes
Internet	Yes	Yes	Yes
Offline Option	No	Yes	Yes
Local Operator Interface	No	No	Yes
Cost	$404.84 CAD	$291.87 CAD	$279.17 CAD
Power Consumption	5.1 W	9.4 W	9.3 W

6.2 Future Works

The work presented in this thesis opens up new directions for research on the development of reliable, secure, low-cost, IoT-based open source SCADA system solutions. However, several knowledge gaps and scope of work could be further addressed. Some of the recommendations for future works are summarized as follows:

- Detailed reliability calculations and analysis of each of the developed IoT-based open source SCADA systems in Chapters 3 to 5 so that proper reliability comparison between the three systems can be done.

- For increased security in each of the SCADA system solutions, data encryption can be implemented on the communication channels of each of the systems

- To further reduce the cost and power consumption of the SCADA 1 (Table 6.1), a new open source SCADA system can be developed with the Emoncms server installed on a more recent Linux machine, while using ESP32 Thing as the RTU, and MQTT protocol for data transfer from the RTU to the MTU.

- The power consumption of SCADA 2 and SCADA 3 can be further reduced by configuring the Raspberry Pi in each case as a Wireless Access Point to provide the needed Wi-Fi connections, thereby eliminating the Wi-Fi Router in each case.

- The ThingsBoard IoT platform is well developed, and as such could be explored further. In SCADA 3, the ThingsBoard MQTT API has been used for data transfer. In the future, different open source SCADA systems can be developed using the CoAP API and HTTP API of the ThingsBoard platform for data transfer so as to compare their performance with the MQTT API used in SCADA 3 option (Table 6.1).

6.3 List of Publications

Refereed Journal Articles

1. Lawrence O. Aghenta and M. Tariq Iqbal, "Design and implementation of a low-cost, open source IoT-based SCADA system using ESP32 with OLED, ThingsBoard and MQTT protocol," AIMS Electronics and Electrical Engineering, 2020, 4(1): 57-86. doi: 10.3934/ElectrEng.2020.1.57.

2. Lawrence Oriaghe Aghenta and Mohammad Tariq Iqbal, Low-Cost, "Open Source IoT-Based SCADA System Design Using Thinger.IO and ESP32 Thing," Electronics 2019, 8(8), 822; https://doi.org/10.3390/electronics8080822.

3. Lawrence O. Aghenta and M. Tariq Iqbal, "Design and Dynamic Modelling of a Hybrid Power System for a House in Nigeria," International Journal of Photoenergy, Volume 2019, Article ID 6501785, 13 pages; https://doi.org/10.1155/2019/6501785.

Refereed Conference Publication

4. Lawrence O. Aghenta and M. Tariq Iqbal, "Development of an IoT-Based Open Source SCADA System for PV System Monitoring," Presented at CCECE 2019, Edmonton, AB, Canada. May 5 - 8, 2019; doi: 10.1109/CCECE.2019.8861827

Regional Conference Publications

5. Lawrence O. Aghenta and M. Tariq Iqbal, "A Low-Cost, Open Source IoT-Based SCADA System Design, and Implementation for Photovoltaics," Presented at the 28th IEEE NECEC 2019, St. John’s, NL, Canada. November 19, 2019.

6. Lawrence O. Aghenta and M. Tariq Iqbal, "Thermal Modelling and Analysis of a House in Nigeria and PV System Design to meet its Energy needs," Presented at the 27th IEEE NECEC 2019, St. John’s, NL, Canada. November 13, 2018.

Poster Presentation

7. Lawrence O. Aghenta and M. Tariq Iqbal, "Internet of Things (IoT) based Reliable Open Source SCADA System for Remote Battery Energy Storage Systems," Presented during the poster session at the NESTNet 2nd Annual Technical Conference, Ryerson University, Toronto, ON, Canada. June 18 - 20, 2018.

Appendix A

Supporting Information for Chapter 3*

Cost and Power Consumption Analyses of the SCADA System

Table A.1: Bill of Materials.

S/N	COMPONENT	QTY	PRICE (CAD)
1	Emoncms Server (Jetson TK1 Dev. Kit)	1	250.00
2	Emoncms Software	1	00.00
3	Node-RED Software	1	00.00
4	Raspberry Pi 2 B	1	45.95
5	Arduino Uno	1	29.00
6	Current Sensor	1	5.25
7	Voltage Sensor	2	11.98
8	8GB SD Card	1	12.66
9	Miscellaneous (Wires, Boxes, etc.)	1	50.00
	Grand Total:		**$ 404.84 CAD**

*This appendix provides the supporting information from "Development of an IoT Based Open Source SCADA System for PV System Monitoring", L. O. Aghenta and M. T. Iqbal, *CCECE 2019*, doi: 10.1109/CCECE.2019.8861827).

Table A.2: Power consumption of hardware components.

S/N	HARDWARE	POWER (W)
1	Raspberry Pi 2 + Arduino Uno + Sensors	2.4
2	Emoncms Server	2.7
	Total Power Consumption :	**5.1 W**

JavaScript Code for Emoncms-Node-RED Flow

```
[
 {
     "id": "1ef4e69f.f0af61",
     "type": "serial in",
     "z": "53bf1c1d.9549b4",
     "name": "Arduino Uno serial",
     "serial": "9f9a39ac.b372c8",
     "x": 90,
     "y": 200,
     "wires": [
         [
             "6fb9166d.ef79d"
         ]
     ],
     "outputLabels": [
         "1"
     ]
 },
 {
     "id": "9f9a39ac.b372c8",
        "type": "serial-port",
        "z": "",
        "serialport": "/dev/ttyACM0",
        "serialbaud": "9600",
        "databits": "8",
        "parity": "none",
        "stopbits": "1",
        "newline": "\\n",
        "bin": "false",
        "out": "char",
        "addchar": false,
        "responsetimeout": "10000"
    }
]
```

Arduino Code for Data Transfer

```
const int analogInput = A2;

const int analogInput2 = A3;

void setup() {
  Serial.begin(9600);
  pinMode(analogInput, INPUT);
}
```

```
void loop(){
 Serial.print(getCurrent());
  Serial.print(",");
  Serial.print(getVoltage());
  Serial.print(",");
  Serial.println(getVoltage()*((getCurrent()/1000)));
  Serial.print(",");
  Serial.print(getVoltage2());
  delay(5000);
}

float getCurrent() {
  float average = 0;
  for(int i = 0; i < 1000; i++) {
    average = average + (.049 * analogRead(A0) - 3.78) / 1000;//this is
    //for the 30A mode, if 20A or 5A mode, modify this formula to
    //(.19 * analogRead(A0) -25) for 20A mode and
    //(.0264 * analogRead(A0) -13.51) for 5A mode

    delay(3);
  }
return average;
}

float getVoltage() {
   const float R1 = 30000.0; //
   const float R2 = 7500.0; //
   float value = analogRead(analogInput);
   float vout = (value * 5.0) / 1024.0; // ADC Conversion
   float vin = vout / (R2/(R1+R2));
  return vin;
  delay(3);

}

float getVoltage2() {
   const float R1 = 30000.0; //
   const float R2 = 7500.0; //
   float value = analogRead(analogInput2);
   float vout = (value * 5.0) / 1024.0; // ADC Conversion
   float vin = vout / (R2/(R1+R2));
  return vin;
  delay(3);
}
```

Appendix B

Supporting Information for Chapter 4[*]

ESP32-Thinger.IO Code for Parsing Data

```
#define THINGER_SERVER "134.153.27.200" //IP Address of the Raspberry Pi hosting

#define _DEBUG_    //Show Server's debug messages on ArduinoIDE
#define _DISABLE_TLS_  //TLS not yet enabled in Thinger.io platform for ESP32

#include <ThingerESP32.h> //Thinger.io ESP32 Arduino Library
#include <driver/adc.h>
#include <WiFi.h>
#include <SPI.h>
```

[*]This appendix provides the supporting information from "Low-Cost, Open Source IoT-Based SCADA System Design Using Thinger.IO and ESP32 Thing", L. O. Aghenta and M. T. Iqbal, *Electronics* **Vol.8, No. 8**, p. 822, electronics8080822 (2019).

```
#define USERNAME "Lawrenzo2" //Username of Thiner.io Account

#define DEVICE_ID "esp32"  //Device ID of Thinger.io Account created.

#define DEVICE_CREDENTIAL "Lawrenzo911" //Device ID Credential of


#define SSID "SCADA"   //Local WiFi Name

#define SSID_PASSWORD "ABcdEF6789"  //Local WiFi Password


ThingerESP32 thing(USERNAME, DEVICE_ID, DEVICE_CREDENTIAL);


#define ANALOG_PIN_0 32   //PV Current

#define ANALOG_PIN_1 34   //PV Voltage

#define ANALOG_PIN_2 35   //Bat. Voltage


float current_pv;

float voltage_pv;

float voltage_b;

float power_pv;


void setup() {


  Serial.begin(115200);

  thing.add_wifi(SSID, SSID_PASSWORD);


  // Thinger.IO Output Resource Definition (i.e. reading sensor values)

  thing["Current_pv"] >> outputValue(current_pv);

  thing["Voltage_pv"] >> outputValue(voltage_pv);
  thing["Voltage_b"] >> outputValue(voltage_b);

  thing["Power_pv"] >> outputValue(power_pv);


  adc1_config_width(ADC_WIDTH_BIT_12);

  adc1_config_channel_atten(ADC1_CHANNEL_4, ADC_ATTEN_DB_11);

  adc1_config_channel_atten(ADC1_CHANNEL_6, ADC_ATTEN_DB_11);

  adc1_config_channel_atten(ADC1_CHANNEL_7, ADC_ATTEN_DB_11);


}


void loop() {


  Serial.println(" ");


  current_pv = getCurrent();

  voltage_pv = getVoltage();

  voltage_b = getVoltage2();

  power_pv = (voltage_pv * ((current_pv)));


  Serial.print(current_pv);

  Serial.print(" ");

  Serial.print("Amps");

  Serial.print(",");

  Serial.print(voltage_pv);

  Serial.print(" ");

  Serial.print("Volts");
  Serial.print(",");
  Serial.println(voltage_pv * ((current_pv)));
  Serial.print(" ");
  Serial.print("Watts");
  Serial.print(",");
  Serial.print(voltage_b);
  Serial.print(" ");
  Serial.print("Volts");
  thing.handle();

  Serial.print("Current_pv: "); Serial.println(current_pv);
  Serial.print("Voltage_pv: "); Serial.println(voltage_pv);
  Serial.print("Voltage_b: "); Serial.println(voltage_b);
  Serial.print("Power_pv: "); Serial.println(power_pv);

  delay(5000);
}

float getCurrent() {
  float average = 0;
  float Amps = 0;
  for (int i = 0; i < 1000; i++) {  // sample 1000 times by 1 ms
    average = ((analogRead(ANALOG_PIN_0)* 3.3)/(4095)); //ESP32 ADC Resolution
    Amps = (average - 2.5)/66; //Current Sensor Sensitivity
    delay(3);
  }
  return Amps;
}

float getVoltage() {
  const float R1 = 30000.0; //R1 of Voltage Sensor 1
  const float R2 = 7500.0; //R2 of Voltage Sensor 1
  float value = analogRead(ANALOG_PIN_1);
  float vout = ((value * 3.3)/(4095)); // Resolution of ESP32 ADC
  float vin = vout / (R2 / (R1 + R2)); //Voltage Divider for Voltage Sensor 1
  return vin;
  delay(3);

}

float getVoltage2() {
  const float R1 = 30000.0; // R1 of Voltage Sensor 2
  const float R2 = 7500.0; // R2 of Voltage Sensor 2
  float value = analogRead(ANALOG_PIN_2);
  float vout = ((value * 3.3)/(4095)); // Resolution of ESP32 ADC
  float vin = vout / (R2 / (R1 + R2)); //Voltage Divider for Voltage Sensor 2
  return vin;
  delay(3);
}
```

Appendix C

Supporting Information for Chapter 5*

ESP32-ThingsBoard MQTT Code for Data Publishing

```
#include <WiFi.h>

#include <ThingsBoard.h>

#include <driver/adc.h>

#include <SSD1306.h>

#define SS 18

#define RST 14

#define DI0 26


#define WIFI_AP "SCADA"

#define WIFI_PASSWORD "ABcdEF6789"

#define TOKEN "ESP32_OLED_TOKEN"
```

*This appendix provides the supporting information from "Design and implementation of a low-cost, open source IoT-based SCADA system using ESP32 with OLED, ThingsBoard and MQTT protocol", L. O. Aghenta and M. T. Iqbal, *AIMS Electronics and Electrical Engineering, 2020,* **4(1):**,57-86. doi: 10.3934/ElectrEng.2020.1.57.

```
#define ANALOG_PIN_0 32   //PV Current

#define ANALOG_PIN_1 34   //PV Voltage

#define ANALOG_PIN_2 35   //Bat. Voltage


char thingsboardServer[] = "134.153.27.200"; //Local Server  IP Address


WiFiClient wifiClient;


SSD1306 display (0x3c, 4, 15);


ThingsBoard tb(wifiClient);


int status = WL_IDLE_STATUS;

unsigned long lastSend;


float current_pv;

float voltage_pv;

float voltage_b;

float power_pv;


void setup()

{


//************************

pinMode (16, OUTPUT);
pinMode (2, OUTPUT);
digitalWrite (16, LOW); // set GPIO16 low to reset OLED
delay (50);
digitalWrite (16, HIGH); // while OLED is running, GPIO16 must go high
//*****************

  Serial.begin(115200);
  delay(10);

  adc1_config_width(ADC_WIDTH_BIT_12);
  adc1_config_channel_atten(ADC1_CHANNEL_4, ADC_ATTEN_DB_11);
  adc1_config_channel_atten(ADC1_CHANNEL_6, ADC_ATTEN_DB_11);
  adc1_config_channel_atten(ADC1_CHANNEL_7, ADC_ATTEN_DB_11);

  InitWiFi();
  lastSend = 0;

  display.init ();
  display.flipScreenVertically ();
  display.setFont (ArialMT_Plain_10);
  delay (500);
}

void loop()
{
  if ( !tb.connected() ) {
    reconnect();
  }

  if ( millis() - lastSend > 1000 ) { // Update and send only after 1 second
    getAndSendSensorData();
    lastSend = millis();
  }

  tb.loop();

  delay(3000);  //delay for 3sec
}

void getAndSendSensorData()
{
  Serial.println("Collecting Sensor Data.");
  Serial.println(" ");

  current_pv = getCurrent();
  voltage_pv = getVoltage();
  voltage_b = getVoltage2();
  power_pv = (voltage_pv * ((current_pv)));

  display.clear ();
  display.setTextAlignment (TEXT_ALIGN_LEFT);
  display.setFont (ArialMT_Plain_10);
  display.drawString (0, 0, "Current_pv:");
  display.drawString (90, 0, String(current_pv));
  display.drawString (0, 15, "Voltage_pv:");
  display.drawString (90, 15, String(voltage_pv));
  display.drawString (0, 25, "Voltage_b:");
  display.drawString (90, 25, String(voltage_b));
  display.drawString (0, 35, "power_pv:");
  display.drawString (90, 35, String(power_pv));

  display.display ();

  Serial.print(current_pv);
  Serial.print(" ");
  Serial.print("Amps");
  Serial.print(",");
  Serial.print(voltage_pv);
  Serial.print(" ");
  Serial.print("Volts");
  Serial.print(",");
  Serial.println(voltage_pv * ((current_pv)));
  Serial.print(" ");
  Serial.print("Watts");
  Serial.print(",");
  Serial.print(voltage_b);
  Serial.print(" ");
```

```
  Serial.print("Volts");
  Serial.println(" ");

  Serial.print("Current_pv: "); Serial.println(current_pv);
  Serial.print("Voltage_pv: "); Serial.println(voltage_pv);
  Serial.print("Voltage_b: "); Serial.println(voltage_b);
  Serial.print("Power_pv: "); Serial.println(power_pv);

  tb.sendTelemetryFloat("Current_pv", current_pv);
  tb.sendTelemetryFloat("Voltage_pv", voltage_pv);
  tb.sendTelemetryFloat("Voltage_b", voltage_b);
  tb.sendTelemetryFloat("Power_pv", power_pv);

}

void InitWiFi()
{
  Serial.println("Connecting to AP ...");
  // Attempt to connect to WiFi network

  WiFi.begin(WIFI_AP, WIFI_PASSWORD);
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("Connected to AP");
```

```
}

void reconnect() {
  // Loop until we’re reconnected
  while (!tb.connected()) {
    status = WiFi.status();
    if ( status != WL_CONNECTED) {
      WiFi.begin(WIFI_AP, WIFI_PASSWORD);
      while (WiFi.status() != WL_CONNECTED) {
        delay(500);
        Serial.print(".");
      }
      Serial.println("Connected to AP");
    }
    Serial.print("Connecting to ThingsBoard node ...");
    if ( tb.connect(thingsboardServer, TOKEN) ) {
      Serial.println( "[DONE]" );
    } else {
      Serial.print( "[FAILED]" );
      Serial.println( " : retrying in 5 seconds]" );
      // Wait 5 seconds before retrying
      delay( 5000 );
    }
  }
}
```

```
float getCurrent() {
  float average = 0;
  float Amps = 0;
  for (int i = 0; i < 1000; i++) {  // sample 1000 times by 1 ms
    average = ((analogRead(ANALOG_PIN_0)* 3.3)/(4095)); //ESP32 ADC Resolution
    Amps = (average - 2.5)/66; //Current Sensor Sensitivity
    delay(3);
  }
  return Amps;
}

float getVoltage() {
  const float R1 = 30000.0; //R1 of Voltage Sensor 1
  const float R2 = 7500.0; //R2 of Voltage Sensor 1
  float value = analogRead(ANALOG_PIN_1);
  float vout = ((value * 3.3)/(4095)); // Resolution of ESP32 ADC
  float vin = vout / (R2 / (R1 + R2)); //Voltage Divider for Voltage Sensor 1
  return vin;
  delay(3);

}

float getVoltage2() {
  const float R1 = 30000.0; // R1 of Voltage Sensor 2
  const float R2 = 7500.0; // R2 of Voltage Sensor 2
  float value = analogRead(ANALOG_PIN_2);
  float vout = ((value * 3.3)/(4095)); // Resolution of ESP32 ADC
  float vin = vout / (R2 / (R1 + R2)); //Voltage Divider for Voltage Sensor 2
  return vin;
  delay(3);
}
```