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IoT-Based Battery Monitoring System for Improving Microgrid Management

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Abstract

The notable increase in renewable energy sources has initiated a shift in power generation grids and spurred the development of new grid systems, such as smart grids and microgrids. However, these systems require advanced management and monitoring solutions to ensure efficient operation. This project investigates the integration of Internet of Things (IoT) technology into various aspects of a microgrid's functionality. The main objective is to design a system that improves the reliability and efficiency of battery monitoring systems through an IoT-based data acquisition scheme.

The study starts with an overview of recent and conventional grid technologies, emphasizing the benefits, features, and limitations of each grid type. It then transitions to analyzing the role of IoT technology in modern smart grids and microgrids, following a multi-faceted approach to various systems and grid-related concepts.

This report presents an approach to integrating IoT into one of the main elements of microgrids: battery monitoring. The findings contribute to a more autonomous and user-friendly system with a simpler schematic compared to wire dependent systems that are more frequently subjected to environmental errors, enhanced by the ease of use of wireless communication.

The proposed system is designed and implemented via simulation after a thorough comparison of each device comprising the system (Microcontroller, sensors…etc). The framework utilizes a set of sensors and algorithms to extract and process the required data. The results are analyzed, demonstrating a significant improvement in response time and efficiency of data acquisition compared to standard systems.

Keywords: Microgrid, Smartgrid, IoT, Battery monitoring, Proteus, ESP32.

Acknowledgement

In the name of Allah, the Most Gracious and Most Merciful, we begin by praising and giving thanks to Almighty Allah for His blessings and guidance throughout the completion of this thesis in the field of power engineering. We would like to express our deepest gratitude and appreciation to all those who have contributed to the successful completion of this research endeavor.

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Additionally, we would like to extend our appreciation to our friends and families for their unwavering support, encouragement, and understanding throughout this academic journey. Their belief in our abilities and their continuous encouragement have been instrumental in our success.

Dedication

We dedicate this master thesis to the unwavering support and encouragement from our beloved parents, whose love and guidance have been our guiding light throughout our academic journey. To our siblings, whose unwavering belief in our abilities has been a constant source of motivation. To our friends, who have shared in our triumphs and challenges, providing invaluable camaraderie and support. Lastly, to the countless mentors, teachers, and individuals who have shaped our intellectual growth, this work stands as a testament to your wisdom and guidance.

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ADC	Analog to Digital Converter
API	Application Programming Interface
DOD	Depth of Discharge
DER	Distributed Energy Sources
Emf	Electromotive force
ESS	Energy Storage System
HAN	Home Area Network
HESS	Hybrid Energy Storage System
IoA	Internet of Asset.
IoT	Internet of Things
IDE	Integrated Development Environment.
MG	Microgrid
MCU	Micro Controller Unit
NAN	Neighborhood Area Network
OCV	Open-circuit voltage.
SOE	State of energy
OCV	Open-circuit voltage.
PV	Photovoltaic
PCC	Point of Common Coupling
RER	Renewable energy resource
SPI	Serial Peripheral Interface
SG	Smart Grid
SOC	State of charge
SOE	State of energy

SC	Super Capacitor
WAN	Wide Area Network

General Introduction

The increasing innovation in the domain of renewable energy sources and their integration to the power grid has given shape to the concept of microgrids. Microgrids are a door to a more efficient, reliable, and sustainable energy management. However, as any technology, they come with limitations and challenges. One of these challenges is ensuring the reliable operation of battery energy systems, which are an essential part of any microgrid in order to assure backup power at any moment in time.

The advent of the Internet of Things (IoT) has also offered a novel approach to push the limitations associated to microgrid systems. With efficient IoT integration, real-time monitoring, display, and analysis of numerous elements from a notable distance is now possible. In our case, it is now possible to develop an enhanced battery monitoring system supported by IoT technology.

This master's project focuses on the development and implementation of an IoT-based battery monitoring system designed to improve microgrid management. This project is comprised of four chapters. An introductory chapter as chapter1, it will focus on providing any background theoretical information concerning the features and challenges of modern grid systems. The second chapter serves as a development to the field of IoT, and sets meaningful examples via structures and architectures to showcase the way IoT may impact modern grid systems. The third chapter delves into the concepts that govern a battery monitoring system and supports each concept with mathematical equations or phenomenon explanation. Finally, chapter 4 is a set of simulations and circuit design.

1 Chapter 1: Theoretical background.

1.1 Introduction:

Since the installation of the first reliable electrical networks in the 1800s, the demand for power consumption has increased through the years[1]. The standards and needs of power delivery coupled with the technological advancements in the domains of control, communication and renewable energy production shined a light on the problems and inconveniences of the traditional power grid. In a world where hospitals and various businesses operate on electricity, a power shortage can mean the difference between life and death at various scales. The shift in the design and operation of electrical grids has aligned with a more flexible, resilient and ecological alternative: Microgrids

In this chapter we will explore the fundamental advanced grid systems -namely: microgrids and smart grids- by examining their characteristics, benefits, flaws and structure. We will then compare them to the traditional grid and conclude by verifying the necessity of the novel energy systems.

1.2 Smart Grids:

1.2.1 Smart grid definition:

The concept of smart grids (SG) was born from analyzing the flaws of the pre-existent power grid. In a traditional power grid, energy is generated from stationary central generators, it is then distributed to loads via transmission lines.

The main raised issues from such a system are the lack of interactive services and the used technologies that were lagging behind in comparison to what research had achieved at the time. A SG is a network that intelligently integrates new technologies to improve the monitoring and control of the operation of electrical systems; specifically, in generation, distribution, in addition to being able to incorporate the connected users' actions. These networks are characterized by implementing, within the system, innovative equipment and services, new communication, control, monitoring, and self-diagnosis technologies. [2]

1.2.2 Smart grid characteristics:

SGs are distinguished from other energy networks by a set of features and characteristics listed below:

- Flexible: A SG is inherently defined by its capacity to adapt to the required changes of any system, for instance, the constant load and power flow direction variation. [3][4]
- Resilient and safe: As developed in [4] through self-healing, reliable technology and demand response; SGs exhibit high robustness. The ability to measure sensible data changes using reliable technology and the expanded use of data enables a SG to respond to varied faults and errors.[5]
- Power consumption optimization: Demand response and dynamic demand allow a reduced loss by balancing supply and demand. Practical instances of this characteristic

would be timed energy storage charging depending on renewable energy availability or sudden power demands. [3][5]

- Sustainable and ecological: SGs offer the option of coupling multiple RERs (Renewable Energy Resources), which improves the efficiency issues of RERs by alternating between fossil fuels if necessary and RERs. [5]
- Better communication: SG users benefit from a more interactive consumer experience thanks to IoT (Internet of Things) sensors making energy consumption management easier. At a network level, communication is improved between DERs (Distributed Energy Resources) and controlling units. [5][3]

1.2.3 Smart grid concept model:

The Figure 1.1 below illustrates a conceptual model of an operating smart grid.

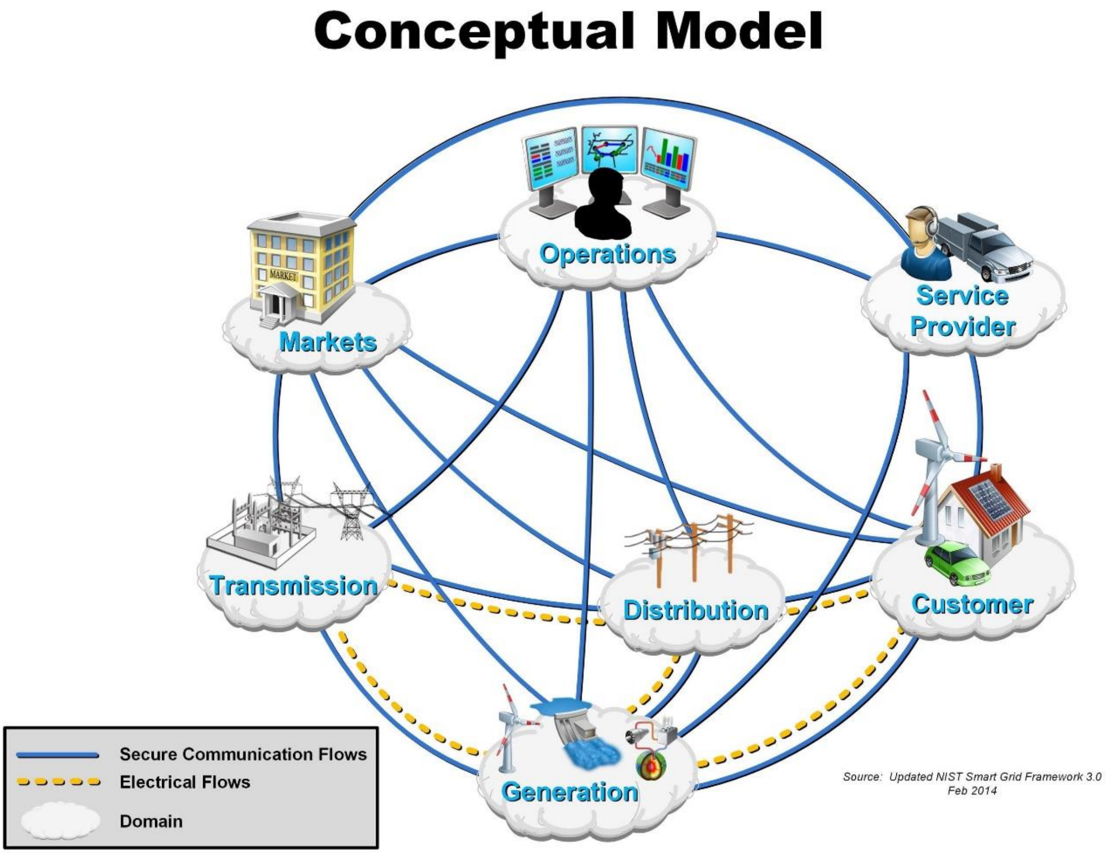


Figure 1.1 Smart grid conceptual model [6]

The model above introduces the different acting parties of SG utilization as ‘’domains’’: [7]

- Generation domain: Power generation based on various traditional and renewable energy sources. The generated power is measured and recorded in real time.
- Transmission domain: Power generated in the previous domain is transmitted to substations and high scale consumers. Transmission is subjected to smart stabilization and optimization depending on current load flow.
- Distribution domain: Distributes the power to customers while keeping an external communication interface with the operations and transmission domains.

- Customer domain: Commonly named “loads” in any power network, customer domain includes facilities responsible of power consumption.
- Operations domain: The operations domain is situated at the center of the model as it is responsible to maintain communication and control between the remaining domains.
- Markets domain: Manages the financial aspects of a smart grid.
- Service provider: The main bridge from the customer to the smart grid.

1.2.4 Comparison between traditional and smart grids:

The main differences between a SG and a traditional power grid are encompassed in the Table 1-1 below:

Table 1-1 Comparison between SG and traditional power grid [8]

Aspect	Traditional power grid	Smart grid
Technology used	Electromechanical power grid focused on analog systems and manual operating.	Digital technologies are used to monitor, control, and optimize the grid.
Generation methods	Power is generated in heavy centralized power plants. Mainly dependent on fossil fuels.	Power generation in distributed through numerous substations with various energy sources.
Sensor technology	Limits the number of possible sensors, required human management of acquired data.	Enables an efficient lining of many IoT sensors. Data is managed faster, which limits fault locations and increases system resilience.
Energy control	Outside of provider’s control.	Two-way data transfers allow a better control and optimization of delivered power.
Restoration and repairing	Faults need manual interactions from involved personnel.	Faults can be corrected thanks to the SG’s self-healing.
Power outage management	Contingency plans for customers are difficult to put in place. Even if they are prepared, the analog communication slows the process.	Alternative energy sources may greatly reduce power outage period and occurrence.
Choices of consumers	The customer and provider have no interaction outside of billing.	SGs offer a panel of choices related to energy consumption and preferred source of energy.

1.2.5 Smart grid challenges:

While SGs exhibit uncontestable advantages, numerous challenges and disadvantages are to be faced. By synthesizing from [8], [9], and [10] SG disadvantages focus mainly on the following issues:

- Implementing a SG implies a large initial capital. Given the advanced included systems for communication, measurement…etc, financial assistance is required.
- A SG is tied to a network. The unavailability of network for natural causes may be a significant challenge for SGs during natural catastrophes.
- SGs follow the tendency of every significant technical advancement to be limited by laws and regulations. In addition, there are yet to be concrete safety standards for SGs.
- Some outdated infrastructures may struggle to receive a SG and may need numerous upgrades to be adequate, which adds up to the already high initial costs.
- SGs may have a negative impact on the social status. While work opportunities would appear, some work displacements may unfortunately occur. The financial aspect also limits SG access to certain communities.
- The constant data traffic generates privacy worries with customers. If the cyber security of the grid is not competent, it may result in data leaks or theft.

1.3 Microgrids:

1.3.1 Definition of microgrids:

The term “microgrid” has been defined by various sources (engineers, researchers or institutions).

According to the US department of energy a MG is defined as:” a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.” [11]

While other researchers regard it as: “the concept of roaming DERs and various loads in the existing power system, such as solar-PV, wind turbines, micro-turbines, and storage devices which can be operated either in grid-connected mode or in stand-alone mode.” [12]

By analyzing the provided definitions, we synthesize the term as: “A microgrid is a self-sufficient energy system that provides electrical power to a distinct geographic location such as: a college, a hospital or a remote village…etc. A MG is the combination DERs (solar panels, batteries, generators…), a MG controller and a load.” [13][14]

1.3.2 Microgrid characteristics:

- Local: As previously defined, a microgrid is responsible for the electrical power generation of a geographically limited area. The locality of the DERs is a main characteristic that reduces the distribution costs and losses but also restricts the produced power to a single infrastructure. [13]
- Diverse: Microgrids can use various energy sources and alternate between them depending on the current operating conditions such as: Solar energy, wind or fossil fuels. [15]
- Intelligent: Microgrids benefit from having a centralized controlled unit that optimizes the load flow throughout the system by managing the generators, batteries and nearby building energy systems with a high degree of sophistication. The goal is to maximize the energy output for an optimal cost.

- Reliable: Microgrids offer a reliable power source that is-as mentioned before-independent from the main grid, however a MG is only a secondary energy consumption option and should not be used as extensively as the main grid. [16]

1.3.3 Advantages of microgrids:

The advantages of a MG can be summarized in the following points:

- Improved power reliability: This can be especially beneficial in emergency situations or for critical facilities such as hospitals and emergency shelters. For example, during Hurricane Sandy in 2012, Princeton University's microgrid remained operational even when the surrounding area lost power. [16]
- Increased energy efficiency: The application of modular local micro-sources in a microgrid can contribute to a more efficient and cost-effective energy system. In addition, unused produced energy is stored in batteries for later use.
- Ecological and socio-economic impact: Microgrids reduce fossil fuel dependency. The costs and carbon emissions related to using fossil fuels have an increase for more than half a century [17]. With renewable technologies powering microgrids, the cost will fall, again making the service affordable and accessible and optimistically make electricity a reliable source of power worldwide.

1.3.4 Disadvantages of Microgrids:

The disadvantages of a MG can be summarized in the following points:

- High initial cost: A commonly quoted price range for a microgrid is $2 to $4 million/MW. But the figure requires extensive footnoting. Cost depends on where and why the microgrid is built and what kind of generation it uses. However, the cost is still determined to be a high capital to invest. [18]
- Technical challenges: As with any novel technology, technical barriers are born from lack of knowledge and examples to be learnt from. MGs are still electrical grids and as such require constant maintenance and various knowledge depending on the DERs used. Systems of control, protection and communication are also part of an MG. This issue is set to gradually disappear given the era of fast circulating information we live in. [16]
- Limited scale: The locality of a MG can be seen as an advantage but it is also an issue. Installing a MG is an investment that has to be input through rigorous case studying by professionals to ensure end goals are met.

1.3.5 Architecture of MGs:

The MG system is based on: DERs, energy storage system (ESS) and loads. These units are linked through electrical feeders (cables, relays, circuit breakers, inverters…etc) The subsystems are supervised by the MG control unit through communication and control channels (IoT sensors, smart switches…etc) as described in the Figure 1.2 below.

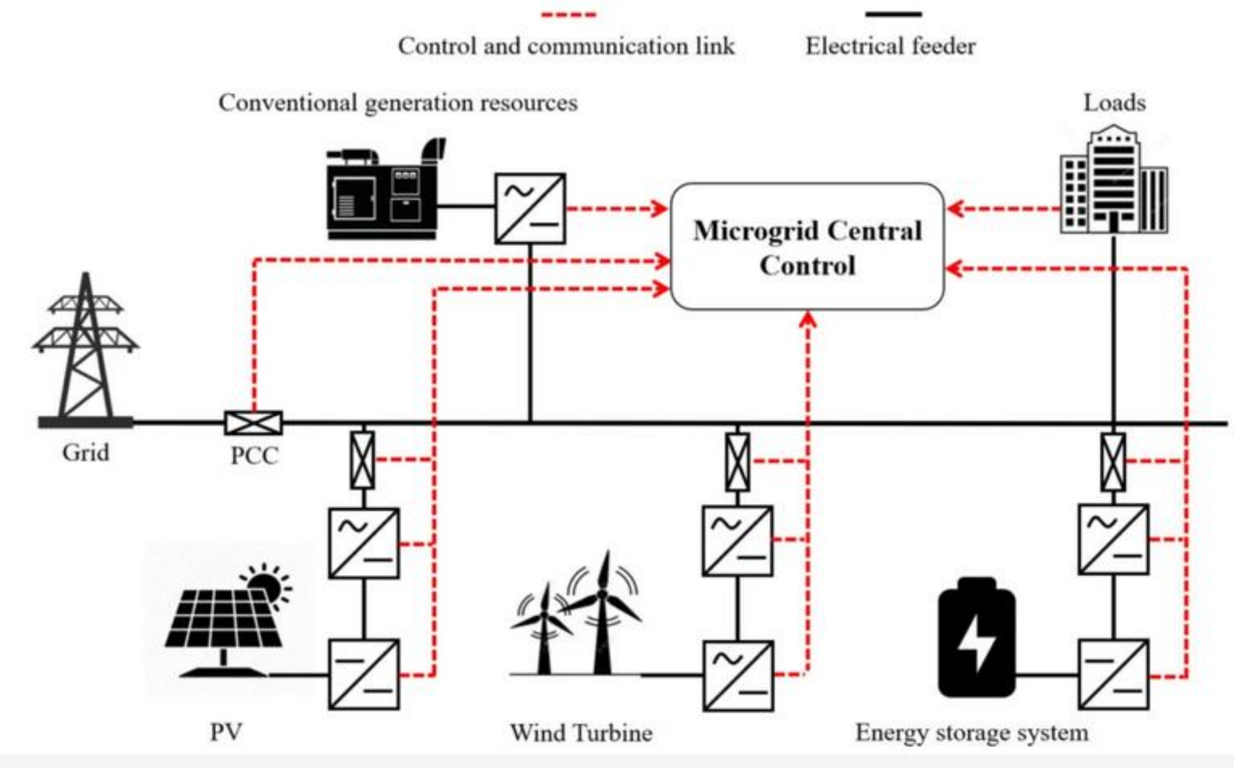


Figure 1.2 Microgrid architecture. [19]

- Distributed energy resources:

DERs include a variety of generating units, such as: PV panels, wind turbines, fossil fuels generators…etc. However, in a MG, the main generation units used are RERs. As of the last recent climate and ecological challenges, and gradual diminishing of fossil fuels, the reliance on these resources has known a steady increase [20].

- Energy storage system:

ESSs have the pivotal role of ensuring a continuous energy supply. In a MG, the generation capacities of a DER -especially RERs- are limited and tied by external factors such as: weather, irradiance…etc. An ESS can store energy surplus and provide it when needed under command of the MG control unit.

For instance, when the RER used is solar energy, a hybrid energy storage system (HESS) can be designed using supercapacitors and batteries. Figure 1.3 below showcases the use of a HESS in a DC MG.

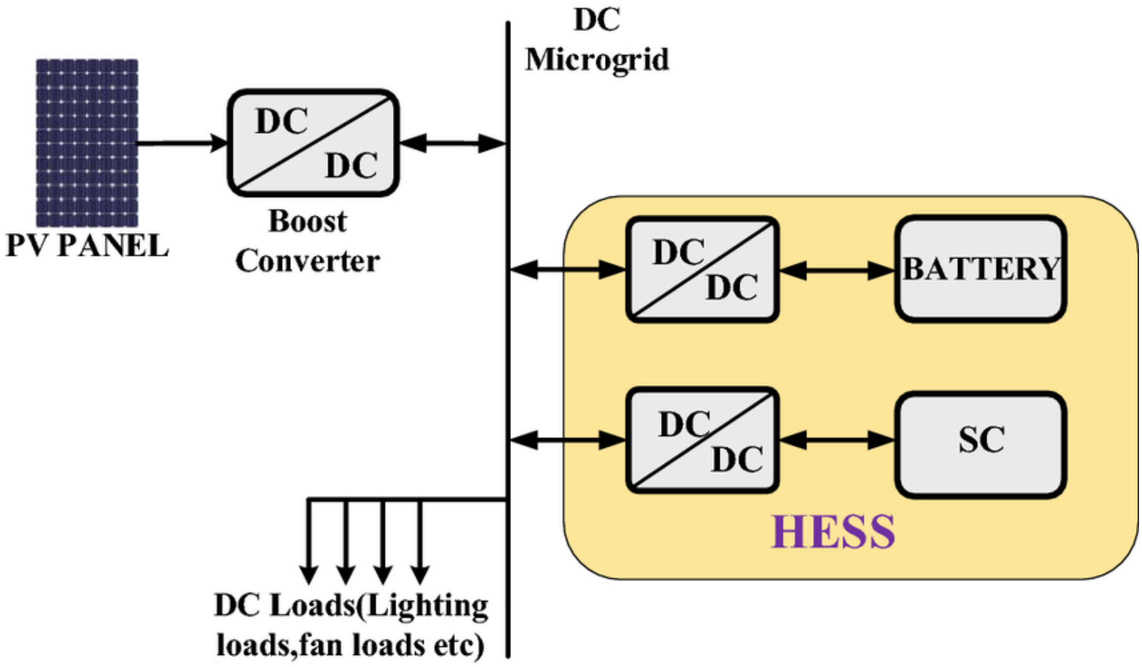


Figure 1.3 Hybrid ESS in a DC MG. [21]

- Loads:

Loads are the end consumer of the energy produced in a MG. Loads can be divided based on relative importance into: [22]

- Sensitive loads: Necessary loads that should be able to operate at any given moment (hospitals, nursing facilities…)
- Non-sensitive loads: Loads that can be disconnected or reduced to allow further generation to begin (air-conditioning, heating…)
- Emergency loads: First loads to be disconnected in case of emergencies (residential users, infrastructures with backup generators…)

1.4 Integration of IoT in modern power grids:

As much as SGs and MGs are impressive concepts in theory, the practical side of two-way data communication and nearly automated control are no easy task. The most efficient way to satisfy the technological requirements of each alternative may the use of IoT.

The goal of IoT is to connect the unconnected, as such, it can be viewed as the shortcut to satisfy the main objectives of a SG and its shortcomings. IoT equipment such as smart meters, sensors or actuators play a pivotal role in automating and improving the rate of data acquisition in a grid [4]. A higher data flow allows a significant reduction in the time needed for preemptive action in cases of fault or natural disasters.[5]

Applying IoT to power industry infrastructures comprises three stages. The first step is digitalizing assets and data, secondly, collecting the digitalized data; and finally, developing related algorithms within control systems. Each stage has to adapt to the security and protocols that are part of the industry, in addition to improving the quality of service offered by previous alternatives.

1.5 Conclusion:

The purpose of this chapter was to introduce the main concepts of microgrids and smart grids. The benefits and challenges of each power network have been subjected to thorough evaluation, in addition to a comparison that promotes key topics. The last sub-section highlights the importance of using an up-to-date technology to ensure the success and correct functioning of any power network, especially but not only, in MGs.

The next chapter will focus on a more detailed study of IoT implementation in various power networks daily operations.

2 Chapter 2: IoT integration in power grids.

2.1 Introduction:

This chapter introduces the concept of IoT and its architecture in a general manner. The focus is then shifted mainly, but not solely, on the integration of IoT technology in the various aspects of MGs and SGs. It emphasizes on the benefits of utilizing IoT technology in various devices and operating sectors of a power network, in order to simplify the assignments of each equipment.

The later parts of this chapter will showcase possible IoT implementation architectures in three types of networks: A general smart grid, a general microgrid, a microgrid based solely on a PV system.

2.2 The aspects of IoT:

The term Internet of things was first coined by Kevin Ashton -a British inventor- in the late 1990s, and he defined its concept as: "A world of interconnected smart devices''. [23]

However, if one analyses its aspects in a more meticulous fashion, they may conclude the following insights[24]:

On an internet-based point of view, IoT objects should share the "smart" characteristic by utilizing the IP protocol specification.

From a things-based approach, IoT promotes the long-distance tracking of included objects, in addition to unique identification.

From a semantic and context-based perspective, the whole IoT expression symbolizes the synthesizing of data from numerous smart objects.

2.3 Characteristics of the IoT:

Characteristics of IoT can be mainly introduced in these bullet points[25]:

- Fully aware: Smart objects -mainly but not restrained to sensors- provide real time data from various points of a network.

- Reliable transmission: Value and time accurate data are a main focus of IoT, any inconsistencies in data are not permitted and considered fatal faults of a system.

- Intelligent processing: Objects used for controlling systems use cloud computing algorithms to analyze large data sets.

2.4 IoT architecture:

As explained by[26] [27], data in an IoT system moves through a three-level design along four channels. The specified architecture is shown in Figure 2.1, which allows a clear understanding of the possible transmission channels: device to device, device to gateway, gateway to cloud and cloud to cloud.

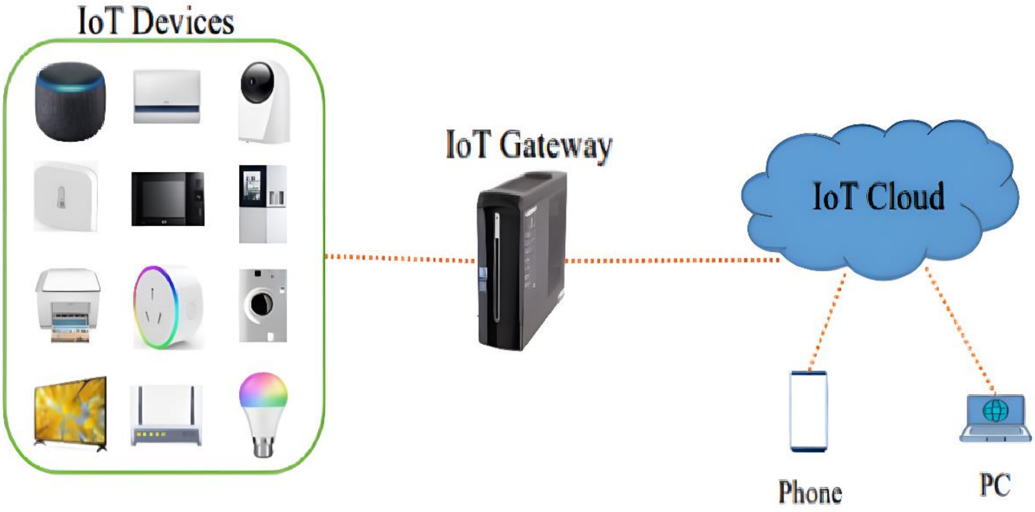


Figure 2.1 IoT network architecture.[27]

2.5 Network types in a smart grid:

Given the variety of subsystems that are part of SGs, numerous communication networks are established to ease data access at each subsystem. These networks are based on IoT technologies and satisfy architectural and characteristic requirements listed in 2.3 and 2.4:

- HAN: Home area network, manages customer level smart devices and home appliances. Any electrically dependent device is subjected to smart metering and controllable consumer’s power demand.
- NAN: Neighborhood area network, acts as a bridge between HANs and WAN. It guarantees transmission of data collected in HANs to a larger network.
- WAN: As seen in 1.2.2, a SG promotes communication between generation, transmission and control units of a power grid. A Wide Area Network allows collaboration between these systems at a large scale.

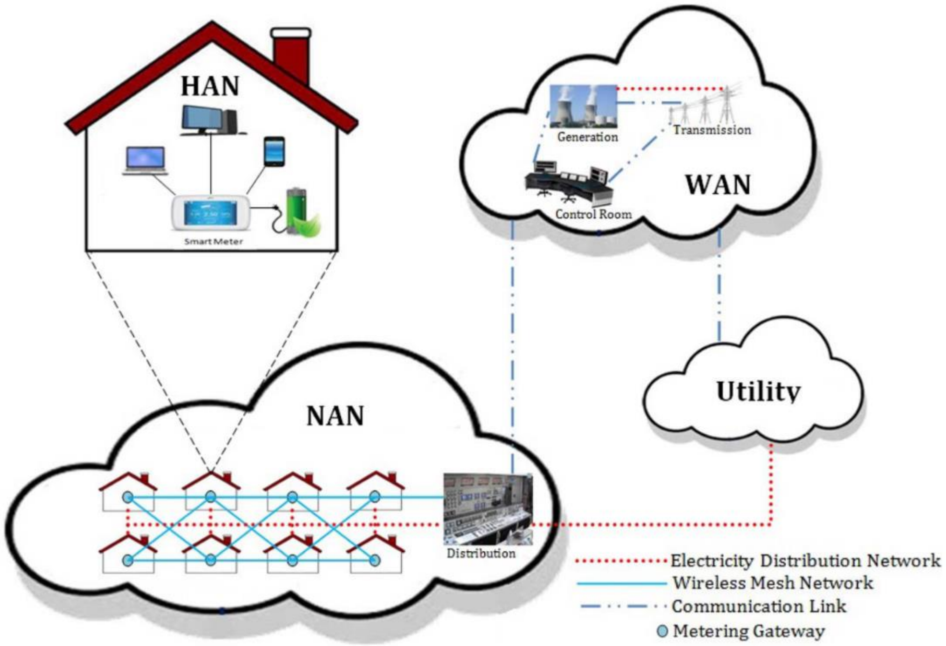


Figure 2.2 Different parts of SG communication network. [32]

2.6 IoT integration in a smart grid:

From the data and explanation provided in this chapter thus far, in addition to definitions and characteristics of SG from chapter 1; we can conclude that IoT technology may be the key to satisfying all previous smart grid requirements for a thorough implementation. Using IoT, we can ensure a real time data aggregation from various sources and networks. Interconnected control equipment can benefit from IoT by offering concise, clean, and customizable interfaces using applications such as Blynk for remote use.

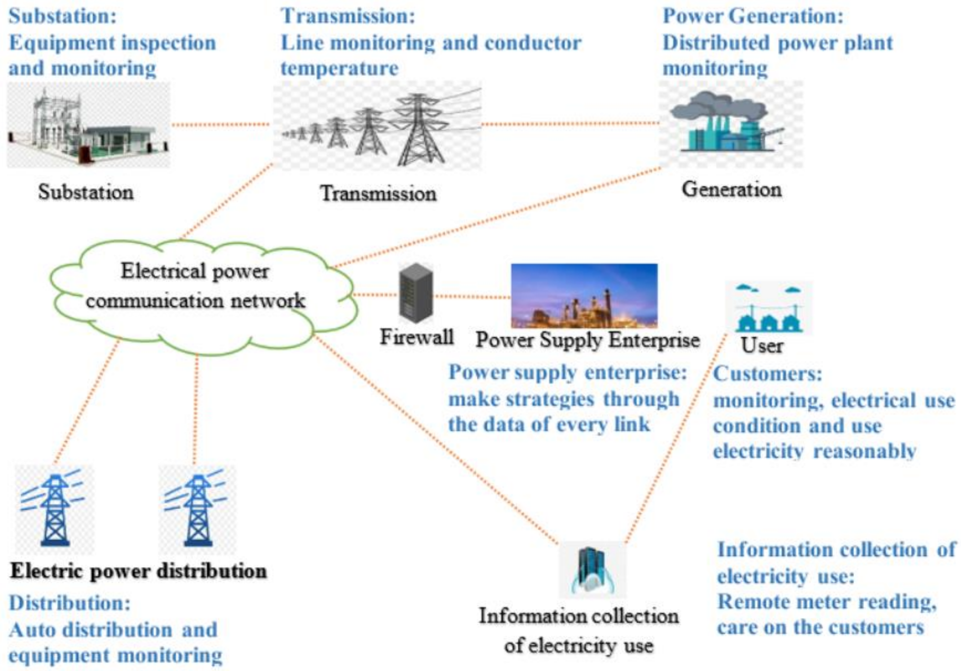


Figure 2.3 Different applications of IoT in all SG subsystems.[27]

IoT technologies cover three main expertise areas related to data: acquisition (collection), transmission, and processing. Data acquisition is responsible of collecting the position and state of smart devices connected to the network, along with any real time data from sensors. Data transmission is, as named, involved in transmitting the collected data; to be then processed by control units or interpreted by adequate recipients (engineers, experts, technicians…etc) [28][29]

Figure 2.3 showcases the integration of these different aspects in a SG, and they are as follows.

2.6.1 IoT in Power Generation:

In the generation subsystem, IoT technology is used to monitor DERs of various types (fossil fuels, PV systems, wind…etc). Each energy resource is associated with a specified set of data to oversee, for instance, a PV system transmits voltage, current, and temperature irradiation. Monitoring also includes overseeing possible faults or degrading environmental circumstances. Some main information transmitted via IoT may contain: energy consumption, energy storage, unwanted residues (pollutants such as gas emissions, chemicals…), and environmental changes affecting generation (wind, irradiation…). This concludes the main uses of IoT in the generation sector.[29]

2.6.2 IoT in Power Transmission:

Power transmission networks are mainly constituted of: Transmission lines, towers, and electrical equipment such as relays. In this case, IoT is used to monitor these lines to detect faults, mitigate them, and indicate their location. Moreover, remote fault management decreases risks of accidents during emergency maintenances. Additional sensors may be placed for environmental forecast and preemptive action depending on acquired data. Cloud algorithms are used to assess and process the acquired information and execute remote instructions.[27]

2.6.3 IoT in Substation:

As in previous sectors, IoT technology is used to acquire data, provide ease of utilization and safety, in addition to real time monitoring of equipment.[27]

2.6.4 IoT in Distribution, Utilization and Dispatch:

The features of IoT technology in these subsystems concern: Accurate load flow analysis, consumption data, advanced metering (smart meter). IoT additionally permits one of the most important characteristics of SG at this stage: Two-way data communication. Data usage and interaction from both the consumer and producer sides give access to wider power management options. [33]

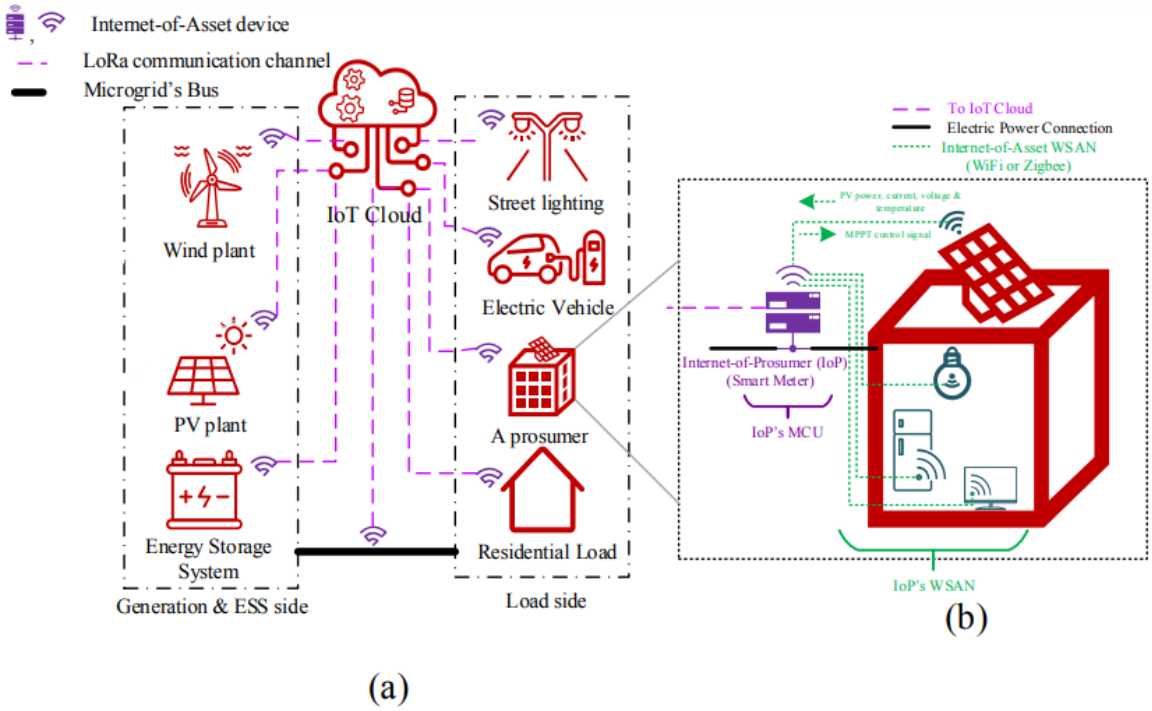
2.6.5 IoT in Smart Metering:

Since IoT has proven to be highly efficient in generation, transmission, and distribution; it is only natural to implement it in smart metering applications. Adding IoT to the smart metering infrastructure (AMI) may add a new layer of reliability and resilience to the transmitted data.[30][34]

2.7 IoT integration in a Microgrid:

2.7.1 Architecture of IoT integration in a MG:

As the challenges of optimizing the whole traditional power grid to reach SG standards become more apparent, building a series of smart microgrids may be a more feasible alternative. While the uses of IoT technology in a SG are mainly concentrated on: monitoring and data acquisition, a MG -especially in islanded mode- uses IoT to improve its interconnectivity at various levels. [31] designs a smart MG architecture that allows an entry to the wireless connected world while retaining the base construct of a MG. The Figure 2.4 below represents a possible IoT architecture for control and energy monitoring/management in a MG.



(a) The proposed smart microgrid architecture.
(b) The proposed Internet-of-Asset architecture.

Figure 2.4 Smart MG architecture. [31]

The architecture is composed of two main parts [31]:

2.7.2 The smart MG architecture:

Marked as (a) in Figure 2.4. It includes the main part of a MG: DERs (Power plants), ESS, and loads (electric vehicles, appliances, lighting…). An IoT cloud serves as an interactive database between every part of the MG, while being connected using communication lines, in this case Long Range (LoRa). However, the communication technology may vary depending on numerous factors such as range, power availability, network reliability needed. Each asset (equipment) is paired with a set of sensors called: Internet-of-asset (IoA). For instance, the IoA paired to a battery is to be called: Internet of Battery.

2.7.3 Internet-of-asset architecture:

Marked as (b) in Figure 2.4. The IoA described is that of a Prosumer, however the general architecture is composed of: Sensors, actuators, wireless network, and a microcontroller unit (MCU). Each component is responsible of:

- Sensors: Collecting data relative to the attached equipment. The data retrieved from each sensor is associated with a specific IP address or URL to allow singular recognition by the MCU.
- Communication technique: Several communication techniques can be used in a MG. The technique used depends on various factors such as: protocols used, data rate and range covered. Given the geographical limits of a MG, extreme range technologies such as satellite internet are unnecessary.

The Table 2-1 below is a comparison of some selected communication technologies that are common is MGs:

Table 2-1 Comparison of communication technologies for a MG.[32]

Technology	Data rate	Covered range
LoRa	27 Kbps	Up to 15 Km
Ethernet	Mbps -10 Gbps	Up to 100m
Bluetooth	721 Kbps	Up to 100m
ZigBee	250 Kbps	Up to 100m
Wifi	2-600 Mbps	Up to 100m

Preferably a short-range network with a high data rate, for instance Wi-Fi or ZigBee is used in an IoA. Sensor data is transmitted using the short-range communication technology to the MCU and to the long-range network technology used i.e., LoRa.

- MCU: The MCU used depends on the availability and financial status of the MG. The types of data to be acquired is an important factor as well given the limited number of pins in an MCU. The main MCUs used in IoT are Arduino, Raspberry pi, and ESP32. Each of the three MCUs has varying characteristics depending on the exact development board used, however the exhibit the following similarities:[35]
  - Arduino: Arduino is a beginner friendly microcontroller that offers a consistent experience for low power applications between 3.3 to 5.5 V. The software associated with Arduino is the Arduino IDE, using mostly C and C++ language concepts.
  - Raspberry pi: While Raspberry pi may be less accessible to a beginner, it offers more computational power, the possibility to add an SD card as a hard drive, and implementing python programs.
  - ESP32: The ESP32 is a versatile MCU created by Espressif, it benefits from affordable prices and low-power consumption. While it has various uses, its embedded Wi-Fi and Bluetooth are by far its most important features in an IoT context.[37]

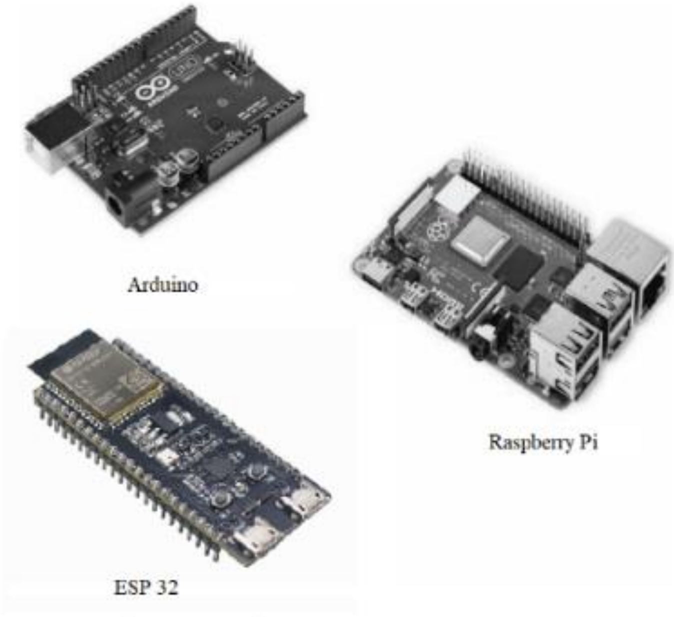


Figure 2.5 MCUs used in IoT.

- It intervenes to make computations related to monitoring systems such as the Battery Monitoring System BMS using algorithms previously inputted.

Using an IoA exhibits a second advantage, which is allowing the system to be updated while keeping previously existing equipment without buying smart equipment from scratch.

2.8 IoT monitoring in a PV based microgrid:

2.8.1 PV systems monitoring via IoT architecture:

As an example, to illustrate previously introduced concepts in 2.6 and 2.7, we introduce the following PV based microgrid architecture in Figure 2.6.

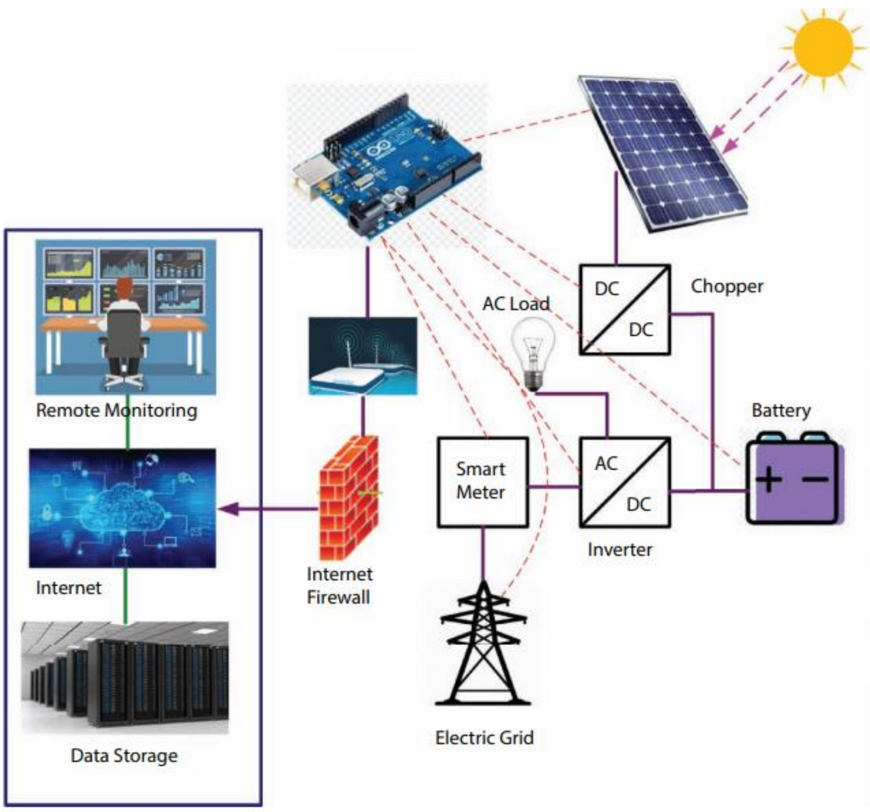


Figure 2.6 IoT implementation in a PV system.[35]

The architecture in Figure 2.6 focuses on the main parts of a PV system, including a MCU coupled with cloud access for the monitoring of the system. Each part of the architecture carries an important function that is helped in some way by the IoT implementation as follows:

2.8.2 PV panels monitoring:

PV panels are an arrangement of PV modules into PV arrays. They are responsible for the generation of voltage using irradiation.

The block diagram in Figure 2.7 illustrates a method that can be used to acquire and monitor data from a PV panel. The panel is equipped with four sensors in order to register: voltage, current, temperature, and irradiation (light intensity). Other sensors may be added to register other information such as humidity for example. The acquired data is transmitted to a MCU (in this case Arduino ATMega2560) and transmitted to an IoT server (Thingspeak). Since the used MCU is used for its high ADC accuracy, but does not dispose of an in-built wireless transmission mean (Wi-Fi or Bluetooth); thus, a wireless antenna (NodeMCU ESP8266) is used.[38]

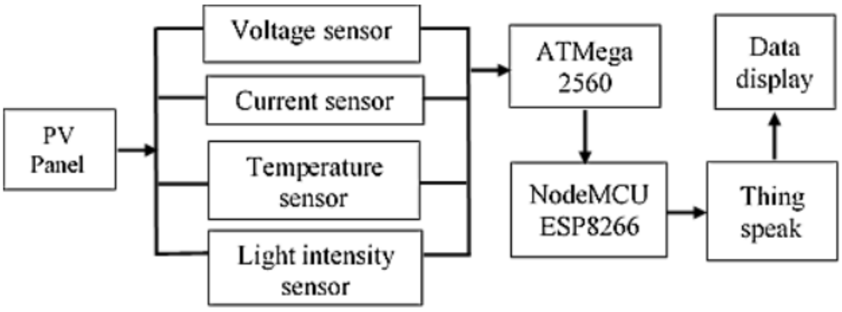


Figure 2.7 PV panel monitoring block diagram.[38]

The acquired data can be used for regular monitoring, in addition to Maximum Power Point Tracking (MPPT).

2.8.3 DC-DC power converters (choppers):

Choppers are used to regulate the power output from PV panels to match DC loads operating requirements. Many types of choppers may be used in a PV system such as: Buck converter, boost converter, buck boost converter. IoT mainly helps power electronics converters by automating their control and locating possible faults. IoT is not usually used to monitor such equipment given their low and apparent fault rate.

2.8.4 DC-AC power converters (inverters):

Inverters are used to convert previously generated DC current into AC current for AC loads, or to feed the power grid for grid connected Microgrids. As inverters are power electronics converters too, they have the same use for IoT as choppers.

2.8.5 ESS (battery):

ESS are used to store unnecessary generated power for later distribution. The use of a specific ESS is dependent of numerous factors: Rated load characteristics, space requirements, performance, rated power grid characteristics, availability of additional power to be stored, response time…etc. The ESS used in a PV system is usually a Battery Energy Storage (BES). While the characteristics of a BES are subject to change based on the used battery, some general characteristics can be deduced and organized in Table 2-2.

Table 2-2 BES characteristics.[36]

Energy Storage Technology	Discharge/charge rate (MW)	Discharge duration	Response time	Ramp rate	Efficiency (%)
Battery Energy Storage (BES)	0-40	ms-hours	ms	MW/sec	70-90

2.8.6 Smart meter:

Heavily reliant on IoT for wireless data transmission, smart metering allows an accurate data acquisition of used power through the network.

2.8.7 Smart sensors:

While not highlighted in Figure 2.6, smart sensors are part of nearly every equipment composing a smart PV system. They are devices attached to equipment, while being responsible of acquiring various types of data (environmental, mechanical, electrical…etc.) and transforming it into signal form. Numerous sensors are shown in Figure 2.8 below.[35]

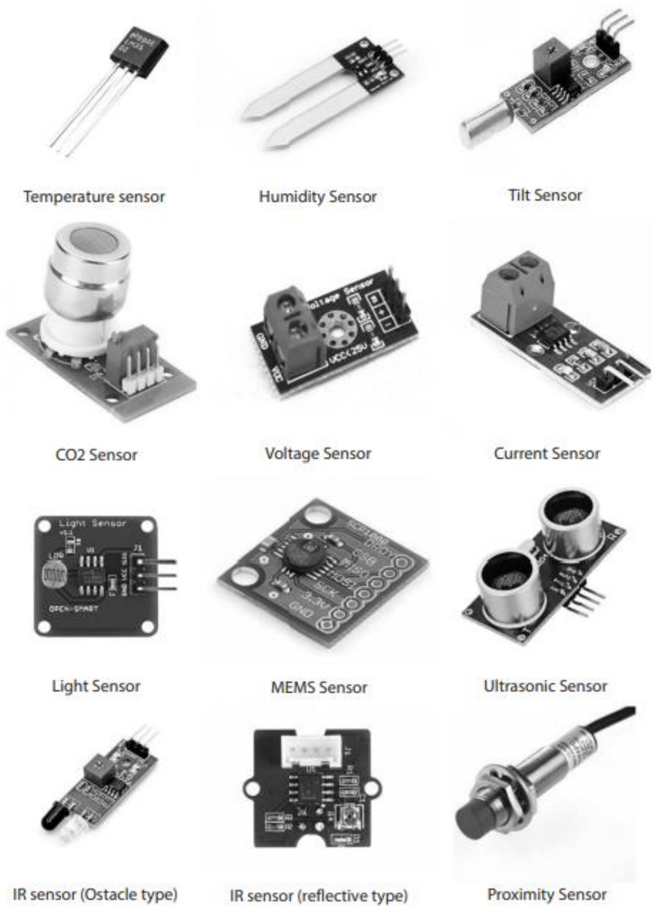


Figure 2.8 Types of sensors used in a smart PV system. [35]

These sensors either include a MCU that directly sends the data to a cloud, or are connected to the central MCU used in the system. The main sensors used in a PV system are:

- Tilt sensors are used to measure the position and orientation of the attached equipment based on axes of reference. In the case of a PV panel, tilt sensors are important parts of solar tracking devices.
- CO2 Sensor: Carbon dioxide sensors are responsible for keeping CO2 levels in check. These sensors are mainly used in gas substations, however, in order to follow the carbon footprint of electricity producing systems these sensors become more and more essential.
- Voltage and Current Sensor Voltage and current sensors are used for voltage and current monitoring throughout the whole system.

- Temperature sensors: While every electrical equipment is at risk of overheating, these sensors are mainly attached to batteries and other ESS components.

2.8.8 Microcontroller unit:

May vary depending on the system requirement as developed in 2.7.3, is considered to be responsible for the transmission of data from designated sensors to a cloud server.

2.8.9 Cloud server:

Serves as a temporary data base, most of the data is stored in a permanent data base for later revision while real time data is constantly monitored.

2.9 Conclusion:

This chapter featured a comprehensive overview of the integration of IoT in numerous systems with detailed options at every design stage. Each system exhibits numerous ways of conforming to the IoT general architecture presented at the beginning of the chapter. The last subsection 2.8), serves as a detailed example of how IoT can significantly impact the design of a MG.

The following chapter will focus on the study of battery monitoring system and the technologies used to monitor such systems.

3 Chapter 3: Battery parameter monitoring.

3.1 Introduction:

After a thorough explanation of the systems of microgrids and smart grids and the importance of IoT integration in each system, this chapter will address concepts and ideas attached to battery energy systems and the equipment used to monitor the main characteristics of these systems -namely, voltage and current-.

3.2 What is a battery energy system?

A battery is defined as one of -if not the most- used electrical energy storage system, it is based on converting chemical energy into electrical using oxidation-reduction (redox). The micro unit responsible of storing energy is called a cell.

Each cell has two electrodes: The cathode (positive), the anode (negative), and an electrolyte separating the two plates, as displayed in Figure 3.1. The voltage of a battery cell at rest (battery is neither in charge nor discharge) is equivalent to the cell's emf (electromotive force) and is labeled open circuit voltage (OCV).

As stated before, the operation principle of a battery is related to electrochemical reactions. During discharge, an oxidation reaction is started at the anode, which produces an electron release and positively charge ions. These electrons are consumed by the cathode, creating an electric current. The interaction of positive and negative ions in the electrolyte maintains an electric neutrality stopping electrons from going back.

The desired levels of voltage and current are obtained by an adequate arrangement of battery cells in parallel or in series. During the charging of the cell, the terminal voltage exceeds the OCV while during discharge it is less that the OCV. [39]

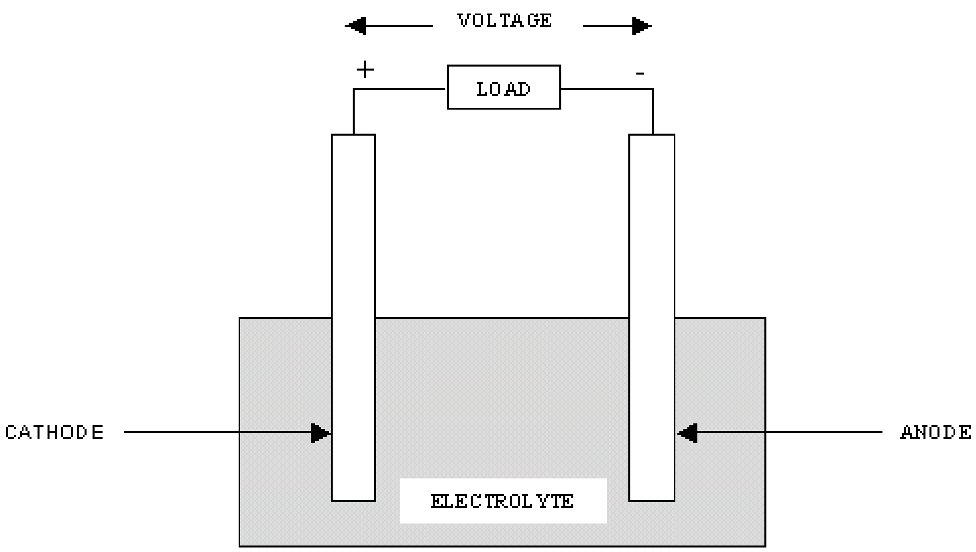


Figure 3.1 Battery layout.[40]

3.3 Concepts related to batteries:

3.3.1 Capacity:

Capacity of a battery is defined as the maximum amount of electrical energy generated by a battery based on the arrangement of its cells and their internal impedance. It is measured in ampere-hours (Ah). The equation (3.1) below describes the capacity of a battery as:

$$Q = \int_{Ei}^{Ef} I(t)\, dt \qquad (3.1)$$

Where: I(t) is current in (A).

- E_i, E_f are initial and final energy states respectively.
- Q: Amount of usable electric charge in (Ah or C).

Other factors affect a battery's capacity such as: The electrolyte density, the cell arrangement, the age of the battery…etc. However, these factors are all under precise control in order to determine the nominal capacity of a battery. The terms "nominal" or "rated" battery capacity refer to the measured capacity under precise conditions, and should be considered to determine adequate battery choices. [40]

3.3.2 State of Charge and State of Energy:

A battery is a device that undergoes charge-discharge cycle during its lifetime. The state of charge (SOC) is derived as a percentage expressing the remaining energy in the battery compared to its maximum capacity.

The state of energy (SOE) of a battery, while being an indicator of battery capacity like the SOC, also takes into consideration the battery voltage at a given SOC to give a more precise depiction of the energy in a battery. Generally, the SOC is more widely used than the SOE.[42]

Equation (3.2) is a general mathematical description of the SOC of a battery:

$$SOC(t) = \frac{Q_{remaining}}{Q_{rated}} \times 100 \qquad (3.2)$$

Where:

- SOC(t) is the state of charge at instant t.
- $Q_{remaining}$ the remaining capacity at time t.
- Q_{rated} is the total capacity.

3.3.3 Depth of Discharge:

While the SOC depicts the remaining charge in a battery, the depth of discharge assesses the energy used by the battery relative to the rated capacity. Based on the definition of the SOC in 3.3.2, we conclude that DOD and SOC are inversely proportional.

The operational cycle of a battery is defined as the complete cycle of charge and discharge of a battery, through these cycles, the DOD tends to increase with each cycle imposing stress on battery cells and heavily affecting the lifespan of the device. [43]

The equation (3.3) below represents the relationship between SOC and DOD:

$$SOC(t) + DOD(t) = 100\% \qquad (3.3)$$

With:

- SOC(t), and DOD(t) the state of charge and depth of discharge at an instant t respectively.

3.3.4 Battery operational cycle and cycle lifetime:

The battery operational cycle generally shortened to cycle, is the period of full discharge followed by a full charge. This definition serves as a unit to the term “cycle lifetime”. The cycle lifetime of a battery is the number of operational cycles the battery can go through before its maximum capacity fades to 80% of its original rated capacity. Capacity and cycles are inversely proportional: As the number of cycles increase, the maximum capacity decreases.

Many parameters can affect the relationship between the cycle lifetime and the effective capacity such as temperature and DOD. [41]

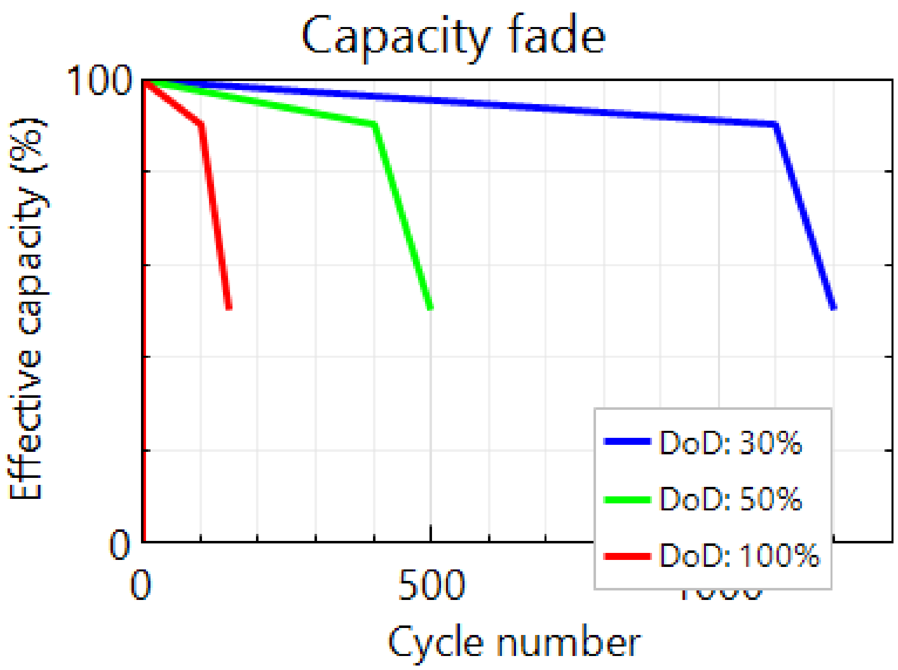


Figure 3.2 The effective capacity (%) vs cycle number at different DOD rates for a flooded lead-acid battery. [41]

The graph in Figure 3.2 shows that for different DODs, the slope of capacity fade varies. The lesser the DOD the lesser the capacity fade slope and the greater the cycle lifetime.

3.3.5 State of Health:

The state of health of a battery (SOH) is a measure of a battery’s aging, taking into consideration the state of its cells. Along the cycle lifetime, the SOH is a second measure to assess the state of health of a battery. The SOH is a percentage that pinpoints the current state of a battery relative to its beginning and end of life.[42]

Computing the SOH follows the equation (3.4) below:

$$SOH(\%) = \frac{C_{current}}{C_{rated}} \times 100 \qquad (3.4)$$

Where:

- SOH is the state of health.
- $C_{current}$ is the current maximum capacity of the battery.
- C_{rated} is the rated capacity.

3.3.6 C-rate:

The C-rate is the ratio of the current actually passing through a battery to the nominal current needed for the battery to operate in rated condition (rated capacity, voltage …etc) within an hour. Its unit is hours to the power of negative one (h^{-1}).[44]

3.3.7 Internal resistance:

When a battery operates polarization occurs, a tension difference occurs between the OCV and the actual battery voltage. Due to this difference, the internal resistance of the battery naturally meets the needed current output. The internal resistance may vary based on many factors such as temperature, SOC, and battery aging.[44]

3.3.8 Efficiency:

Coulombic efficiency (η_C) relates the total charge retrieved from a battery during discharge to the total charge introduced in the battery during its charge. The loss of coulombic efficiency is mostly due to cells aging or secondary electrochemical reactions that may be induced by defective electrolyte. The equation (3.5) below describes coulombic efficiency:

$$\eta_C(\%) = \frac{Q_{discharged}}{Q_{charged}} \times 100 \qquad (3.5)$$

Where:

- $Q_{discharged}$ is the total electric charge extracted from battery during discharge in(C).
- $Q_{charged}$ is the total electric charge supplied to the battery to fully charge in (C).

Voltage efficiency (η_V) relates the voltage of the battery when it is fully charged to the voltage during discharge. Coulombic efficiency is the most reliable efficiency to evaluate the state of a battery.[41]

3.4 SOC determination methods:

Concepts related to batteries all hold some level of importance as thoroughly explained in 3.3; however, any battery user mainly focuses on seeing a clear SOC. Determining the SOC of a battery is an effort evidenced by the usual complications that a daily battery user encounters when using a phone or a laptop. Batteries are relatively volatile devices in the domain of electronics that tend to age at different paces especially at varying operating conditions. The operation conditions that mainly affect the SOC determination of a battery are: discharge rate, temperature, battery age, charging efficiency, electrochemical balance, and self-discharge current.

While numerous types of methods can be used to determine the SOC of a battery given the wide range of processes happening in it such as: chemical, thermodynamical or experimental and mathematical measures. In this study, we will focus on apprehending SOC determination from a mathematical approach supported by algorithmic methods.[45]

3.4.1 OCV method:

The OCV method is based on precisely measuring voltage to situate the actual SOC or DOD based on a pre-established discharge curve by the battery manufacturer. For instance, Figure 3.3 shows the discharge curves for two types of batteries.[45]

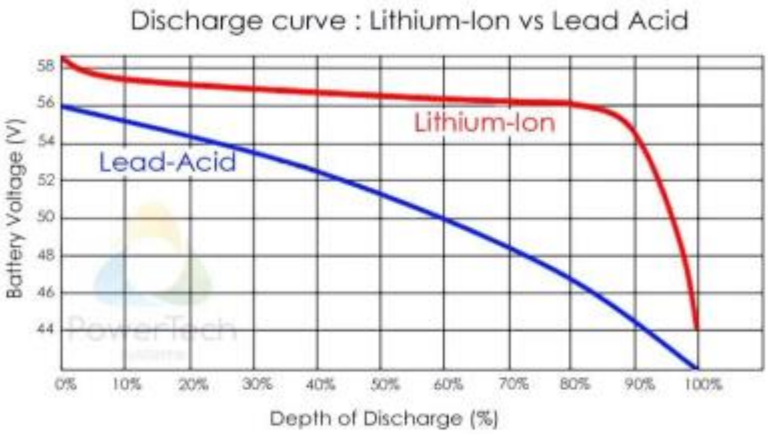


Figure 3.3 Typical discharge curves for Li-Ion and Lead-acid batteries.[45]

As stated before, the accuracy of this method is entirely dependent on an accurate estimation of the voltage; however, since the discharge curves provided by manufacturers are based on the open-circuit voltage, many factors parasite the voltage measurement which means the measured voltage does not equate the OCV. The internal resistance described in 3.3.7, high current batteries induce a voltage drop between the terminals, sudden chemical reactions.[46]

In addition to inaccuracies in voltage measurement, obtaining the current battery OCV would necessitate electrochemical equilibrium, which happens after letting the battery rest for approximately 2 hours -a highly unpractical scenario-.[45]

Moreover, discharge curves of certain battery types such as the lithium-Ion curve in Figure 3.3 are extremely flat and cause mathematical inaccuracies.

3.4.2 Coulomb counting:

Coulomb counting refers to the method of determining the remaining charge in a battery by continuously integrating the current flow. It is one of the most commonly used data keeping techniques for estimating State of Charge (SOC). Equation (3.6) is a mathematical depiction of the coulomb counting method:

$$SOC(t) = SOC(t_0) + \int \frac{\eta(T, SOC, I, I_C) I(t)}{C_a} dt \qquad (3.6)$$

Where:

- The term η(T, SOC, I, Ic) refers to the coulombic efficiency, for a specific temperature (T), I_c (charging current), discharge current before the charge (I), and SOC.
- C_a is the actual capacity of the battery, which is replaced by the nominal capacity during the charging process of a new battery or by the maximum capacity for a used battery.
- I(t) is the current flowing through the battery.

When coulomb counting accounts for temperature and the Peukert effect, which will be discussed in later subsections, it is referred to as Enhanced Coulomb counting. The limits of coulomb counting mainly show in: estimating of the initial SOC ($SOC(t_0)$), the accumulation of integration approximation that reduce the overall computation accuracy, and the accuracy of the current measurement.[47]

3.4.3 Coulomb counting with OCV calibration:

Combining the two previously mentioned methods results in a robust algorithm that mitigates the issues previously discussed [10]. Initially, the SOC of the battery is determined by disconnecting the battery for approximately two hours prior to powering the circuit. During this period, the circuit automatically measures the terminal voltage and maps the initial SOC using the discharge curve. It is important to note that this process is specifically applicable to lead-acid batteries, which exhibit an approximately linear discharge curve. As illustrated in Figure 3.3, Li-ion batteries display very flat discharge curves in the mid-range from 90% to 10% depth of discharge (DOD); however, beyond this range, the curve exhibits a significant slope. The initial SOC can be estimated from these regions, provided the battery has been charging for an extended period. Notably, the regions outside the middle range (100% to 90% and 10% to 0%) are characterized by low charge flow (indicating an almost full or almost empty battery), allowing for relatively accurate SOC estimation from the terminal voltage in these regions [14].

In order to reduce the errors relative to both methods, we try combining them. Essentially, we measure the initial SOC using the OCV method and carry with the coulomb counting integral computations. The combined method follows these steps:[48]

- Before connecting a battery to a circuit, let it rest for at least 2 hours to reach electrochemical neutrality.
- Measure the open-circuit voltage to situate the initial SOC in a discharge curve.
- Measure and bookkeep the current through the battery.
- Use coulomb counting to compute the SOC at a given time t.

As its predecessors, this method shares some limits such as: If the discharge curve is too flat, estimating the SOC accurately may be troublesome. For instance, for the discharge curve of the Li-Ion battery in Figure 3.3, this method is difficult to implement in case the battery is not fully charged or empty at t_0, since at the ranges (0-10) % and (85-100) % are not flat and allow SOC estimation; discharge curves should be analyzed with attention in each case. [48]

The Figure 3.4 below is a summary of which of the two methods to use depending on the shape of the discharge curve:

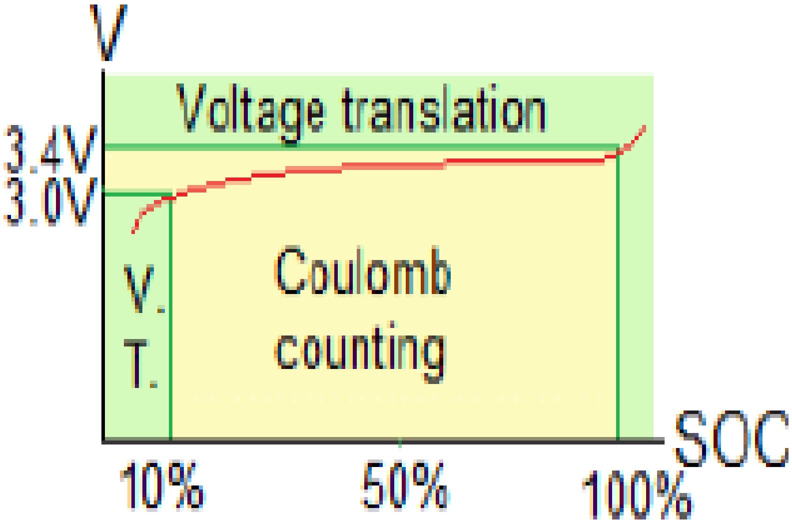


Figure 3.4 Coulomb counting and OCV method for SOC estimation.[48]

3.5 SOC determination limitations and alterations:

3.5.1 Peukert effect:

As explained before, the nominal capacity of a battery is determined under heavily controlled conditions. During the testing of a battery, the C/20 test is practiced on new batteries, this test aims to determine the discharge rate of the product by discharging the battery at a current that will completely deplete the battery's charge in 20 hours. When using a battery repetitively, the increase of the DOD with each cycle decreases the maximum battery capacity making the nominal battery capacity listed as unreliable. This phenomenon is stated as the Peukert effect, which is due to numerous factors that may happen at different times of a battery's operational cycle, successively or concurrently, such as: voltage drop due to varying discharge currents, electrolyte movements, or internal resistance variations.[49][50]

In most cases, a mathematical model of the Peukert effect is highly inefficient due to causes that cannot be empirically measured; however, in the context of SOC determination it is possible to approximate the alteration generated by the Peukert effect using an exponent called the Peukert exponent (denoted as pc or n), ranging from 1 to 1.5 depending on the used battery. The Peukert exponent mimics the behavior of the same named effect by multiplying the current during capacity computation to indicate that higher currents allow voltage drops that induce higher DODs and capacity decrease as show in equation (3.7):[49]

$$C_p = I^{pc} * t \tag{3.7}$$

Where:

- C_p is the Peukert capacity which is constant no matter the discharge rate for a single battery (not analogous to the actual capacity).
- I is the actual discharge rate in Amps.
- t is the duration of discharge in hours.

This, in turn, gives equation(3.8):

$$C_a = \frac{C_n (I_n)^{pc-1}}{I^{pc}} \tag{3.8}$$

Additionally, we can define an effective current I_{eff} which we integrate directly to get the change in SOC as follows:

$$I_{eff} = \frac{I}{C_a} \tag{3.9}$$

$$SOC = SOC(t_0) + \Delta SOC \tag{3.10}$$

$$\Delta SOC = \int I_{eff}\, dt \tag{3.11}$$

Implementing these computations is only possible after determining the value of the Peukert exponent. We find the exponent by discharging the given battery at two discharge rates. One rate should be as close as possible to the average discharge rate of the used circuit called I_1 (approach nominal conditions), while the latter should be much lower to be able to map the range of possible discharge rates and mitigate the impact of the changes the battery's potential inconsistencies could cause to the exponent. [51]

Given that the Peukert capacity C_p remains constant across different discharge rates, we define Cp_1 and Cp_2 based on equation (3.13) for the respective discharge rates as follows:

$$C_1 \left(\frac{C_1}{t_1}\right)^{pc} = C_2 \left(\frac{C_2}{t_2}\right)^{pc} \tag{3.12}$$

$$C_{p1} = C_{p2} \tag{3.13}$$

Where C_1 and C_2 are the available capacities at the discharge rates I_1, and I_2 respectively, and t_1, t_2 are the obtained discharge durations after the discharge tests. We solve for pc and find:

$$pc = \frac{\log(t_2) - \log(t_1)}{\log(I_1) - \log(I_2)} \tag{3.14}$$

The Peukert exponents and the effect on the battery's discharge on the battery's capacity are linked, the greater the exponent the greater the battery's dependency.

3.5.2 Self-discharge:

Because of battery's constant chemical processes, a constant internal current in the battery causes an energy loss named the self-discharge. The associated current is called self-discharge current.

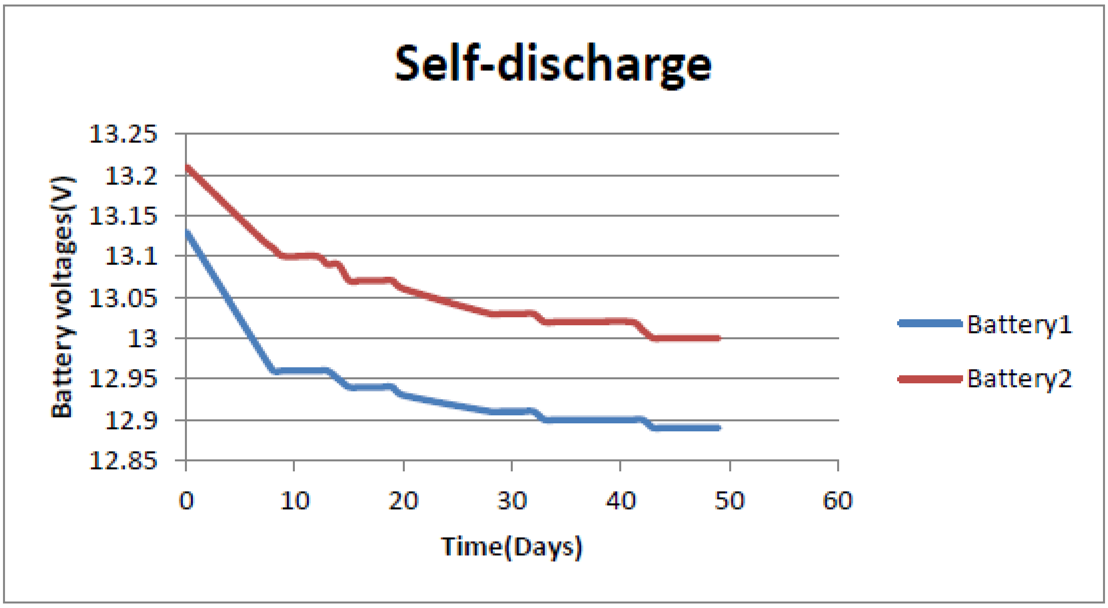


Figure 3.5 Self-discharge curves of two Lead-acid batteries.[50]

The plot in Figure 3.5 shows the evolution of battery voltages over a total period of 49 days, for two Lead-Acid batteries with full charge terminal voltage of 13.2V for battery 2 and 13.12V for battery 1. Measurements are taken every three days. During the mentioned time period, no current was drawn from the batteries. As explained before, since no current is drawn from the batteries, we can use the OCV method to situate the SOC of each battery, we notice that the SOC of each battery is naturally reduced even if no current is drawn from them. [50]

Self-discharge is an essential factor to be taken into consideration when determining the SOC of a battery. It affects the coulombic efficiency, and enables a better understanding of the Peukert effect, since the self-discharge of a battery is a discharge rate in and of itself. The fact that the discharge current of a battery is never null also solidifies equation (3.14) the actual capacity never approaches infinity.

3.5.3 Coulombic efficiency:

The concept of coulombic efficiency was already explained in 3.3.8; however, we will now explain the effect of coulombic efficiency in determining the SOC. Coulombic efficiency can be influenced by various parameters such as the discharge rate, temperature, current SOC of the battery, and the battery's charging rate. Moreover, the self-discharge current cannot be neglected given its impact on the battery's discharge rate. Thus, a mathematical and empirical approach to computing the coulombic efficiency will not suffice, which marks it as outside the scope of this study.[49][46]

3.6 BES parameter monitoring:

3.6.1 Voltage measurements:

Given the analog nature of battery voltage, using an MCU to measure said voltage is only possible utilizing analog-to-digital conversion. Any conversion method is suitable as long as the sampling offers enough resolution to reduce quantization errors, whether it is using analog-to-digital converters (ADCs) or successive approximation registers (SARs). The accuracy of a converter and the ability to reduce the output's terminal voltage sensitivity to noise is a critical characteristic when considering ADC or SAR choice.[52]

3.6.1.1 ADC Characteristics:

- **ADC definition and function:**

Since microcontroller only process digital signals, ADCs are an essential part of any microcontroller's signal processing system. For this reason, the great majority of MCUs possess an integrated ADC; however, attaching an external ADC to your circuit is possible if the integrated one does not meet required characteristics.

- **ADC noise:**

ADC conversion inherently includes a certain level of uncertainty, and thus, noise. The noise in an ADC essentially includes: input voltage noise and computation (quantization) noise. Since analog signals contain an infinity of data, while the conversion result (digital signal) contains a finite number of digits; quantization errors are bound to happen. The sensitivity of an ADC to noise is represented by the signal to noise ration as shown in equation (3.15) :

$$SNR = \frac{V_{signal}(RMS)}{V_{noise}(RMS)} \tag{3.15}$$

- **ADC linearity:**

ADC linearity is the criteria that denotes the difference between the ideal linear response and the actual output response. It can be described empirically and graphically. Empirically, it is the RMS difference between the perfectly linear and the experimental response. Graphically, it can be observed as the tilt degree or noticeable deviation between the two responses.[53]

- **Reference Voltage Calibration:**

Reference voltage calibration aims to mitigate the internal reference voltage of the device. This can be done by measuring this internal reference (named "bandgap"), by using internal circuitry and adjusting the circuit accordingly. It can also be achieved by using external circuitry such as a high-accuracy external source to estimate the bandgap.[54]

For instance, when using the ESP32 module, the internal ADC reference voltage is calibrated manually by rerouting the voltage to a general-purpose input/output pin (GPIO) and measuring it. Some MCUs contain automatic calibration means such as reading the internal e-fuse.[54][55]

- **Quantization error:**

As stated before, quantization errors are always a part of analog-to-digital conversion due to the nature of the conversion of infinite to finite data. The limited resolution of an ADC prevents the accurate estimation with total precision. The quantization noise of ADC is represented by equation (3.16) below:

$$Err = \pm \frac{RES}{2} \tag{3.16}$$

Where Err is the quantization error and RES is the resolution given by:

$$RES = \frac{V_{ref}}{2^{n-1}} \quad (3.17)$$

Where V_{ref} is the ADC reference voltage and *n* is the number of resolution bits.

3.6.1.2 Voltage dividers:

Voltage dividers are multi-usage circuits that are very simple to implement. Firstly, they reduce the amplitude of measured signals to meet the limited range of an MCU's GPIOs, preventing possible faults or over-voltage. Moreover, even without considering GPIO ranges, transposing measured voltage to lower ranges allow a considerable increase in accuracy.

3.6.2 Current measurement:

Current interactions are numerous in the fields of electronics, even in a single circuit. Principles such as Ohm's law, the Hall effect, or Faraday's law are native to multiple types of circuitries and can be used to an engineer's advantage to develop current measurement methods to use depending on the situation.[56]

3.6.2.1 Resistive sensors:

Resistive sensors are based on ohm's law in order to measure current. This method is simply based on connecting a shunt resistor in series with the load (named sense resistor), the voltage drop is then measured using an ADC. Ohm's law is then used to compute the sensed current utilizing the measured voltage:

$$I = \frac{V_{in}}{R_{sense}} \quad (3.18)$$

These sensors generally use a differential amplifier or a PGA (Programmable Gain Amplifier) to eliminate the common mode noise and to avoid loading the resistor nodes. They are generally more accurate than other types of sensors. Figure 3.6 is the simplest existing topology for a current sensor.

As illustrated in Figure 3.6 this type of sensor tends to use differential amplifiers or Programmable gain amplifiers to eliminate or reduce the inherent voltage noise. These sensors tend to be the most dependable given the simplicity of the design and measurement accuracy.

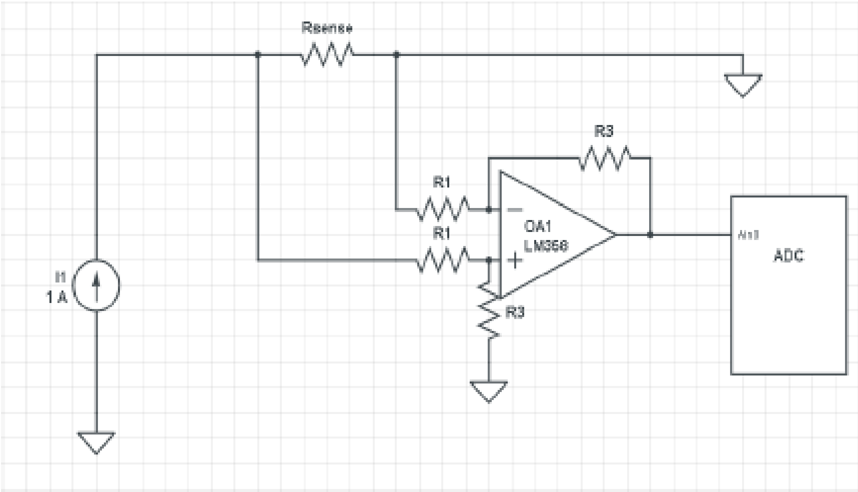


Figure 3.6 Simple current sensing circuit

3.6.2.2 Hall effect sensors:

This method is based on the Hall effect, discovered by Edwin Hall in 1879. Hall effect states that a current passing through a sheet of conductive material called a Hall element, while being subjected to a magnetic flux density, generates a voltage perpendicular to the current and magnetic field. In order to measure the current, we use a magnetic core to direct the magnetic flux perpendicular to the hall element. The Figure 3.7 below depicts the open loop use of the hall effect as a current sensor.

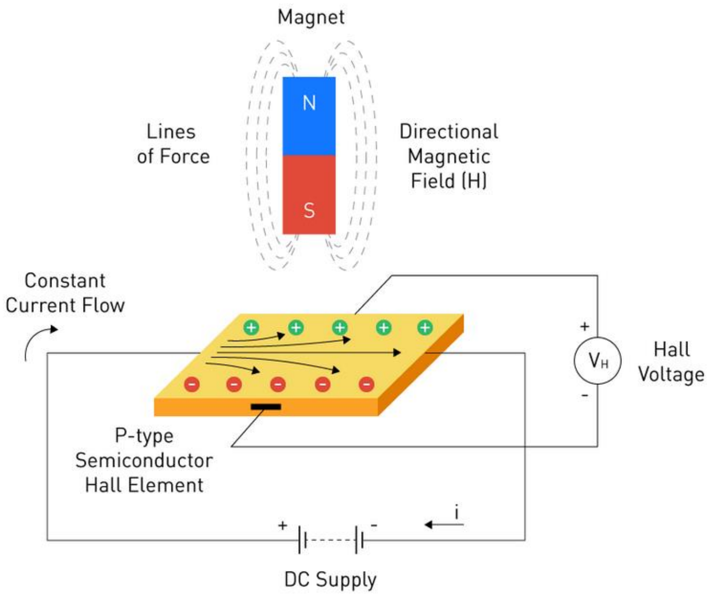


Figure 3.7 Current sensing using hall effect.[57]

While the open loop method of current measurement is accurate to a certain degree, it is subjected to certain limitations such as: a lack of robustness that does not take into consideration the effect of non-linearity, gain errors, temperature, magnetic core saturation. To avoid these issues, we turn to closed loop hall effect sensors that will be developed in the subsequent section.

3.6.2.3 Current transformer:

Current transformers (CTs) are sensors that measure current using Faraday's law of induction:

$$v = -N\frac{d\varphi}{dt} \quad (3.19)$$

Where:

- N is the number of turns.
- φ denotes the magnetic flux.
- v is the generated voltage.

Current transformers differ from one another depending on the associated circuitry. For instance, certain current transformers are described as "DC capable". A "DC capable" current transformer is one that can measure DC and low-frequency AC current. An example of that is the closed loop Hall effect sensors that use primary and a secondary winding to measure current.

As illustrated in Figure 3.8 below, the primary current I_P flows through the wire (or hall element), generating a magnetic flux in the core. The Hall effect sensor detects this magnetic field and produces a voltage, which is then amplified to drive a current through the secondary winding (the wound coil). This secondary current generates a flux that opposes and nullifies the flux caused by the primary current. Consequently, an attenuated replica of the primary current is produced in the secondary winding I_S flowing through R_S [60][61] . This configuration is sometimes referred to as the Zero-Flux CT [61].

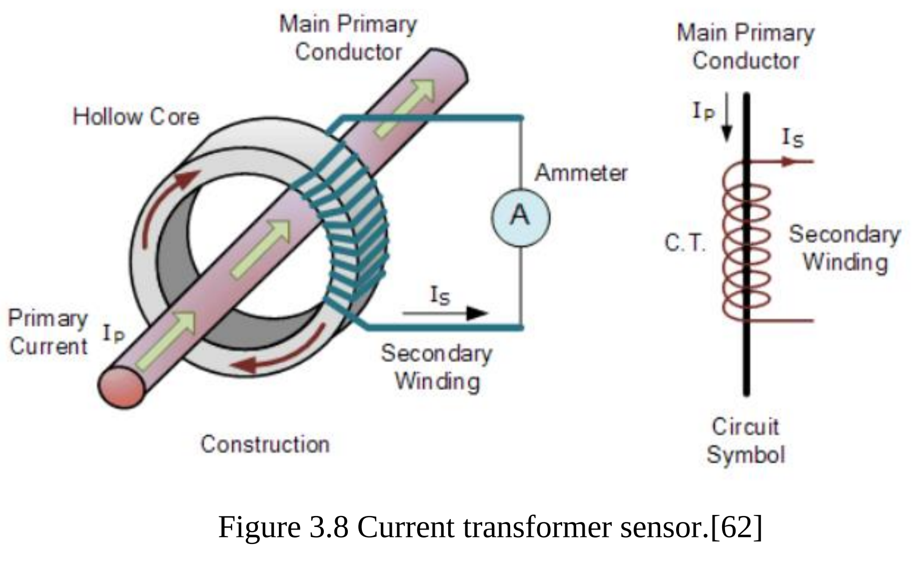


Figure 3.8 Current transformer sensor.[62]

The primary advantage of this design is its capability to measure currents with both AC and DC components without core saturation and more sensor robustness to outside effects such as voltage noise and temperature thanks to the processing circuit that follows the primary winding as shown in Figure 3.9. This enables the accurate measurement of AC, DC, and varying DC currents with high precision.

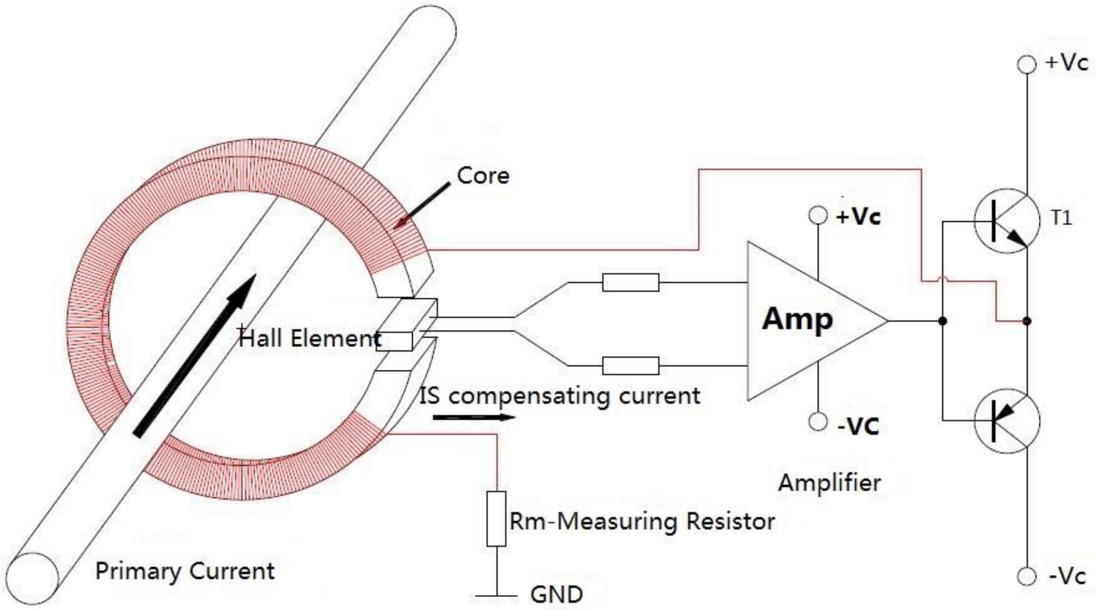


Figure 3.9 Closed loop hall effect sensor using current transformer.

3.7 Conclusion:

This chapter featured an in-depth study of concept related to batteries. Additionally, it covered various methods to compute some of these concepts, especially the SOC, and the limitations that such computations would arise.

The following chapter will focus on the design of a circuit capable of incorporating battery monitoring in an IoT integrated system, paired with simulation and results.

4 Chapter 4: Design and simulation of battery monitoring system.

4.1 Introduction:

This chapter utilizes elements introduced in previous chapters to design and simulate an IoT-based battery monitoring system. This system integrated data acquisition via sensors, wireless data transmission, and real-time data display to ensure the optimal data acquisition system. A comparative analysis of available components will be done to determine the most affordable and easy to implement design for such a purpose. Finally, we verify the effectiveness of the designed system through various simulation tests.

4.2 Experimental specifications:

4.2.1 Battery related specifications:

The experimental results relative to this study have been conducted using equipment following the listed specifications:

- The utilized battery is a 12V Lead-acid battery with a rated capacity C_{rated}=7Ah.
- The maximum current drawn from the used battery is I=50A.
- Current and voltage measurements were conducted with an ANENG8009 multi-meter with a ± 1% voltage error and a ± 2% current measurement error.
- The established design allows a maximum measurement error of 3% and 2% for voltage and current respectively.

4.2.2 Voltage measurement specifications:

While devising this circuit, ADC (Analog to Digital converters) related issues were noticed, issues such as noise or lack of accuracy that could prove problematic. Voltage measurement is an essential part of battery monitoring and battery data acquisition in general. As such, this design took into consideration two possible pieces of hardware in order to attain a maximum accuracy. The following subsections will be a comparative study of the internal ADCs of the ESP-WROOM-32 and the Arduino Uno.

4.2.2.1 Noise Tolerance Comparison:

In order to identify the robustness to noise of each ADC, we compare the provided graphs of each microcontroller. The Arduino IDE was used to plot 200 serial samples, where the x-axis is the number of the serial samples and the y-axis is the ADC output in digits (meaning the ADC output bits were converted into decimal and shown as output). Since this comparison only takes into consideration the shape of each plot and not actual computational data, the graphs have been scaled down to ensure a clearer read.

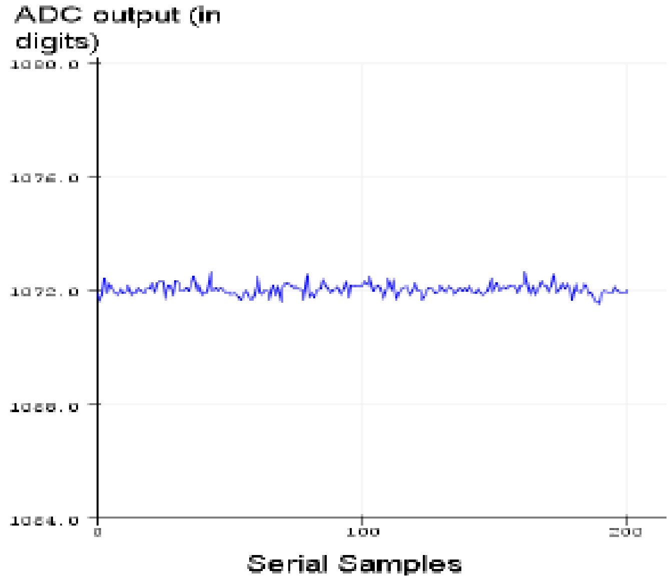


Figure 4.1 Noise graph of the ESP32 ADC.

Ideally, the output of an ADC is to be linear; however, in this case, we notice non-negligeable fluctuations. The ADCs of the ESP32 are thus non-linear in nature.

In the graph below, the non-linearities at the lower and upper ends of the input voltage are clearly visible.

The graph in Figure 4.2 clearly showcases the non-linear behavior of the ADCs from 2.5V to 3.3V.

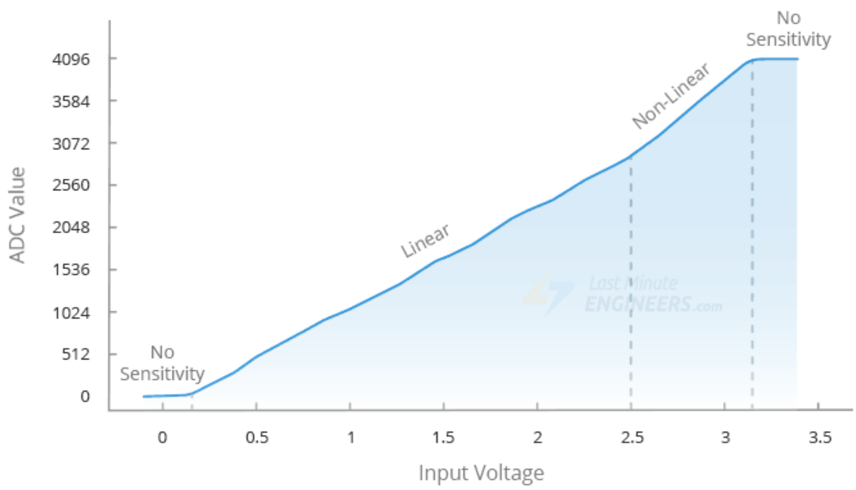


Figure 4.2 ADC accuracy related to input voltage in ESP32. [63]

The output ADC value of the ranges [3.2-3.3] V and [0-0.13] V are fixed at (4095) and (0) respectively. In short, this means the ADC does not distinguish the voltage values in those intervals, which betrays a lack of accuracy. [63]

Figure 4.3 below shows the response of the ESP32 ADC to a larger number of samples. The same noise can be observed; however, these noises can be attenuated using a capacitor at the output of the ADC. [63]

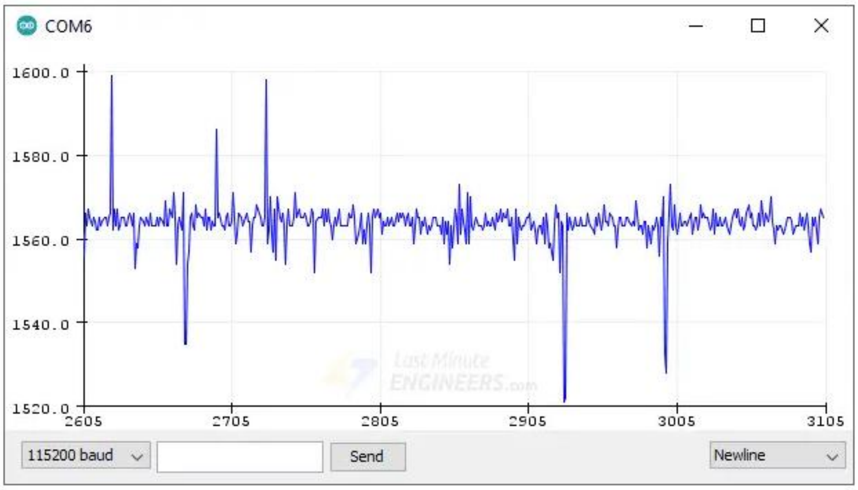


Figure 4.3 ESP32 ADC sensitivity.

While for the Arduino ADCs, using the same sampling method, we obtain the graph in Figure 4.4:

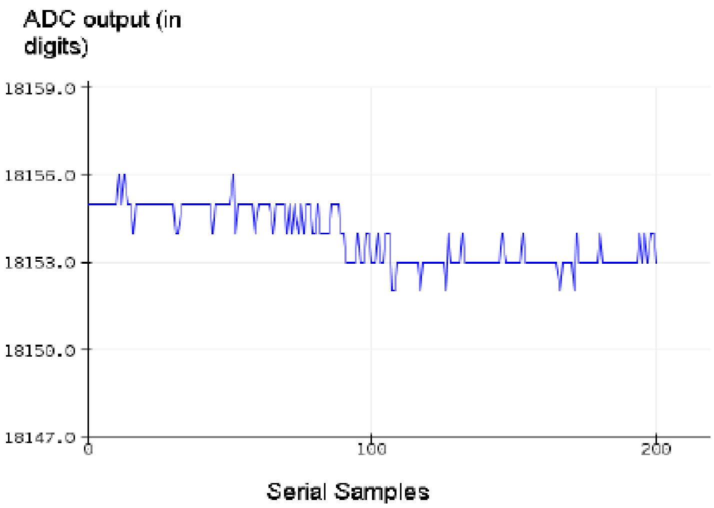


Figure 4.4 Arduino ADC noise sensitivity.

The Arduino's ADC has a surprisingly good noise tolerance.

4.2.2.2 ADC Linearity Comparison:

The second criteria to be examined is an ADC's linearity. In order to examine the linearity of each ADC, a method was devised: A potentiometer is used to record the entire range of the ADC. Measurements are taken each 100 mV and graphed as shown in Figure 4.5. The x axis denotes the actual measured voltage while the y axis denotes the ADC output.

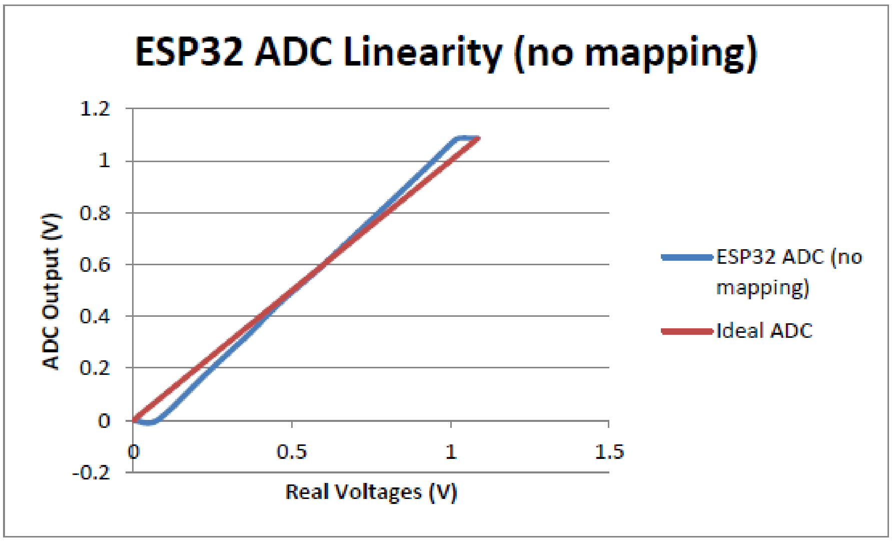


Figure 4.5 ESP32 ADC curve (no mapping).

A red line was incorporated to represent the theoretical model of an ideally linear ADC. Analyzing Figure 4.5 demonstrates the non-linearity of the ESP32's ADC at the edges of the measurement range, such ADC linearity is considered non-viable. Espressif system has devised a plan to mitigate the ADC non-linearity using a calibration software, this software is commonly known as application programming interface (API) and called esp_adc_cal. The effect of this API can be noticed in the graph in Figure 4.6.

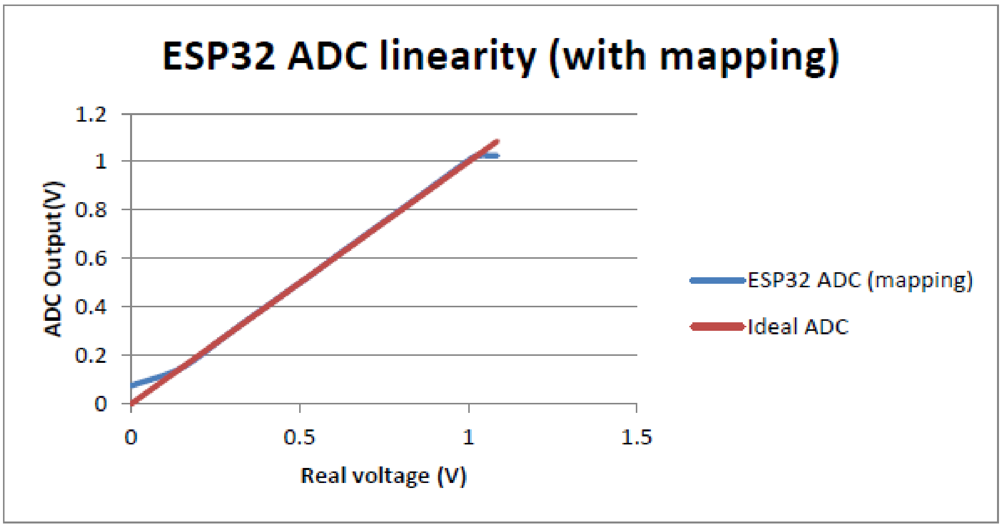


Figure 4.6 ESP32 ADC output curve (with mapping).

Concerning the Arduino, 4.2.2.1 established that ADCs have a greater noise robustness; however, the ADC linearity is far from ideal. There is no internal or integrated way to deal with the ADC's linearity, in this case, two methods are exposed.

Using an external ADC: By utilizing the SPI or I2C interface, connect an external ADC with an adequate resolution depending on the needs of the circuit.

Oversampling: Instead of using an ADC of higher resolution, it can be virtually augmented via oversampling. It involves multiple readings of a same input and averaging them for a more accurate result. The Arduino IDE can be used to achieve oversampling using the analongRead() command. The Figure 4.7 shows the ADC output when oversampling is used.

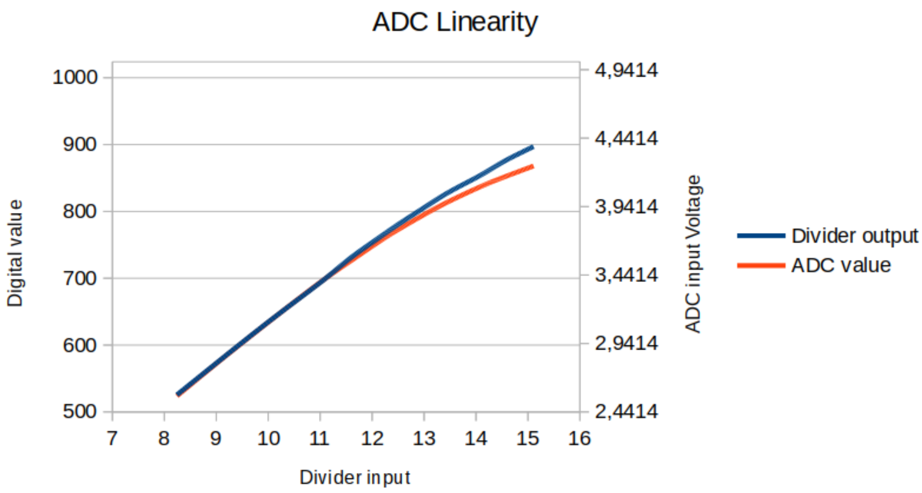


Figure 4.7 Arduino ADC output.

In conclusion, while the ADC linearity of the Arduino board can be enhanced to meet greater standards, the ESP32's ADC is a better alternative given the in-built calibrating API.

4.2.2.3 Comparison conclusion:

After comparing the characteristics of the ADCs of each MCU, we conclude that even if the ADCs of an Arduino microcontroller are more adequate for a voltage measurement circuit, this added value is not enough to surpass the in-built features of the ESP32 such as WiFi and Bluetooth availability.

4.2.2.4 Voltage divider:

The main factor to be considered concerning the voltage measurement circuit (voltage divider) is the attenuation factor. The attenuation factor is the factor by which the input voltage is scaled in order to be comprised within the ADC's range to maximize the accuracy. Using an attenuation factor of 40 to measure the battery voltage (V_{Bat}).

The attenuation factor was also chosen to bias the signal into the middle of the ADC's range, in order to increase the conversion accuracy since the ADC's linearity is quasi-ideal near the middle. The resulting quantization error is $\pm$0.01V with a 12 bits resolution and a reference voltage of 1.1V leads to an error of ± 5.36 mV, which is acceptable. For the desired design we use a 10KΩ resistor in series with 260Ω resistors to obtain the necessary attenuation factor V_{BAT}.

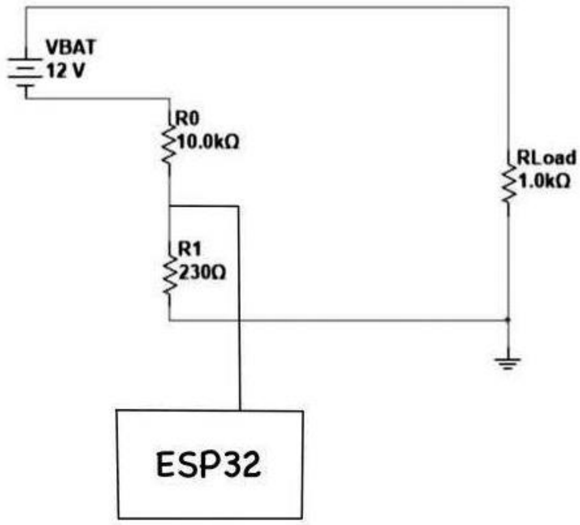


Figure 4.8 Voltage measurement circuit.

4.2.3 Microcontroller and cloud choice:

As specified in chapter 2, IoT technology requires the transfer of the targeted data to a cloud server. In this case, acquired (measured) data such as: voltage or current; is to be uploaded to an online cloud. This operation necessitates the choice of a micro controller, with in-built or external wireless access and a cloud server platform.

The chosen microcontroller is the ESP32-WROOM after the comparison in 4.2.2.3 , made by Espressif systems with a dual Wi-Fi and Bluetooth access.

Concerning the cloud platform, two platforms were chosen: Thingspeak and Blynk. Thingspeak is specified in real time plotting and cloud stored data display. Blynk offers a more interactive display of data and specializes in mobile phone usage.

4.2.4 Current Measurement specifications:

As seen in 3.4, SOC estimation heavily relies on an accurate measurement in the case of coulomb counting. The selection of the most viable current measurement option was done by rigorous testing.

The first type of current sensor tested was the current sensor in Figure 4.9. It operates based on Ohm’s law by connecting a shunt resistor in series with load. The voltage measured across this resistance is then proportional to the current. It can be measured using various methods such as operational amplifiers or differential amplifiers.

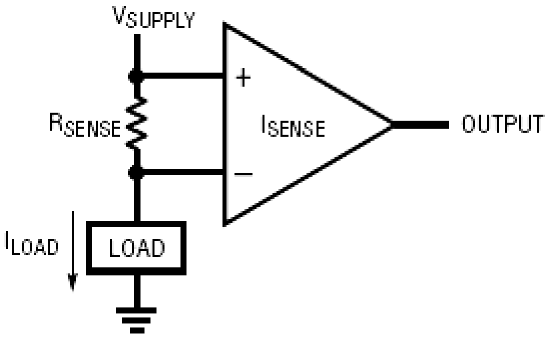


Figure 4.9 Shunt resistor current sensor.[64]

The testing of this measurement method is to measure the output voltage of the grounded load compared to the amplifier's input and make sure of a linear relationship. Despite the low cost compared to other devices but the computable current ranges from very low to medium is the drawback.

Selecting a current sensor is not limited to knowing the theoretical accuracy. The advantage and disadvantages of each option should be taken thoroughly into consideration with experimental confirmation of announced data are necessary steps. Given the bidirectional nature of a battery's operation (charge and discharge) the chosen sensor has to be bidirectional as well.

4.2.4.1 LA 100P current sensor:

The LA 100P is a Hall effect compensated DC current transformer, with a theoretical error ±0.45% under ideal conditions (±15V supply, T=25C°). Its advantages are:

- It is galvanically isolated from the load line. (The wire goes inside the loop without having to place the sensor in series with the load).
  Its disadvantages are:
- The need for an analog to digital conversion stage (ADC) in order to interpret the output.
- The need for a conditioning circuit. A sense resistor of 20 ohms needs to be placed on its output in order to convert the current into voltage which further increases error.
- Its high accuracy is highly subject to variation in temperature and supply voltage. It is required to implement a magnetic offset canceling mechanism before the measurements.
- It is the most expensive option of the three solutions.

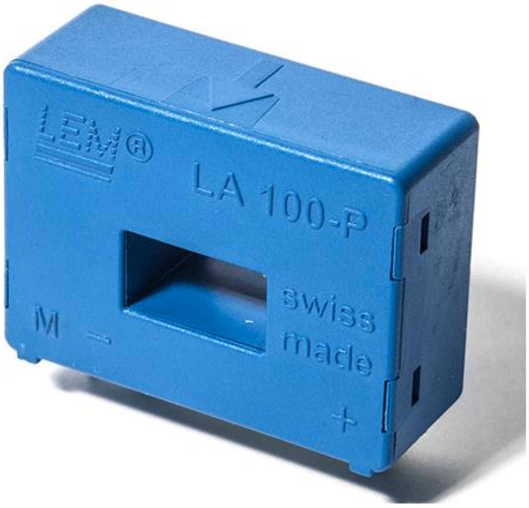


Figure 4.10 LA100P current sensor.

4.2.4.2 ACS712 current sensor:

The ACS712 is a bidirectional Hall effect sensor. It is advertised to have a total error of ±1.2%. Its only advantage compared to its other counterparts is the ability to be placed on the high side. Its disadvantages include but are not limited to:

- Its error is likely to increase with other parameter variations such as temperature.

Despite being a Hall effect sensor, the ACS712 needs to be placed in series with the load: That is because it does not have an incorporated magnetic core to direct the magnetic flux into the Hall effect sensor as we have seen in Figure 3.8, but instead, a current conductor of 100 micro-ohms and a magnetic concentrator as shown in Figure 4.11:

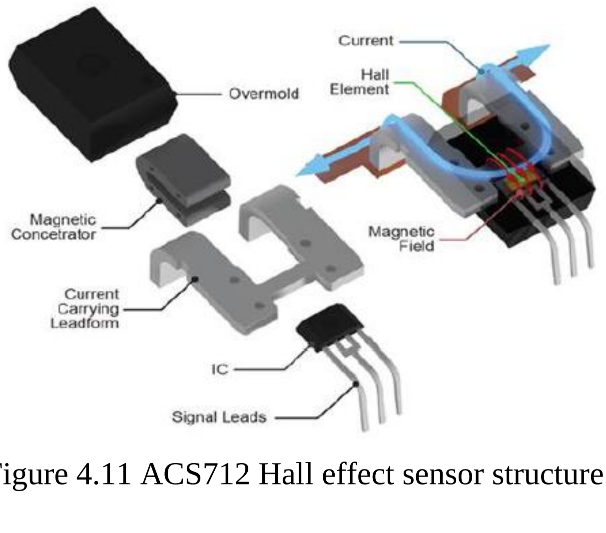


Figure 4.11 ACS712 Hall effect sensor structure.

The reason behind using magnetic concentrators over magnetic cores is being able to shrink the sensor's size for high-density PCB design. This also makes the sensor cheaper since high current ferrite cores are expensive.

We used the circuit in Figure 4.12 for testing the current accuracy for all the sensors, after determining the best sensor through our results, we keep the same circuit and used that sensor for providing feedback to the active load while doing our voltage measurement tests.

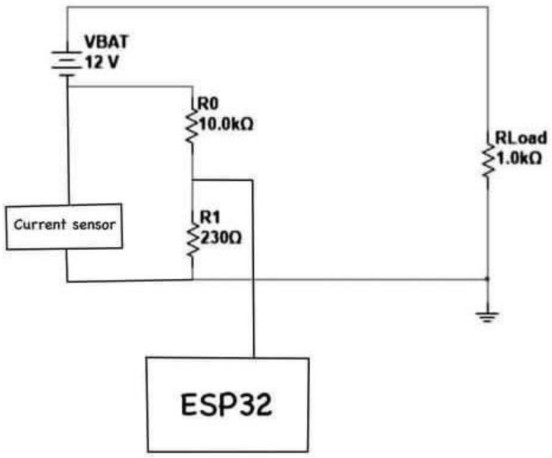


Figure 4.12 Overall circuit for current sensor testing.

4.2.5 Temperature measurement specifications:

Temperature is an essential data set when it comes to battery monitoring systems, as such, an efficient and affordable sensor that is compatible with the used MCU is necessary. The most known and used sensor LM35, cheap and easy to integrate with an ESP32 microcontroller.

4.2.5.1 LM35 temperature sensor:

LM35 is an integrated analog temperature sensor as shown in Figure 4.13 whose electrical output is proportional to Degree Centigrade temperature. LM35 Sensor does not require any external calibration or trimming to provide typical accuracies. The LM35’s low output impedance, linear output, and precise inherent calibration make interfacing to readout or control circuitry especially easy.

The most important advantage of the LM35 temperature sensor is its linearity. For instance, for a gain of 10mv/°C with a measured temperature of 22°C, the resulting output is 220mV.

Figure 4.14 below represents a circuit diagram to explain the connecting of each pin.

Figure 4.13 LM35 temperature sensor.[66]

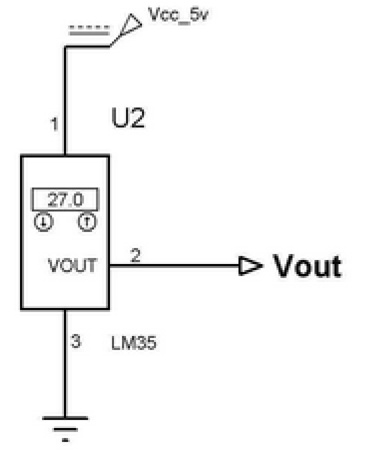


Figure 4.14 LM35 circuit integration. [66]

4.2.6 Software specifications:

4.2.6.1 Proteus:

Proteus 8 professional was utilized to perform a simulation of the designed circuit, verify the calibration of sensor and assure the correct connectivity of the circuit. The main interface of the software is shown in Figure 4.15.

Proteus 8 professional is a software package used to design and simulate circuits. Its main advantages are: The availability of a PCB layout module and real time simulation. However, the features that separate it from other simulation software such as LTspice or Multisim is the possibility of microcontroller simulation and IoT related implementation.

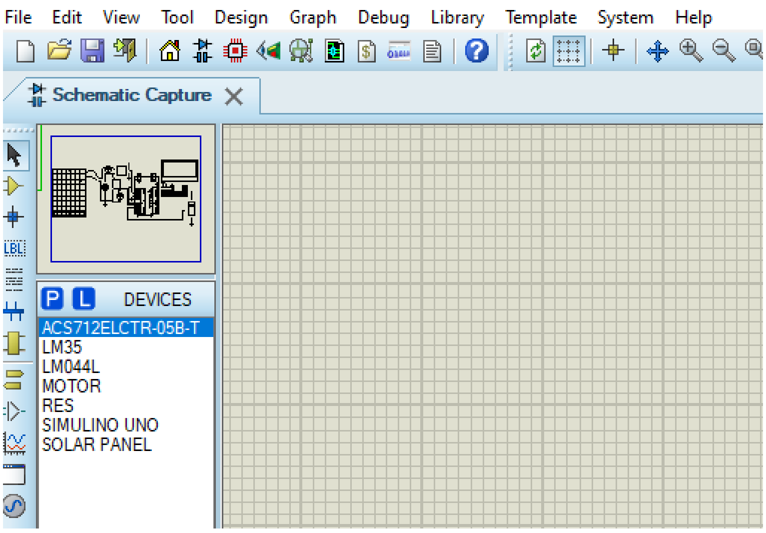


Figure 4.15 Proteus main interface.

4.3 SOC estimation:

The estimation of the SOC of a battery is one of the most consequent parts of this project, thus, we will establish a comparison and a verification of computational and measurement methods in order to attain an accurate SOC measurement.

We will use as a reliable source of comparison, the discharge curve presented in

Appendix A: 6FM7 (12V7Ah) battery. Based on the used current, the curve serves as a reliable reference to assess the accuracy of each method.

4.3.1 OCV practical method:

The first method is a practical bookkeeping of the SOC of the used battery. The measurement methodology used is that of the OCV method: Disconnect the battery to achieve electrochemical balance, measure the OCV, map the measured OCV to identify the corresponding SOC. The experimental measurements were done under supervision of [67], resulting in the Table 4-1 below:

Table 4-1 Battery SOC estimation results.[67]

SOC	Voltage
100	13.12
95	12.85
90	12.76
85	12.71
80	12.68
75	12.62
70	12.56
65	12.51
60	12.46
55	12.42
50	12.36
45	12.29
40	12.24
35	12.18
30	12.11
25	12.04
20	11.97
15	11.9
10	11.86
5	11.74
1	11.66

This experiment was done with a load of 12Ω, using Ohm's law the current generated is on an average of 1.083A. By using the discharge plots for I=0.17C, we notice that the final values (maximum and minimum) are nearly the same, however the behavior of the plot is different. In the discharge curve, a noticeable amount of time is noticed before the decrease in voltage while the decrease is relatively in the experiment. Such errors are an inherent part of the OCV given the number of consecutive measurement and the impossibility of confirming electrochemical stability. These results, are however still considerably close and could be used in a project.

4.3.2 Coulomb counting Simulink simulation:

The Coulomb counting is difficult to implement without designing a specific algorithm. In this case, we strived to establish a Simulink model capable of computing the SOC of various battery types, to that end, we used the battery model provided by Simscape. As shown in Figure 4.16, the battery module offers numerous modulable parameters such as:

- Battery type: Four types are available (Lead-Acid, Lithium-Ion, Nickel-Cadmium, and Nickel-metal-Hydride)
- Rated capacity.
- Rated voltage.
- Initial SOC.
- Discharge parameters (Full charge terminal voltage, nominal discharge current, internal resistance)

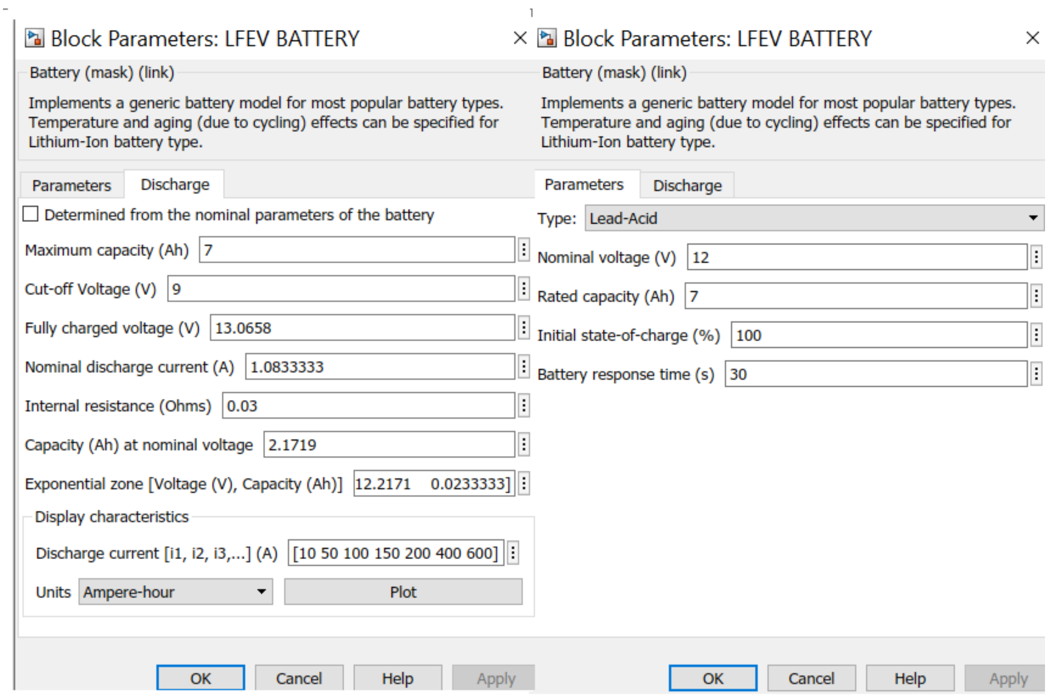


Figure 4.16 Simulink battery module characteristics.

The battery model allows the plotting of a discharge curve as well, the derived discharge curve is shown in Figure 4.17.

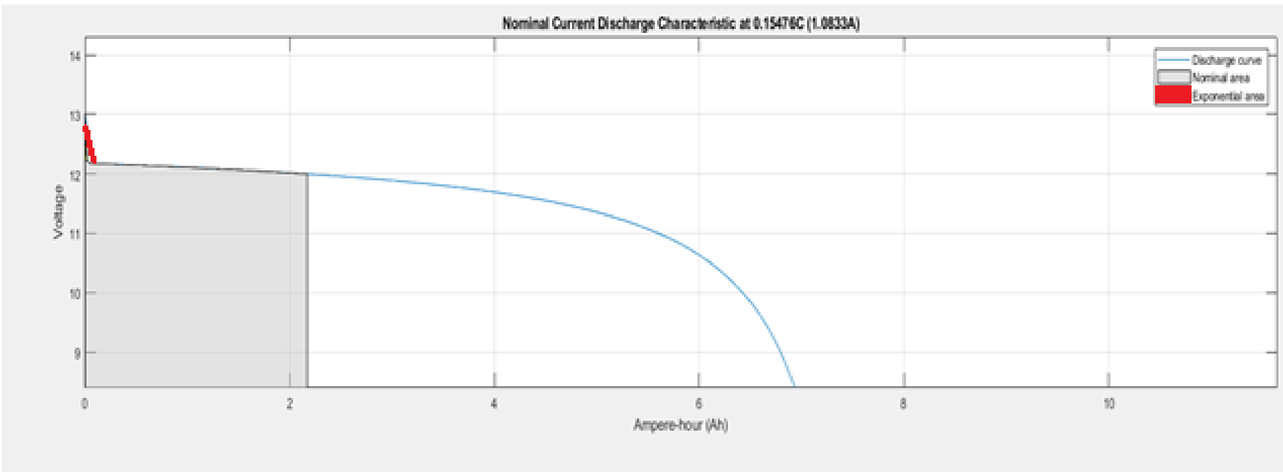


Figure 4.17 Battery discharge curve using Simulink.

We immediately notice that the battery discharge curve generated by Simulink nearly perfectly resembles the provided discharge curve for a similar current, the battery discharge time and voltage behavior are nearly identical. Figure 4.18 shows the developed Simulink model.

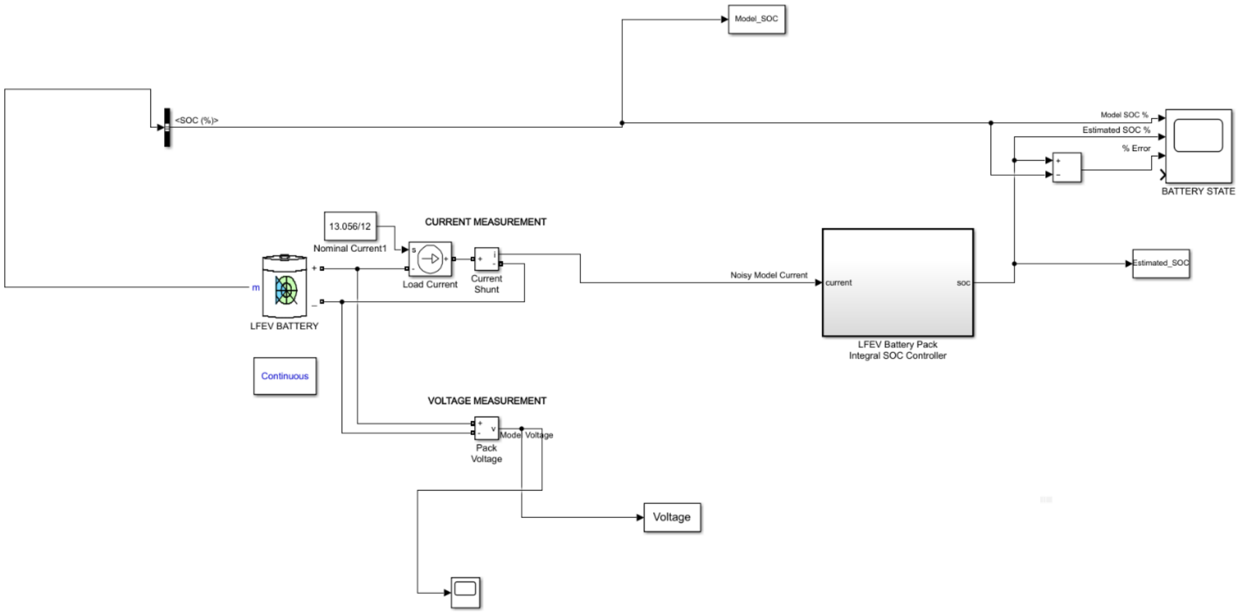


Figure 4.18 Coulomb counting Simulink model.

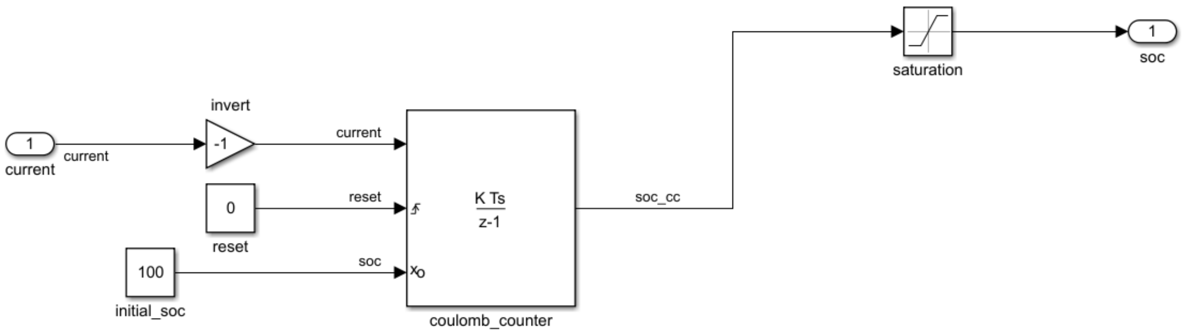


Figure 4.19 SOC integral block.

In order to affirm the effectiveness of the coulomb counting algorithm, we will use two methods: Comparing it with the SOC provided by the model and comparing the voltage to the discharge curve.

The simulation results to the Simulink program are shown in Figure 4.20 and Figure 4.21.

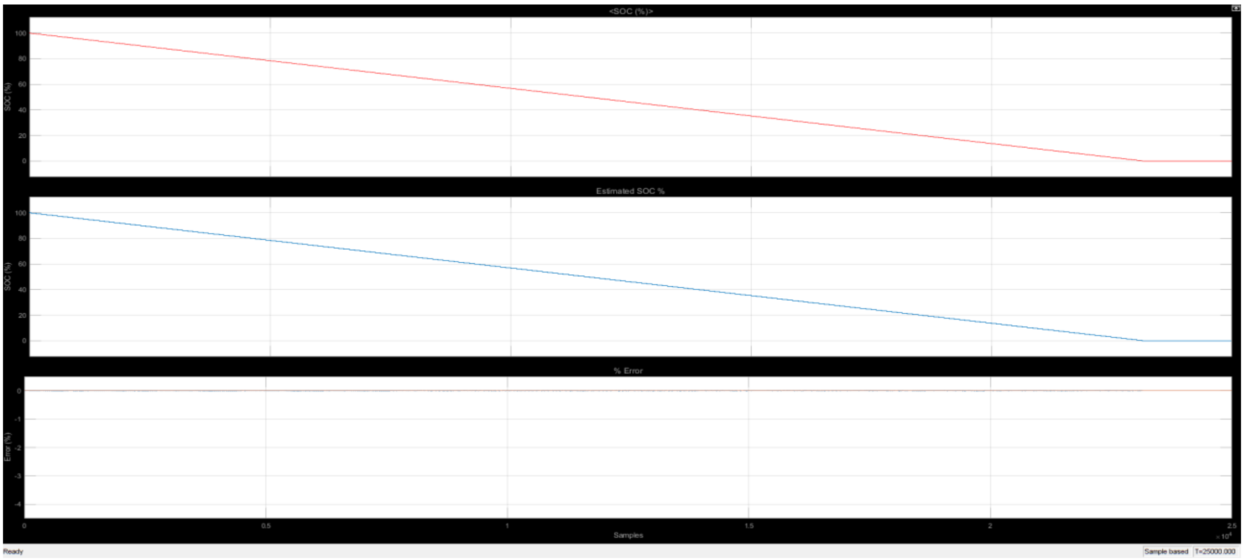


Figure 4.20 SOC estimation Simulink result.

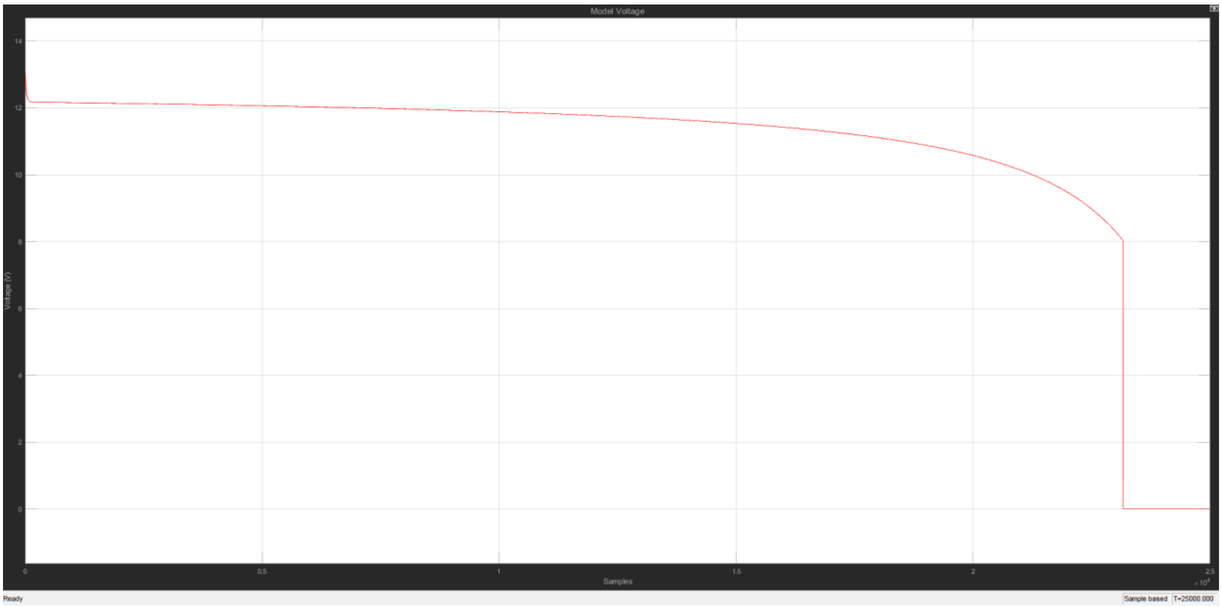


Figure 4.21Voltage Simulink measurement.

Based on Figure 4.20, we notice an extremely low error in the SOC estimation compared to the model SOC (quasi inexistant). Figure 4.21 demonstrates a way more accurate behavior of the battery voltage than the OCV method when compared to the discharge curves.

4.3.3 OCV and coulomb counting comparison:

The comparison between each method extends to the following bullet points:

- While the coulomb counting poses the issue of needing the initial SOC to allow computations, the initial SOC is still easily obtainable if the battery has been completely charged or depleted prior.
- The developed coulomb counting algorithm can adapt to numerous batteries provided the rated conditions of the battery are known, which are wildly available nowadays.

- The coulomb counting method is more practically possible, since it does not necessitate totally disconnecting the battery for long periods of time.
- The OCV method shows no adaptability, a change in loads implies a change of nominal current, which means a change in any derived polynomial.

In conclusion, the devised program is an appropriate replacement to the robustness and flexibility lacking the OCV method exhibits.

The Table 4-2 below is a comparison between the resulting state of charges and voltages:

Table 4-2 SOC estimation comparison methods.

SOC(%)	Coulomb counting voltage (V)	OCV voltage (V)	Error (%)
100	13,0658	13,12	0,41482343
95,000381	12,155503	12,85	5,71343919
90,009397	12,131906	12,76	5,17720437
85,009778	12,10581	12,71	4,99091265
80,001524	12,076793	12,68	4,99476315
75,001905	12,044455	12,62	4,77850413
70,002286	12,008126	12,56	4,59584012
65,002667	11,967017	12,51	4,53733299
60,007365	11,920161	12,46	4,52878517
55,007746	11,866165	12,42	4,66734679
50,00381	11,80326	12,36	4,71683599
45,00419	11,729182	12,29	4,78139057
40,008889	11,640666	12,24	5,14862489
35,00927	11,532827	12,18	5,61156892
30,009651	11,398695	12,11	6,24022953
25,001397	11,22698	12,04	7,2416608
20,006095	11,000452	11,97	8,81371344
15,006476	10,686592	11,9	11,3544918
10,00254	10,22284	11,86	16,014732
5,0029206	9,4698424	11,74	23,9724955
0,0033016	8,0325599	11,66	45,1592037

In the voltage range [11-13] V we remark a very low error between the two measurement methods used, however, the coulomb counting method accounts for a voltage range not attained by the battery in an experimental setting. This can be mainly due to not enough waiting time before attaining electrochemical stability or simply to a reduced DOD due to battery aging.

4.4 Final circuit design and simulation:

4.4.1 Circuit block diagram:

The designed system is summarized in the block diagram of Figure 4.22. The main objectives of this system are monitoring battery characteristics such as voltage, current, and temperature and providing an accurate SOC estimation. The data is acquired using sensors and processed using the ESP32 microcontroller. The data is then displayed and monitored using the Blynk IoT platform.

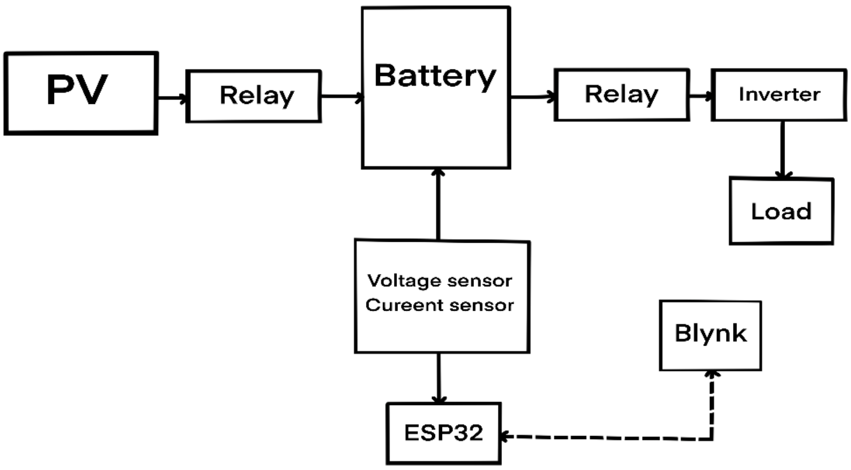


Figure 4.22 System block diagram.

4.4.2 Circuit simulation:

The circuit is constructed on the Proteus software as demonstrated in Figure 4.23.

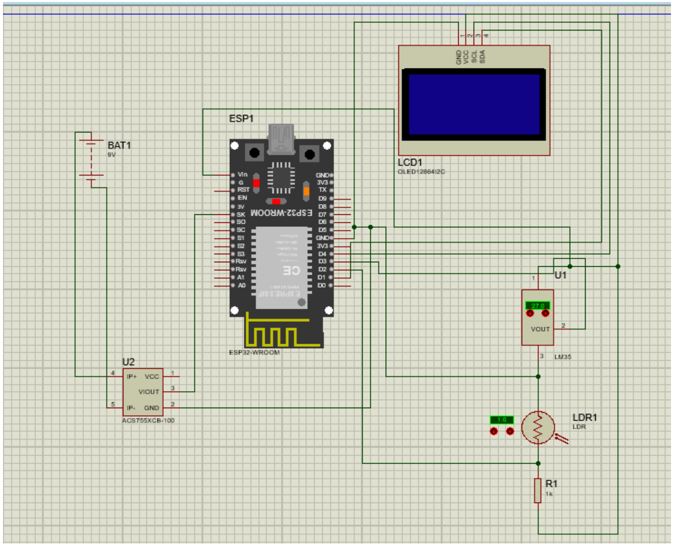


Figure 4.23 Proteus sim circuit.

The generation system consists of a modeled 12V acid-lead battery model. Arduino IDE was used to develop the required code for the ESP32. The full discharge simulation results are depicted in Figure 4.24.

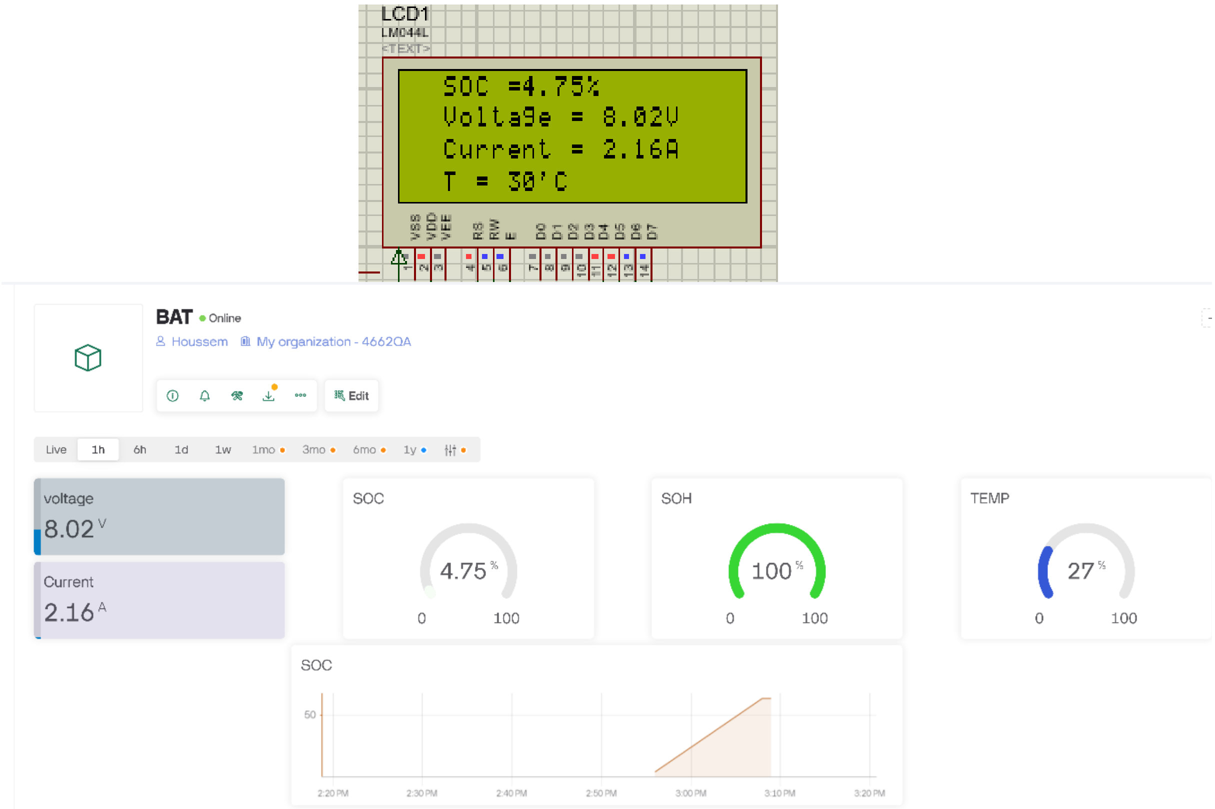


Figure 4.24 Battery data measurements using Proteus.

Then we used an Arduino board to verify the SOC and current parameters, but this time connected to load(DC motor) with a nominal voltage of 12V and a load resistance of 40Ω)And we got the following results:

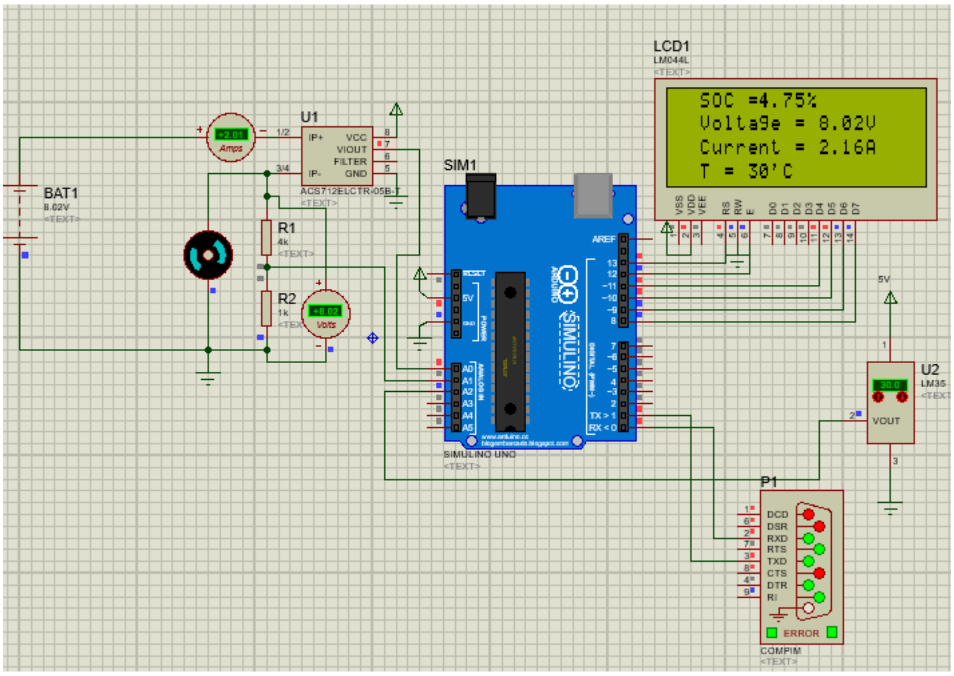


Figure 4.25 IoT battery monitoring simulation using Proteus.

The SOC here was determined using the polynomial (4.1):

$$SOC(v) = -3.1890845596v^5 + 168.0985078780v^4 - 3519.8341801527v^3 + 036598.0233201704v^2 - 188942.8890455419v^1 + 387400.3748664637v^0 \quad (4.1)$$

Where:

- v is the battery voltage.

Remark:

This equation is only viable in the case of this battery's application for pre-set appliances. This equation was developed using a set of measured voltage and current values following the charge and discharge patterns of the specifically used battery in a specific set of conditions. Other polynomials can be developed using the same method (coulomb counting followed by interpolation).

The simulation results for a different set of values are shown in Figure 4.26 then transmitted to an IoT platform as shown in Figure 4.27 below.

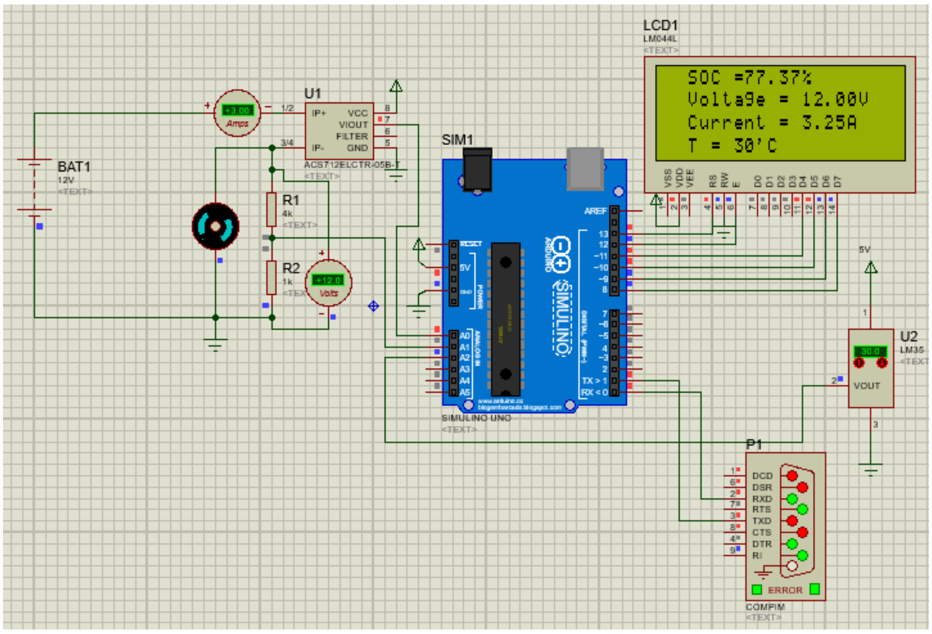


Figure 4.26 Simulation of battery monitoring circuit for V=12V.

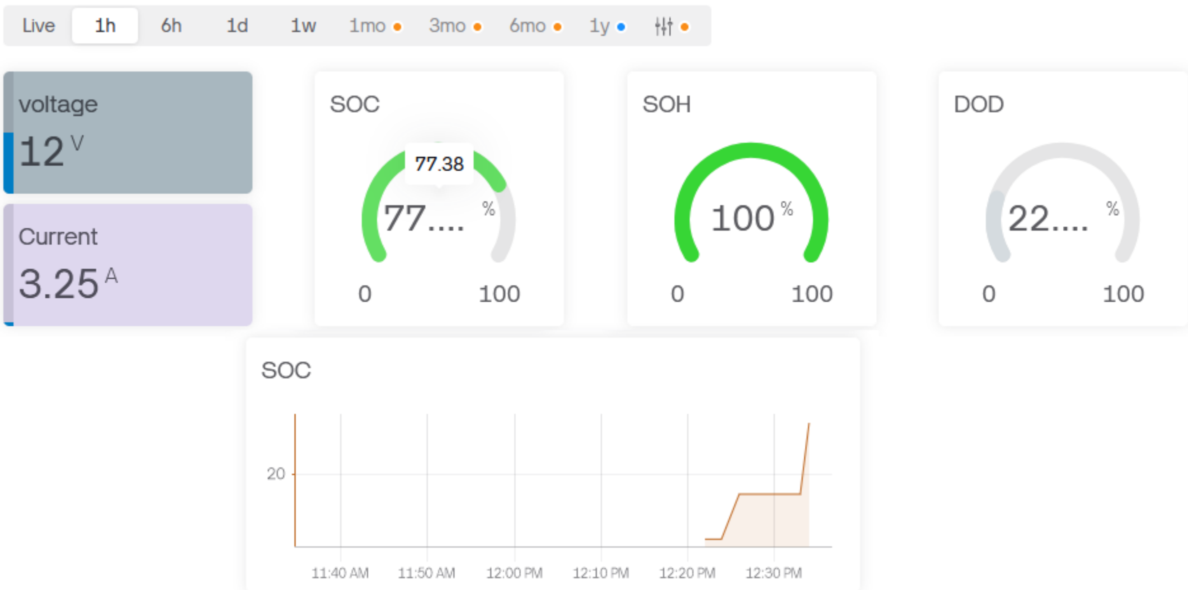


Figure 4.27 IoT data monitoring including additional battery parameters.

4.5 Conclusion:

The design and simulation of the IoT-based battery monitoring system have demonstrated significant potential in enhancing battery management. Our system effectively monitors battery health, and optimizes usage through real-time data analysis. The simulation results validate the system's capability to maintain battery performance and extend its lifespan.

General conclusion

This master project addresses the research problem of monitoring battery parameters using IoT to optimize microgrid efficiency. The main goal is the acquisition, wireless display, and monitoring of measured data such as voltage, current, and temperature. This data will be utilized to compute the State of Charge (SOC) of a battery. The project aims to explore various methods of modernizing the components and infrastructures of microgrids and smart grids using IoT, and to demonstrate the efficiency of such implementations by simulating a battery monitoring system.

This project provides an overview of modern grid systems, highlighting the benefits and limitations of each type and the reasoning behind modernizing power grid systems. It emphasizes the importance of reducing the impact and high usage of fossil fuels as primary energy sources.

The research phase is essential to deconstruct the traditional methods of data acquisition. Additionally, it focuses on systems that would benefit the most from such implementation, i.e., smart grids and microgrids, allowing better insight into the aspects to target while developing the project.

The simulation part of this report is crucial as it provides a clear understanding of the objectives to be attained. This would not be possible without a thorough investigation of the mathematical laws and models that govern a battery energy system. Understanding characteristics such as rated capacity, SOC, Depth of Discharge (DOD), and efficiency served as a guide to limit the project's scope. Simulating the designed circuit with a functioning IoT data acquisition scheme confirms our intended objectives.

While this project represents a significant step toward simplifying access to power grids for any user, it serves as a foundation for future work that would greatly benefit from IoT technology in power engineering. However, we cannot unsee the limitations of this project, such as a need to developing a new polynomial for each new system or associated load.

Our future work will focus on extending the technology used in this project to various elements of a microgrid, such as solar panels and generation substations. Additionally, we aim to enhance the IoT interface to set the stage for the ever-evolving world of power grid systems, which will become increasingly essential as humanity advances.

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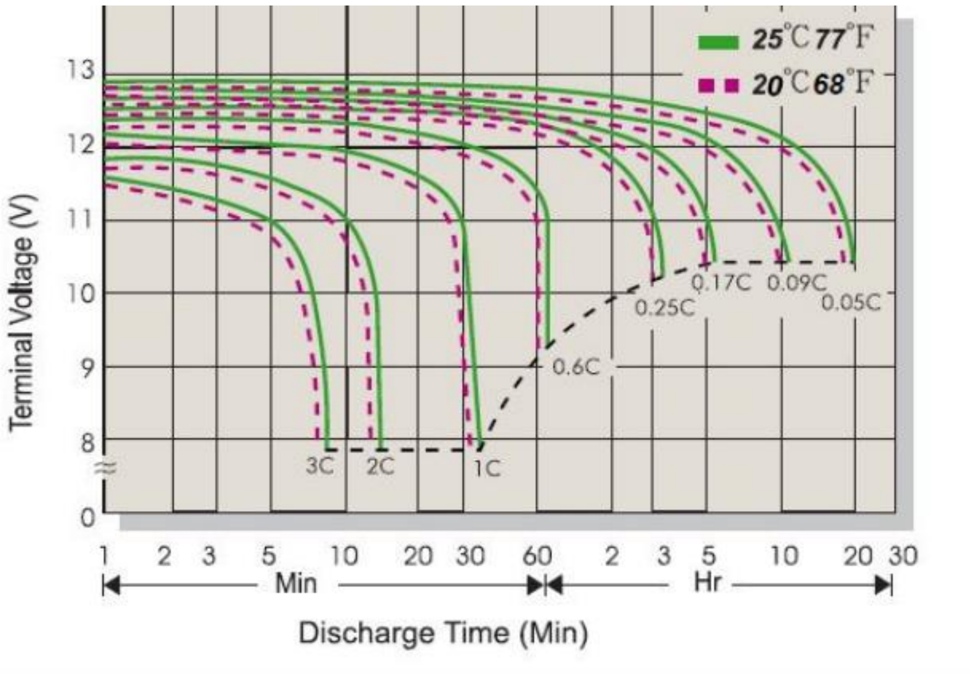
Appendix A: 6FM7 (12V7Ah) battery

6FM7 is a general-purpose battery up to 5 years in star service or more than 260 cycles at 100% discharge in cycle service. As with all LONGWAY® batteries, all are rechargeable highly efficient, leak proof and maintenance free.

Battery specifications:

Cells per Unit 6	6
Normal Voltage	12V
Capacity	7Ah@20Hr-rate to 1.75V per cell@25℃
Weight	Approx.(2.00±3%)kg (4.41lbs)
Maximum Discharge Current	70A(5sec)
Internal Resistance	Approx. 30mΩ full charged @25℃
Operating Temperature Range	Discharge: -20℃~60℃ Charge: 0℃~50℃ Storage: -20℃~60℃
Nominal Operating Temperature Range	25℃±3℃
Float Charging Voltage	13.7~13.9VDC/unit Average @25℃
Maximum Charging Current	2.1A
Equalization and Cycle Service	14.4V~15.0VDC/unit Average @ 25℃
Self Discharge	Valve Regulated Lead Acid (VRLA) batteries can be stored for more than 6 months at 25℃. Self-discharge ratio less than 3% per month at 25℃. Please charge batteries before using.
Terminal	F1(0.187)/F2(0.250)
Container Material	ABS(UL94-HB) *Flammability resistance of (UL94-V0) can be available upon request

Discharge characteristics:



Final Discharge Voltage (V)	1.75	1.70	1.65	1.60
Discharge current I (C)	I<0.2C	0.2<I<0.5	0.5<I<1.0	I>1.0

Appendix B ESP32 microcontroller:

ESP32 Microcontroller overview:

- ESP32 chip:

As provided by the IoT integration architecture in 2.7, MCUs are a necessary part of implementing IoT technologies. While modern engineering offers an impressive set of possible MCUs, for the sake of satisfying economical and energy requirements of this thesis, the ESP32 has been chosen.

The ESP32 is a versatile MCU created by Espressif, it benefits from affordable prices and low-power consumption. While it has various uses such as: Embedded systems, data logging and analysis, and security systems, we will focus on the IoT applications of the ESP32.

- ESP32-WROOM module:

This module uses ESP32-D0WD-V3 as its chip and exhibits the features stated in the table below:

Feature	Details
CPU and OnChip Memory	• ESP32-D0WD-V3, Xtensa dual-core 32-bit LX6 microprocessor, up to 240 MHz • 448 KB ROM • 520 KB SRAM • 16 KB SRAM in RTC • ESP32-D0WDR2-V3 also provides 2 MB PSRAM
Integrated Components on Module	• 40 MHz crystal oscillator • 4/8/16 MB SPI flash
Antenna Options	• ESP32-WROOM-32E: On-board PCB antenna • ESP32-WROOM-32UE: external antenna via a connector
WiFi	• 802.11b/g/n

	• Bit rate: 802.11n up to 150 Mbps • A-MPDU and A-MSDU aggregation • 0.4 µs guard interval support • Center frequency range of operating channel: 2412 ~ 2484 MHz
Bluetooth	• Bluetooth V4.2 BR/EDR and Bluetooth LE specification • Class-1, class-2 and class-3 transmitter • AFH • CVSD and SBC
Operating Conditions	• Operating voltage/Power supply: 3.0 ~ 3.6 V • Operating ambient temperature: - 85 °C version: -40 ~ 85 °C - 105 °C version: –40 ~ 105 °C.
Peripherals	• SD card, UART, SPI, SDIO, I2C, LED PWM, Motor PWM, I2S, IR, pulse counter, GPIO, capacitive touch sensor, ADC, DAC, TWAI® (compatible with ISO 11898-1, i.e. CAN Specification 2.0)