REPUBLIC OF TURKEY

ISTANBUL GELISIM UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

Department of Electrical and Electronics Engineering

DESIGNING A MONITORING SYSTEM FOR PHOTOVOLTAIC APPLICATIONS UTILIZING LORA TECHNOLOGY

Master Thesis

Safaa Thamer Hawas

Supervisor

Asst. Prof. Dr. Ercan Aykut

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DECLARATION

I hereby declare that in the preparation of this thesis, scientific ethical rules have been followed, the works of other persons have been referenced in accordance with the scientific norms if used, there is no falsification in the used data, any part of the thesis has not been submitted to this university or any other university as another thesis.

Safaa Thamer Hawas

7/5/2024

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The thesis study of Safaa Thamer Hawas titled as **Designing a Monitoring System for Photovoltaic Applications Utilizing LoRa Technology** has been accepted as MASTER THESIS in the department of Electrical and Electronics Engineering by out jury.

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SUMMARY

Solar array systems with photovoltaic (PV) modules are extensively utilized in remote fields, agriculture, military, and various other sections. However, the challenge lies in the long distances between these installations and end-users, necessitating remote monitoring systems. In this study, we leverage Long Range (LoRa) wireless communication technology due to its extended range, cost-effectiveness, and user-friendly nature. Our thesis focuses on the design and implementation of a Monitoring System (MS) tailored for PV applications, utilizing LoRa technology. The primary objective is to enhance the efficiency, reliability, and maintenance of PV installations by continuously monitoring system health and performance. The MS encompasses sensors, microcontrollers, and processors to collect and process data on PV, battery banks, load, and grid parameters, including voltage, current, temperature, and state of charge (SoC). Processed data is transmitted via LoRa to a centralized control station for analysis and decision-making. LoRa's attributes, such as long-range coverage, low power consumption, and obstacle penetration, make it particularly suitable for remote PV installations. We provide a detailed overview of the system architecture, components, communication protocols, as well as data processing algorithms and battery health estimation techniques. Experimental evaluation conducted on a test PV setup demonstrates the MS's effectiveness in monitoring battery health, anomaly detection, and facilitating remote maintenance in the normal and up-normal conditions and modes. Simulation on the MATLAB Simulink platform validates the system's functionality under various operating conditions, ensuring robust performance.

Keywords: Renewable Energy, Solar-Cell, PV, Monitoring System (MS), LoRa, Battery, Operating Conditions and modes.

ÖZET

Fotovoltaik (PV) modülleri ile güneş paneli sistemleri uzak alanlarda, tarım, askeri ve çeşitli diğer alanlarda yaygın olarak kullanılmaktadır. Ancak, bu kurulumlar ile son kullanıcılar arasındaki uzun mesafe zorluk oluşturmakta ve uzaktan izleme sistemlerini gerektirmektedir. Bu çalışmada, geniş menzili, maliyet etkinliği ve kullanıcı dostu yapısı nedeniyle Uzun Menzilli (LoRa) kablosuz iletişim teknolojisinden faydalanıyoruz. Tezimiz, LoRa teknolojisini kullanan PV uygulamaları için özelleştirilmiş bir İzleme Sistemi (MS) tasarımı ve uygulanmasına odaklanmaktadır. Temel amaç, PV kurulumlarının verimliliğini, güvenilirliğini ve bakımını sürekli olarak izleyerek artırmaktır. MS, voltaj, akım, sıcaklık ve şarj durumu (SoC) gibi PV, batarya bankaları, yük ve şebeke parametrelerine ilişkin verileri toplamak ve işlemek için sensörler, mikrodenetleyiciler ve işlemciler içerir. İşlenmiş veriler, analiz ve karar verme için LoRa üzerinden merkezi bir kontrol istasyonuna iletilir. LoRa'nın, uzun menzil kapsama alanı, düşük güç tüketimi ve engelleri aşma gibi özellikleri, uzaktaki PV kurulumları için özellikle uygun hale getirir. Sistem mimarisi, bileşenler, iletişim protokolleri ve veri işleme algoritmaları ile batarya sağlığı tahmin teknikleri hakkında detaylı bir açıklama sunmaktayız. Normal ve anormal koşullar ve modlarda batarya sağlığını izleme, anormallik tespiti ve uzaktan bakımı kolaylaştırma gibi MS'nin etkinliğini gösteren deneysel değerlendirme, test PV kurulumunda gerçekleştirilir. MATLAB Simulink platformunda yapılan simülasyonlar, sistemin çeşitli işletim koşullarında işlevselliğini doğrulamaktadır, böylelikle sağlam performans sağlanmaktadır.

Anahtar kelimeler: Yenilenebilir Enerji, Güneş Hücresi, Fotovoltaik (PV), İzleme Sistemi (MS), LoRa, Batarya, İşletim Koşulları ve Modları.

TABLE OF CONTENTS

ABBREDIVATIONS

AC	**:**	Alternative current
AM	**:**	Amplitude modulation
ANN	**:**	Artificial neural network
BTS	**:**	Base transceiver station
BW	**:**	Bandwidth
CR	**:**	Coding rate
CST	**:**	Concentrating solar thermal
DC	**:**	Direct current
DUT	**:**	device under test
FEC	**:**	Forward error correction codes
GSM	**:**	Global system for mobile
IEC	**:**	Electro-Technical Commission
IoT	**:**	Internet of things
LoRa	**:**	Long Range
LPSP	**:**	Loss of power supply probability
LPWA	**:**	Low power wide area
LPWAN	**:**	Low power wide-area network
OSH	**:**	Open-Source Hardware
PCM	**:**	Phase change materials
PV	**:**	Photovoltaic
SAPV	**:**	Stand alone PV

SC	**:**	Super capacitor
SE	**:**	Solar energy
SEGS	**:**	Solar electric generating systems
SF	**:**	Spreading factor
SRU	**:**	Solar receiver unit
WSN	**:**	Wireless Sensor Network
WTGs	**:**	Wind turbine generators

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PREFACE

Throughout the process of preparing and writing this thesis, I express my **gratitude to Asst. Prof. Dr. ERCAN AYKUT** for the support rendered and to the members of the Thesis jury for their valuable comments and suggestions that assisted in managing and advancing the thesis. Last but not least, my sincere appreciation goes to my family for their support.

INTRODUCTION

The rapid evolution of the Internet of Things (IoT) has transformed our digital landscape, offering unprecedented connectivity and intelligence to our everyday devices. Initially conceived for interpersonal communication, the IoT has evolved into a sophisticated ecosystem of interconnected smart devices, reshaping industries and societies alike.

With the integration of intelligent systems, remote communication using techniques like LoRa envisions a future where our surroundings, from smart cities to digital health systems, are augmented with intelligent functionalities. As remote communication permeates every aspect of our lives, understanding its profound implications becomes paramount. However, the lack of a universally accepted definition of remote communication has led to ambiguity surrounding its scope and implications. Various terminologies, such as M2M, WoT, and IoE, have emerged to encapsulate different facets of remote communication, reflecting its diverse applications and interpretations. Despite these challenges, remote communication promises transformative benefits across multiple domains. In smart cities, remote communication-enabled sensors optimize resource management and enhance urban infrastructure, leading to improved efficiency and sustainability. Similarly, in healthcare, remote communication devices empower remote patient monitoring and personalized care, revolutionizing medical practices. Moreover, the integration of remote communication technologies in industries enhances production processes, enables real-time monitoring, and improves supply chain management. From precision agriculture to industrial automation, remote communication-driven innovations optimize operations and drive competitive advantage. However, realizing the full potential of remote communication relies on addressing critical challenges, including power consumption, communication efficiency, and data security. Traditional wireless communication technologies may fall short in meeting the demands of remote communication applications, especially in remote or off-grid scenarios. To overcome these challenges, emerging technologies like LoRa offer compelling solutions. LoRa's long-range communication capabilities and low power consumption make it ideal for remote communication deployments, particularly in battery monitoring systems for photovoltaic applications. By leveraging LoRa technology, we aim to design and implement a reliable, energy-efficient, and scalable battery monitoring system that ensures optimal energy management and extends battery lifespan. In this study, we delve into the development of a LoRa-based battery monitoring system for photovoltaic applications, addressing the pressing need for efficient energy solutions in a rapidly evolving digital landscape. Through comprehensive analysis and experimentation, we seek to demonstrate the efficacy of our proposed system in overcoming existing challenges and unlocking the full potential of renewable energy technologies in the remote communication era. In this study, we delve into the development of a LoRa-based battery monitoring system for photovoltaic applications, addressing the pressing need for efficient energy solutions in a rapidly evolving digital landscape. Through comprehensive analysis and experimentation, we seek to demonstrate the efficacy of our proposed system in overcoming existing challenges and unlocking the full potential of renewable energy technologies in the IoT era.

CHAPTER ONE

INTRODUCTION

1.1. OVERVIEW OF RESEARCH

The Internet of Things (IoT) denotes a system where physical devices, appliances, vehicles, and other objects are interconnected through sensors, software, and internet connectivity. This network enables the collection and exchange of data over the internet, allowing for remote monitoring and control. IoT enables seamless integration between the physical world and computer systems, facilitating data gathering, analysis, and automation to improve efficiency and decision-making processes, ultimately enhancing quality of life. IOT signifies a significant advancement in comparison to the existing Internet infrastructure (Bello et al., 2016). First, it provided opportunities for interpersonal communication, but has subsequently transformed into a complex system of interlinked technological gadgets (Bello et al., 2016). With the assistance of these aids, utilizing web protocols to facilitate interactions with the physical environment, and the requirements for acquiring environmental information are essential. The Internet of Things (IoT) paradigm visualizes a future in which our current environments are enhanced by the integration of intelligent systems, such as smart cities, smart homes, smart grids, digital health, and automated pollution control (Mineraud et al., 2015). It facilitates the interconnection of all entities, both animate and inanimate, across the globe so the implications of this are extensive. A diverse range of network media is utilized to establish connections between devices (Sehrawat et al., 2019). The primary objective of the IoT is to enhance operational efficiency and facilitate adaptation. The spread of smart objects and devices within the IoT has experienced a substantial growth (Sehrawat et al., 2019). This phenomenon facilitates the manifestation of intelligent behaviour in a diverse range of devices. IoT-enabled items have been equipped with intelligent functionalities, including sensors, RFID technology, and other forms of embedded computing (Sehrawat et al., 2019). The notion of a globally networked future is no longer confined to futuristic technology significant of science fiction. The various devices and objects in our surroundings are interconnected inside a network commonly referred to as the Internet of Things (IoT) (Jara et al., 2014).

In order to conduct a comprehensive analysis of study tendencies, it is important to develop a thorough understanding of the IoT and its impact on various aspects of society, business, and emerging business models (Čolaković et al., 2018). During the initial phase, individuals are actively engaged in the process of formulating their own interpretations and conceptualizations of the IoT in accordance with their respective requirements and perspectives (Čolaković et al., 2018). Consequently, a universally accepted definition of the IoT is lacking, leading to a lack of clarity regarding its implications (Čolaković et al., 2018). Numerous acronyms and abbreviations have been devised to denote the concept of the IoT, including M2M (Machine to Machine), WoT (Web of Things), CoT (Cloud of Things), and IoE (Internet of Everything) (Čolaković et al., 2018). While there are writers who contend that the two expressions possess identical meanings, there are others that establish evident differentiations between them (Čolaković et al., 2018). The Internet of Things (IoT) is a complex network that has the potential to introduce numerous innovative concepts and societal conventions (Weber et al., 2016). The topic of appropriate behavioural norms is presently under discussion among scientists, legislators, and chief executive officers of prominent corporations in Europe and the United States (Weber et al., 2016).

It is imperative for regulators to consider the intricate nature of IoT systems. This necessitates the implementation of a multifaceted strategy to address the issue at hand (Weber et al., 2016). The influence of market regulation on technological innovation, organizational flexibility, and the adoption rate of the Internet of Things is substantial (Weber et al., 2016). Privacy, security, ethics, data confidentiality, competitiveness, economic development, and freedom of innovation are among the key challenges associated with the Internet of Things (IoT) that have been extensively examined in both the business domain and the general public (Weber et al., 2016).

IoT becomes the first actual evolution of the Internet with the ability to change our way of life (Madakam et al., 2015). These devices find application in a diverse range of IoT solutions (Sethi et al., 2017). There has been a progressive transition towards the utilization of sensors capable of detecting not just electrical activity, but also chemical and biological components, physiological characteristics, ambient circumstances, and even medical disorders (Sethi et al., 2017). Additionally, the growing prevalence of photovoltaic (PV) fluctuation systems, power generation, and the unpredictable patterns of energy consumption by loads has led to a heightened interest in grid-connected energy storage systems (Dallalbashi et al., 2023). These systems serve the purpose of regulating power flows and delivering electric power of superior quality (Dallalbashi et al., 2023). The deployment of energy storage devices in conjunction with battery banks is a prevalent approach to augment the capacity of variable electricity generated by grid-connected generators (Dallalbashi et al., 2023). The implementation of control techniques plays a crucial role in ensuring the efficient operation of a DC and AC microgrid's power sources. One example of such a system is the circuit and monitoring mechanism employed for the purpose of regulating and verifying the status of the battery (Dallalbashi et al., 2023). The system monitors essential parameters and offers timely alerts in the event of a power outage. The aforementioned statement highlights the significant impact that the monitoring system of each energy source can have on the reliability and security of the grid within the system.

The charging and discharging characteristics of several batteries are illustrated in (Dallalbashi et al., 2023). The duration and longevity of the battery backup may be diminished if the rates of charging and discharging fail to meet their respective criteria. There exists a potential scenario wherein the batteries inside a battery bank may deplete their power at varying intervals if the load is dispersed throughout the bank without considering the individual batteries' rated capacity and intended usage (Dallalbashi et al., 2023). When utilizing a discharged battery as a load, it becomes necessary to extract electricity from the power provider (Dallalbashi et al., 2023).

The primary objective of IoT innovations is to streamline operations across diverse sectors, enhancing system efficacy, and ultimately elevating the overall quality of life. This ambitious goal encompasses a multitude of applications, permeating virtually every facet of modern existence (Nižetić et al., 2020):

In contemporary urban planning, the timely detection of infrastructural faults, flaws and the effective management of crucial networks like water, electricity, and gas in smart cities pose significant challenges (Nižetić et al., 2020). Leveraging sensor technologies presents an opportunity to devise innovative solutions aimed at water conservation, optimized parking, heightened security measures, and the improvement of energy systems and urban traffic flow, ultimately mitigating congestion and reducing harmful CO_2 emissions (Nižetić et al., 2020). The interconnectedness of sensors within smart cities facilitates proactive issue resolution, with internet-enabled devices promptly alerting stakeholders to emerging challenges (Nižetić et al., 2020).

Meanwhile, in the healthcare sector, the integration of Internet of Things (IoT) technologies promises a transformative shift in patient care delivery (Ghazal et al., 2021). By deploying personalized networks for post-illness rehabilitation and monitoring clinical indicators, particularly in elderly populations, IoT solutions revolutionize healthcare provision (Ghazal et al., 2021). Connected medical devices enable remote monitoring of vital signs such as heart rate, skin temperature, and movement patterns, empowering patients and caregivers alike with real-time insights.

Similarly, the incorporation of IoT technologies into industrial processes reshapes manufacturing paradigms, fostering enhanced production processes and seamless communication between human operators and machinery (Javaid et al., 2022). This comprehensive monitoring extends across the production chain, from quality control to logistics and distribution, ensuring operational efficiency and minimizing losses to bolster market competitiveness (Javaid et al., 2022).

In a groundbreaking advancement, a Monitoring System (MS) that leverages LoRa and IoT technologies in rural areas underscores the transformative potential of wireless sensor networks (WSNs) (Dallalbashi et al., 2023). LoRa, short for Long Range, is a Low-Power Wide-Area Network (LPWAN) protocol that enables long-distance communication between devices with minimal energy consumption. It operates on unlicensed frequency bands, making it suitable for applications in remote and rural areas. LoRa technology is closely intertwined with the Internet of Things (IoT), a network of interconnected devices capable of exchanging data over the internet. In the context of the MS mentioned, IoT facilitates the collection, transmission, and analysis of data from sensors deployed in rural environments. By integrating LoRa with IoT, the MS enables efficient and cost-effective monitoring of various parameters, such as environmental conditions or photovoltaic system performance, over large geographical areas.

Despite challenges like node vulnerability to damage and extreme weather events in photovoltaic systems, innovative solutions such as subterranean sensor networks ensure continuous real-time data acquisition (Dallalbashi et al., 2023). These networks, enabled by LoRa and IoT technologies, enhance the resilience and reliability of monitoring systems in remote locations. Moreover, wireless sensor networks (WSNs) equipped with LoRa technology have become indispensable across diverse sectors, including industry, healthcare, and precision agriculture. They offer versatile monitoring capabilities, allowing for the collection of data in various environmental conditions (Prodanović et al., 2020). This underscores the significance of LoRa-enabled IoT solutions in addressing monitoring and communication challenges across different domains. Additionally, the segment evaluates communication protocols to tackle challenges in contemporary IoT platforms serving photovoltaic batteries (Al-Sarawi et al., 2017). This highlights the importance of selecting appropriate communication protocols, such as LoRa, to optimize data transmission and enhance the efficiency of IoT-enabled monitoring systems in specific applications like photovoltaic systems. In order to furnish a thorough comparison of different LPWAN technologies, encompassing LoRa, Sigfox, NB-IoT, and Zigbee, all of which emerge as potential contenders for expansive IoT implementations (A. Khalifeh, 2019), the authors precisely analyze the technical attributes of these technologies and evaluate their applicability across diverse IoT scenarios (A. Khalifeh, 2019).

Figure 1. shows the characteristics of LoRa as compared to other feasible communication systems like sigfox and others.

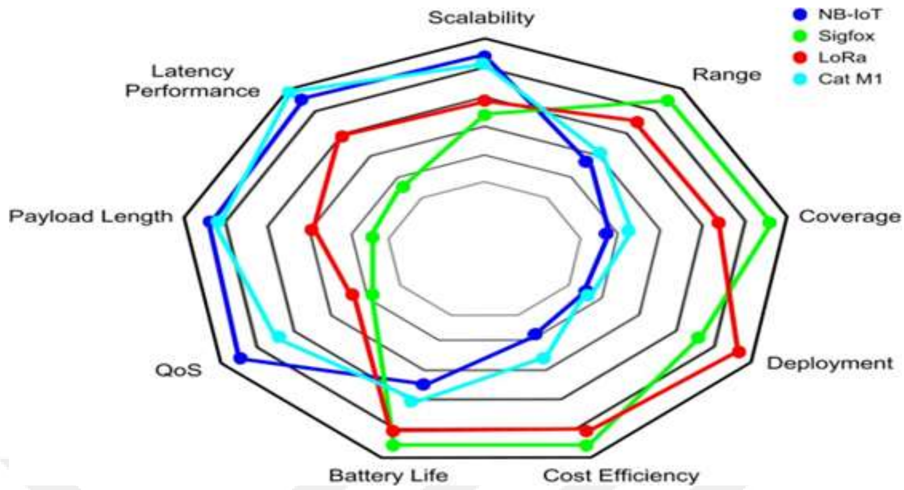


Figure 1. Characteristics of each LoRa competitor (A. Khalifeh, 2019).

Within the realm of the IoT environment, the protocols outlined can be categorized based on their bandwidth and coverage range, as illustrated in Figure 2.

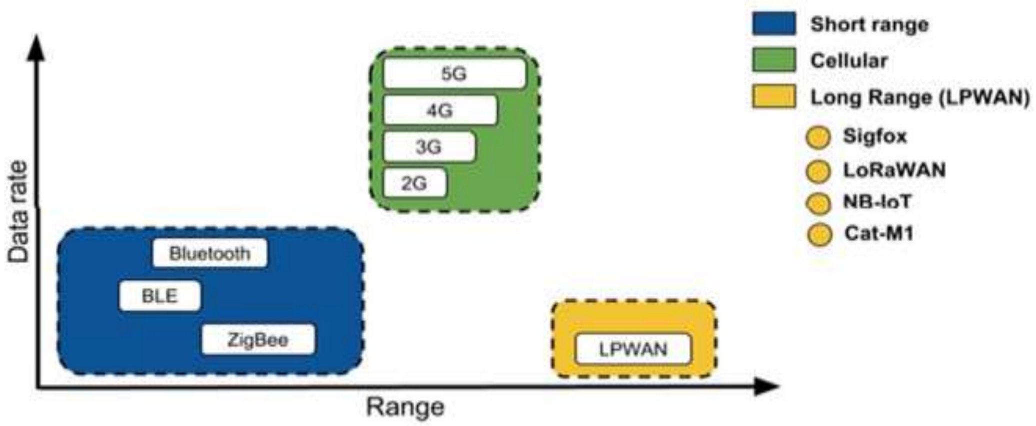


Figure 2. Data (Bit) rate against Range in communication network for LoRa, Sigfox, NB-IoT and Cat-M1 (Hernandez, 2018).

1.1.1. SigFox

Sigfox functionally operates as a narrow wireless cellular network, purposefully designed for applications with a limited number of specialized field devices and necessitating extensive communication needs to span long distance ranges (Ben et al., 2021). Due to its limited coverage area, devices in the field can be set up in a mesh network configuration, allowing data to hop between devices to reach its destination and make up for the network's short reach (Ben et al., 2021). With a daily allowance of 140 messages, each comprising 12 bytes, Sigfox optimizes transmission efficiency by repeating data across different frequency channels (Ben et al., 2021). One notable application of Sigfox technology is evident in its utilization within relocation and monitoring platforms, aiding farmers in tracking their livestock and augmenting agricultural productivity (Ben et al., 2021).

1.1.2. Bluetooth

Bluetooth wireless technology, well-known for its short-range communication capabilities, serves as a vital link between portable devices, offering secure communication within a radius of up to 10 meters (An Overview of the Bluetooth Wireless Technology, 2001). Widely accessible across a myriad of portable devices, Bluetooth finds extensive application in modern agriculture, facilitating remote monitoring of parameters like soil moisture, location, and temperature (Ben et al., 2021). Leveraging its low energy consumption and ubiquitous presence, Bluetooth-enabled smartphones have become indispensable tools in agricultural practices, aiding in tasks such as soil monitoring, migration control, and precise management of fertilizer and pesticide quantities (Ben et al., 2021). Noteworthy among Bluetooth's attributes is its ability to simultaneously transmit data and voice, its capacity to penetrate solid barriers, its omnidirectional coverage, and its independence from line-of-sight positioning of connected devices (Ben et al., 2021).

Designed primarily for low power consumption and short-range communication, Bluetooth technology offers varying transmission distances depending on the class of Bluetooth device utilized, ranging from 1 to 100 meters (Ben et al., 2021). Bluetooth devices are categorized into three classes based on their power consumption and transmission range (Ben et al., 2021):

• Class 1: Designed for short-range communication within a radius of 1 meter, with a maximum permitted power of 1 mW (0 dBm).

• Class 2: Offering a range of up to 10 meters with a maximum permitted power of 2-5 mW (4 dBm).

• Class 3: Providing a transmission range of up to 100 meters with a maximum permitted power of 100 mW (20 dBm).

ZigBee

ZigBee stands out as a wireless sensor network technology widely employed in wireless control and monitoring applications, primarily owing to its low power consumption facilitated by small batteries, alongside its robust mesh networking architecture that ensures high reliability (Aju, 2015). Positioned as a cost-effective alternative, ZigBee, as per its specification, aims for simplicity and affordability compared to other WAN technologies like Bluetooth (Aju, 2015). Tailored for radiofrequency applications demanding prolonged battery life, network security, and low data rates, ZigBee finds optimal utility in sectors such as agriculture, particularly in tasks like irrigation supervision, water quality management, and fertilizer distribution, thanks to its low duty cycle (Aju, 2015). The ZigBee protocol comprises a physical layer housing the RF transceiver, serving as a foundational element for low-level control mechanisms and medium access control within PV monitoring systems (Aju, 2015).

The LoRa wireless protocol offers extensive coverage while consuming minimal power, making it a favorable choice compared to other wireless communication technologies, as depicted in Table 1. This characteristic makes it particularly well-suited for deployment in large agricultural areas (Ben et al., 2021).

Table 1.a LPWAN main techniques (Ben et al., 2021).

Technical Protocol, Year	**Type**	**Number of BS Conn.**	**Frequency Band Used**	**Transmission mode, Distance**	**Trans. Speed**	**Technical Category**
Sigfox, 2009	Sigfox	1,000,000	ISM band, 1 GHz	Urban, 10 km; outskirts, 50 km	100 bps	Terminal device to front-end application
LoRaWAN, 2015	IBM, CISCO	250,000	ISM band, 1 GHz	Urban, 3–5 km; outskirts, 15 km	300 bps–50 kbps	Communication protocol
Weightless, 2015	ARM, NEUL	1,000,000	ISM band, 1 GHz	5 km+(-N) 2 km+(-P)	30–100 kbps(-N), 100 kbps(-P)	Communication protocol
NB-IoT, 2016	3GPP	100,000	GSM or LTE band	20 km	~50 kbps	Communication protocol

Where, ISM is the Industrial, Scientific, and Medical frequency band.

Table 1.b Comparison of various specifications of data transmission modules (Ben et al., 2021).

Module Implemented	**Distance/ Range**	**Power Consumptions**	**Topology**	**Data Trans. Rate, Sampling Rate**
Bluetooth	Short range modules, 100 m	10–500 mW	Point to point	1 Mbps, 44.1 kHz
Wi-Fi	150 m, 11 Mbps	1 W	Star	20 MHz
ZigBee	300 m, 250 kbps	1 mW	Mesh	8 MHz
GSM	Long Range module, 10–30 km	1–5 W	Star	270.8 kbps, 8 kHz
LoRa	10–30 km, 5469–293 bps	Low power, Sleep mode: (1 – 10) µA	Star, Mesh	500 kHz

Module Implemented	Distance/ Range	Power Consumptions	Topology	Data Trans. Rate, Sampling Rate
		Transmission mode: (20-120)mA, depend on transmission power and data rate.		

Comparing LPWAN technologies, including LoRa, Sigfox, Bluetooth, and Wi-Fi, for large-scale IoT deployments. The study concluded that LoRa and Sigfox were more suitable for large-scale IoT applications due to their long-range and low-power capabilities compared to Bluetooth and Wi-Fi, This comparison highlights the advantages of LoRa technology in battery monitoring systems for PV applications (Ben et al., 2021).

1.2. ROLE OF LORA IN IOT

LoRa, short for Long Range, is both a physical layer and a modulation technique utilized to establish robust communication links for data transmission (Ben et al., 2021). It operates within Industrial, Scientific, and Medical (ISM) frequency bands and is specifically engineered for long-range, low-power operations, marking it as a cutting-edge technology in the domain (Ben et al., 2021). Developed by Semtech, LoRa technology leverages chirp spread spectrum (CSS) modulation where the frequency continuously changes (increases or decreases) with time, offering unparalleled wireless capabilities where data packets can be transmitted and received over extensive distances, reaching up to 15 kilometers (Ben et al., 2021). This modulation technique spreads the signal's energy across a wide frequency band, providing resistance to interference and multipath fading. Furthermore, LoRa stands out for its versatility, seamlessly integrating with public, private, or hybrid networks to surpass the coverage provided by cellular networks, while remaining compatible with existing infrastructure. This adaptability makes it an ideal choice for cost-effective, battery-operated Internet of Things (IoT) applications, catering to diverse connectivity needs (Ben et al., 2021). At its core, the LoRa physical layer employs Chirp Spread Spectrum (CSS) modulation, a technique that utilizes wideband linear frequency-modulated chirp pulses to encode information (Ben et al., 2021). CSS offers advantages such as robustness against interference, long-range communication capabilities, and efficient spectrum utilization.

This modulation scheme, depicted in Figure 3, embodies the essence of the physical layer, boasting similar low-power characteristics to traditional frequency-shift keying (FSK) modulation methods (Augustin et al., 2016). Several studies have explored the use of LoRa technology in designing and implementing battery monitoring systems for PV applications. (Ben et al., 2021) proposed a smart battery monitoring system using LoRa technology that provides real-time monitoring of voltage, current, and state of charge (SoC). Suryanto and Prabowo (2019) presented a LoRa-based battery monitoring system for solar panels capable of detecting voltage and current fluctuations and providing alerts to the user (Ben et al., 2021). developed a photovoltaic battery monitoring system using LoRa and IoT for rural areas, enabling efficient energy management and remote monitoring (Ben et al., 2021).

LoRa (Long Range) technology has emerged as a leading communication solution for Internet of Things (IoT) applications due to its unique features and capabilities (Ben et al., 2021). LoRa plays a vital role in IoT by enabling low-power, long-range, and scalable wireless communication between various devices and sensors (Ben et al., 2021). The key benefits of using LoRa in IoT applications include:

- **Short-Range Communication:** LoRa enables long-range wireless communication, with distances of over 10 km in rural areas and several kilometers in urban environments (Centenaro et al., 2015). This extended range allows IoT devices and sensors to connect and transmit data across vast areas without the need for complex and costly infrastructure (Centenaro et al., 2015).

- **Low Power Consumption:** LoRa devices are designed to consume minimal power, making them suitable for battery-powered or energy-harvesting IoT applications (Bäumker et al., 2019). The low power consumption allows for extended battery life, reducing the need for frequent battery replacement or maintenance, which is particularly important for remote or hard-to-reach IoT deployments(Bäumker et al., 2019).

- **Scalability:** LoRa networks are highly scalable, supporting thousands of devices and sensors on a single gateway (Ma et al. 2018). This scalability enables the seamless expansion of IoT networks as the number of connected devices and sensors grows, making it an ideal choice for large-scale IoT deployments (Ma et al. 2018).

- **Penetration and Robustness:** LoRa technology offers excellent penetration capabilities, allowing for reliable communication through obstacles such as walls or vegetation (Centenaro et al., 2015). This feature is particularly useful for indoor or densely-populated urban IoT applications, where signal interference and attenuation can be significant challenges (Centenaro et al., 2015).

- **Security:** LoRa employs advanced encryption techniques to ensure secure data transmission between devices and networks conducted by (Haxhibeqiri et al. 2017). This security is crucial for IoT applications that involve sensitive data or require robust protection against unauthorized access(Centenaro et al., 2015).

- **Cost-Effectiveness:** LoRa-based IoT solutions typically have lower infrastructure and deployment costs compared to other communication technologies (Ben et al., 2021), such as cellular networks. By reducing the costs associated with device connectivity and data transmission, LoRa makes IoT applications more accessible and affordable for various industries and use cases(Ben et al., 2021.).

Some common IoT applications that benefit from LoRa technology include:

- **Smart agriculture:** Remote monitoring of soil moisture, temperature, humidity, and other parameters to optimize crop growth and resource usage (Ben et al., 2021).

- **Smart cities:** Monitoring and control of street lighting, traffic, air quality, waste management, and parking (Ben et al., 2021).

- **Smart utilities:** Remote monitoring and management of water, gas, and electricity consumption for improved efficiency and resource conservation (Ben et al., 2021).

- **Industrial IoT:** Asset tracking, machine health monitoring, and predictive maintenance in industrial environments (Ben et al., 2021).

- **Environmental monitoring:** Tracking air quality, water levels, and other environmental parameters for research and conservation purposes (Ben et al., 2021).

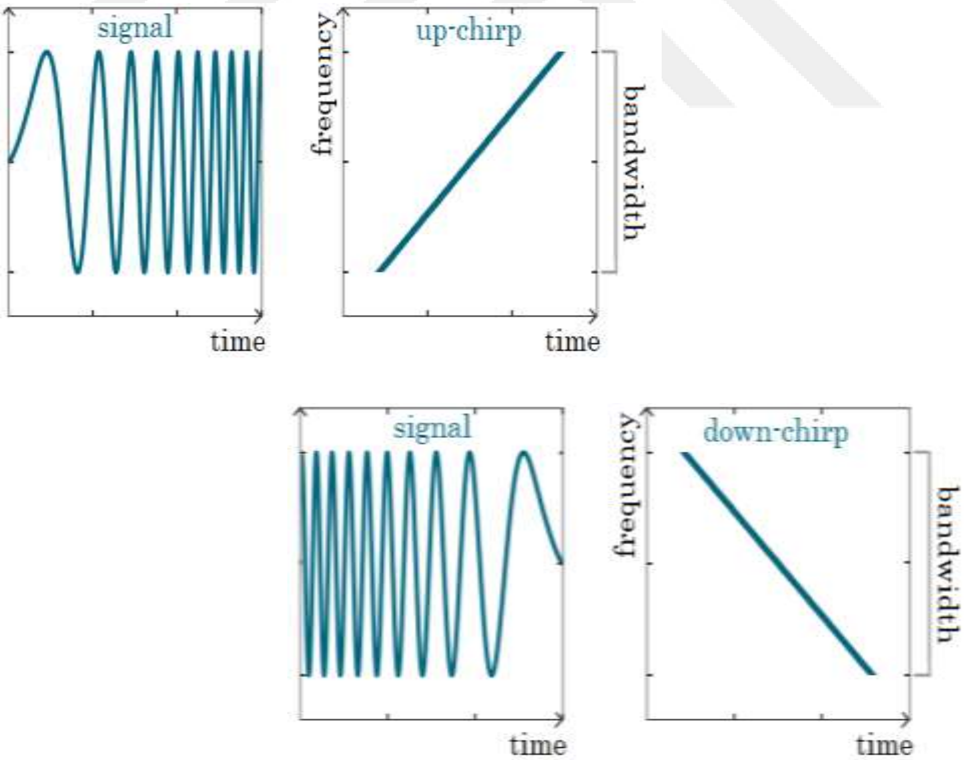


Figure 3. Chirp of LoRa modulation (Ben et al., 2021).

1.3. MOTIVATION

The power consumption issue that poses the greatest challenge in the development of decentralized IoT systems is primarily observed in the data transmission sub-system of the manufactured devices (Cappelli et al., 2021). The aforementioned task necessitates the most exertion on a consistent basis. Considerable efforts have been dedicated in recent years towards the development of revolutionary communication technologies that fulfill two essential criteria: minimal power consumption and extensive data transfer capabilities (Cappelli et al., 2021). The aforementioned phenomenon has resulted in the emergence of a novel category of communication systems referred to as Low Power Wide Area Networks (LPWANs). There exist both cellular (NB-IoT, LTE-M) and non-cellular (Sigfox, LoRa) alternatives, each possessing distinct advantages and disadvantage (Cappelli et al., 2021)s. The LoRa modulation and Low Power Wide Area Network (LoRaWAN) protocol have emerged as prominent technologies in the realm of Internet of Things (IoT) applications, particularly in scenarios that necessitate real-time data collection. Unlike SigFox and cellular infrastructures such as NB-IoT and LTE-M, which do not support the implementation of customized network infrastructures, LoRaWAN Gateways offer end-users the flexibility to deploy them according to specific application needs (Cappelli et al., 2021). Due to this characteristic, the methodology has garnered extensive adoption and is presently being employed in the present investigation. Due to its notable receiver sensitivity, reaching up to 140 dBm, this technology has exceptional capabilities in terms of transmission range, particularly in rural areas where it can extend up to 20 km. Consequently, it has played a significant role in facilitating the accessibility of affordable hardware components on a large scale. LoRaWAN nodes have been engineered to achieve energy autonomy through a range of energy harvesting methodologies, encompassing solar cells, microbial fuel cells, and sea wave motion. A number of prior studies have employed thermoelectric generators (TEGs), with a predominant emphasis on their application within actual implementation scenarios (Cappelli et al., 2021).

The motivation behind developing a LoRa-based PV Monitoring System (MS) for photovoltaic applications stems from several factors, including the growing demand for sustainable energy solutions, the need for efficient energy management, and the challenges associated with existing communication technologies in MS applications (Baldo et al., 2021).

- **Sustainable Energy Solutions:** As global energy demand continues to rise, there is an increasing need to develop and implement renewable energy sources, such as photovoltaic systems (Krishna et al., 2022). Efficient battery management is crucial to ensure the effective operation of these systems, optimizing energy storage and consumption, and extending the battery's lifespan (Krishna et al., 2022).
- **Efficient Battery Management:** Battery banks play a vital role in photovoltaic systems, especially in off-grid installations (Baldo et al., 2021). Accurate monitoring of battery performance metrics, such as state of charge (SoC), state of health (SoH), and remaining useful life (RUL), is essential for maintaining the performance, safety, and reliability of the battery bank. A well-designed MS can help detect potential issues early, prevent damage, and optimize energy storage and consumption (Baldo et al., 2021).
- **Communication Challenges in MS Applications:** Traditional wired communication solutions for MS are often complex, costly, and challenging to install and maintain, particularly in remote or large-scale photovoltaic installations (Cappelli et al., 2021). Wireless communication technologies, such as ZigBee, Bluetooth, and Wi-Fi, have their limitations in terms of range, power consumption, and scalability. These challenges have led to the search for alternative communication technologies that can address these limitations while offering reliable and efficient energy monitoring (Cappelli et al., 2021).
- **LoRa Technology Advantages:** LoRa (Long Range) technology offers a promising solution to the communication challenges faced by traditional MS solutions (Ma et al., 2021). With its long-range communication capabilities, low power consumption, and scalability, LoRa has the potential to revolutionize battery monitoring in photovoltaic applications (Cappelli et al., 2021). Implementing a LoRa-based MS can simplify system design and installation, reduce costs, and enhance the overall performance and efficiency

of photovoltaic systems (Cappelli et al., 2021).

1.4. PROBLEM STATEMENT

The significant problem in recent decades, there is still a lot of room for progress in this field. On the customer side, there are several barriers that still face the widespread adoption of photovoltaic application. Several studies have already been conducted and point out too many barriers that need to be overcome to ensure the global diffusion of photovoltaic application (Mohammadi et al., 2019). According to this studies, these barriers are classified into 3 main categories, the social barrier, technical and economic barrier. Furthermore, a recent study by researchers in 2018 stated that the four main obstacles that still hinder the widespread adoption of photovoltaic application were (Mohammadi et al., 2019): The cost of the batteries, the insufficient range, the long charging times, and the need for a charging infrastructure. In fact, these barriers are essentially linked; the bigger the battery capacity, the more it generally costs (Dinçer, 2011). Additionally, the larger the PV life, the longer it generally takes to charge the batteries. The limited driving range along with the photovoltaic panels cost represent one of the main obstacles for the global acceptance of photovoltaic based energy produced in Middle-East and Turkish region (Dinçer, 2011).

In an attempt to respond to the problems encountered in LoRa based photovoltaic based application while reducing the use of fossil fuels to reduce environmental degradation, the world has been turning its attention to renewable energies (Dinçer, 2011). Among these, the widespread use of photovoltaic energy, which is a free, sustainable, renewable, and clean source, has grown exponentially and is considered the third largest renewable energy in terms of capacity and energy generation (Dinçer, 2011). To sustain this growth, from an economic perspective, such developments are due to a significant drop of about 82% in the global average price of photovoltaic module over the last decade (Dinçer, 2011).

Solar photovoltaic (PV) technology can provide energy to batteries through several ways. The most obvious way is to incorporate the solar photovoltaic panels directly onto the home roof (Mohammadi et al., 2019), so that an additional energy can be generated, thus enabling the home battery to be charged. On the other hand, this approach opens up the possibility for the batteries to be undersized, resulting in direct savings in capital investment in the residential houses and operating costs (Mohammadi et al., 2019).

The increasing adoption of renewable energy sources, such as photovoltaic (PV) systems, has created a demand (Karakaya et al., 2015) or efficient and reliable battery monitoring solutions that can ensure optimal energy management and prolong battery life. However, traditional wireless communication technologies used in battery monitoring systems, such as Wi-Fi and Bluetooth, may not provide sufficient coverage in remote areas or may consume excessive power, leading to inefficiencies and increased maintenance costs (Karakaya et al., 2015).

The implementation of a battery monitoring system for photovoltaic applications based on LoRa technology can potentially overcome these challenges. LoRa offers long-range and low-power capabilities that are well-suited for monitoring and managing battery systems in remote and off-grid locations. The key problem to address is how to design and implement a reliable, energy-efficient, and scalable battery monitoring system using LoRa technology, which can cater to different battery types and photovoltaic system setups while ensuring data security and real-time monitoring and control.

1.5. AIM OF STUDY

The PV based energy uses has an advantages of using a green energy, take as an example of electric vehicle over an internal combustion engine are many; first, the conversion efficiency of electrical energy to mechanical energy is very high and usually lies between 70% and 90%. Another benefit is that it is possible to use electric motor to act as a generator and recover some energy and store it in the batteries during regenerative braking mode (Haxhibeqiri et al., 2017). Based on the motor power and design, the global PV based electricity market is typically segmented into motors with power less than 1 kW range, and motors with power greater than 1.5 kW conducted. Those with motor power in the range of (1-1.5) kW have been dominating the market share due to their operational cost, making it a leading category in the market. However, due to the rapid growth of new technologies and the growing demand for high-speed PV electricity with higher power (~ 5 kW) have begun to arrive on the market and are expected to double their volume in the coming years. Most of the lower power PV based electricity found in the literature are equipped with DC motors because they are less expensive than AC motors and can be operated and handled safely with a minimum of friction losses. However, for LoRa as a proposed technique to be used with PV will have lower power needs, induction motors are considered the best solutions. One of the main barriers to global acceptance of hydro-electric based energy are the higher costs of dams and the limited range. So the adoption of the photovoltaic and LoRa based energy appears as a good option. The relevant work available in the literature on previous studies using on-board photovoltaic systems to charge batteries will be provided in literature review. Most of the studies in the literature will be basedon simulations models used to access the performance, but there will be a considerable amount of works focused on experimental data, which may be used LoRa approach in this research work.

- **Photovoltaic (PV) systems:** PV systems convert sunlight directly into electricity using solar cells, providing a clean and renewable energy source. Battery storage is often used in PV systems to store excess energy produced during the day, allowing for energy consumption during periods of low sunlight or at night.
- **Battery monitoring system (BMS):** A BMS is an essential component of energy storage systems, as it ensures the efficient and safe operation of batteries (Swain et al. 2021). It continuously monitors battery parameters like voltage, current, temperature, and state of charge (SoC), helping to prevent overcharging, overheating, and other potential issues that can lead to reduced performance or battery failure.
- **Long Range (LoRa) technology:** LoRa is a low-power, long-range wireless communication technology that operates in the sub-gigahertz frequency bands (Kumar et al., 2020). It provides a robust and cost-effective solution for Internet of Things (IoT) applications, allowing for data transmission over long

distances (up to 15 km) with minimal power consumption.

- **System architecture:** The proposed BMS consists of a network of sensors and microcontrollers connected to the PV battery banks, collecting and processing data related to battery health and performance. The processed data is transmitted via the LoRa network to a centralized control station for analysis, decision-making, and potential remote maintenance (Miao et al., 2021).
- **Battery health estimation:** The BMS uses various algorithms and techniques to estimate the battery health, such as Coulomb counting and Kalman filtering, which help in determining the state of charge (SoC) and state of health (SoH) of the battery system.
- **Remote maintenance:** By continuously monitoring the battery system and transmitting data to a centralized control station, the proposed BMS allows for remote diagnostics and maintenance, reducing the need for on-site visits and improving the overall efficiency of PV installations.
- **Improved performance and lifespan:** The implementation of a BMS in PV systems can help to enhance the performance and lifespan of the battery storage by optimizing charging and discharging processes, as well as identifying and addressing potential issues before they lead to failures or reduced performance.

1.6. ORGANIZATION OF THESIS

The organization of the thesis on the LoRa-based battery monitoring system (BMS) for photovoltaic applications can be presented in the following structure:

1. **Introduction:** Introduce the research topic, explain the motivation behind the study, and outline the objectives and scope of the work. Provide a brief overview of photovoltaic systems, battery management, and the role of communication technologies, such as LoRa, in MS applications.
2. **Literature Review:** Conduct a comprehensive review of existing research and studies related to battery monitoring systems, photovoltaic applications, and LoRa technology. Analyze the advancements in MS design, the importance of

efficient battery management in photovoltaic systems, and the benefits of using LoRa technology for long-range, low-power communication.

3. **Methodology:** Describe the design and implementation process of the LoRa-based MS, including the selection of appropriate sensors, microcontroller unit (MCU), LoRa transceiver module, and other hardware components. Discuss the software and firmware development for data collection, processing, and transmission. Detail the process of optimizing LoRa parameters and evaluating the system's performance. Analyze the trade-offs between communication range, data rate, and power consumption, and explain how these factors influence the choice of optimal parameters for the specific MS requirements.
4. **Results:** Present the testing and validation procedures used to evaluate the functionality and performance of the LoRa-based MS. Analyze the data obtained from the MS, including battery performance metrics and communication quality, and identify trends, patterns, and potential issues in the data. Provide a comparative analysis of the LoRa-based MS and other technologies, discussing their strengths and limitations in terms of range, power consumption, reliability, complexity, scalability, and cost. Based on the data analysis results and the comparison with existing techniques, propose potential areas for improvement in the MS design, implementation, and performance. Suggest adjustments to the hardware, software, or LoRa parameters that could enhance the system's efficiency and reliability.
5. **Discussion and Conclusion:** Discuss the process and challenges of deploying the optimized LoRa-based MS in a real-world photovoltaic application. Share insights and lessons learned from the field deployment, highlighting the system's performance and effectiveness in managing and maintaining the battery bank. Summarize the findings and outcomes of the study, emphasizing the benefits and challenges of implementing a LoRa-based MS in photovoltaic applications. Reflect on the study's contributions to the field and suggest potential future research directions to further advance the development and application of LoRa-based MS solutions.

CHAPTER TWO

LITERATURE REVIEW AND THEORITICAL ASPECTS

2.1. INTRODUCTION

Several studies have proposed the use of LoRa technology for MSs in PV applications. In a study (Peruzzi et al., 2020), a MS based on LoRa technology was designed and implemented for a 24V battery bank in a PV system. The MS was able to monitor the voltage, current, and temperature of the battery bank and transmit the data wirelessly to a remote monitoring station over a distance of 3 km (Peruzzi et al., 2020). The system was also able to send alerts to the monitoring station in case of battery overcharge or discharge.

In another study, (Ferreira et al., 2019) proposed a MS based on LoRa technology for a 12V battery bank in a PV system. The BMS was able to monitor the SoC, SoH, and SoF of the battery bank and transmit the data wirelessly to a remote monitoring station over a distance of 2 km. The system was also able to send alerts to the monitoring station in case of battery overcharge or discharge (Ferreira et al., 2019).

In a study (Cabello et al., 2022), a BMS based on LoRa technology was designed and implemented for a 48V battery bank in a PV system. The BMS was able to monitor the voltage, current, temperature, and SoC of the battery bank and transmit the data wirelessly to a remote monitoring station over a distance of 1 km (Cabello et al., 2022). The system was also able to send alerts to the monitoring station in case of battery overcharge or discharge (Cabello et al., 2022).

In the study (Talib et al., 2022) focuses on developing a PV monitoring system that can help ensure the efficient operation of photovoltaic (PV) systems. The research was authored by (Talib et al., 2022).

The study begins by highlighting the importance of battery monitoring in PV systems, particularly in remote areas where power supply is unreliable (Raza et al., 2016). The authors emphasize that a reliable battery monitoring system can help prevent downtime, reduce maintenance costs, and prolong the lifespan of the batteries. They argue that a low-power, wide-area network (LPWAN) technology like LoRa (Long Range) can be used to design a cost-effective and efficient battery monitoring system (Raza et al., 2016).

The system consists of a microcontroller unit (MCU), a LoRa module, a battery voltage and current sensor, and a temperature sensor (Khalifeh et al., 2022). The MCU is responsible for collecting data from the sensors and transmitting it wirelessly to a base station via LoRa technology (Khalifeh et al., 2022). The authors explain that LoRa technology is particularly suitable for battery monitoring systems because it provides a long-range communication capability, low power consumption, and high interference immunity (Khalifeh et al., 2022).

Next, the authors (Kutluay et al., 2005) present the results of their experiments to evaluate the performance of the proposed system. They conducted tests on a 12 V lead-acid battery that was charged and discharged at different rates. The results showed that the battery monitoring system was able to accurately measure the battery voltage, current, and temperature, and transmit the data wirelessly to the base station. The authors also noted that the system had a low power consumption and could operate for a long time on a single battery (Kutluay et al., 2005).

The LoRa technology is a type of LPWAN (low-power, wide-area network) that has become increasingly popular in recent years due to its ability to provide long-range communication at a low power consumption (Talib et al., 2022). In the study, the authors use LoRa technology to design and implement a battery monitoring system for PV applications (Talib et al., 2022). LoRa technology was first and has since gained popularity due to its ability to provide long-range communication at a low power consumption. In a paper (Peruzzi et al., 2020), the authors discuss the advantages of LoRa technology, including its long-range communication capability (up to 10 km in rural areas), low power consumption (up to 10 years' battery life), and high interference immunity. The authors also note that LoRa technology is suitable for a wide range of applications, including smart cities, agriculture, and industrial monitoring (Prodanović et al., 2020).

In a study (Mu'Amar, Hernandez, 2018), the authors compare LoRa technology with other LPWAN technologies, including Sigfox and NB-IoT (Mu'Amar, Hernandez, 2018). The authors find that LoRa technology outperforms other LPWAN technologies in terms of long-range communication, low power consumption, and low cost. They conclude that LoRa technology is well-suited for applications that require long-range communication and low power consumption, such as smart agriculture and smart cities (Hernandez, 2018).

Despite its advantages, LoRa technology also has some limitations. In a study (Raza et al., 2016), the authors identify several limitations of LoRa technology, including its limited data rate (up to 50 kbps), susceptibility to interference from other LoRa networks, and the need for a clear line-of-sight for long-range communication (Raza et al., 2016). The authors suggest that LoRa technology may not be suitable for applications that require high data rates or are located in areas with high levels of interference (Raza et al., 2016).

2.2. SYSTEM OF SOLAR ENERGY

Solar power plants are equipped with all of the features necessary to deploying industry equipment and cutting-edge previous knowledge that are capable of reacting to shifting dynamic conditions (Mekhilef et al., 2011). These plants also have all of the needed characteristics for employing industrial electronics (uncertainties and nonlinearities). As a result of increased control system reaction, an increase in the operational hours of the solar plants would result in a decrease in the price each kilowatt-hour generated (Mekhilef et al., 2011).

Solar energy can be converted into usable electricity in a number of different ways. Two of these ways involve the production of steam, which is then put to use in driving a turbine. These processes are referred to, respectively, as photovoltaics and collecting and concentrating solar power (CSP) (Sezer et al., 2019). The generation of direct current (DC) electricity from solar energy is predicated on a phenomenon known as the photovoltaic effect, which explains how photons of light can raise the energy level of electrons (Gandini et al., 2017). In spite of the fact that PVs were initially used to power spacecraft, there are a number of applications for PV power production that can be used in day-to-day life (Mekhilef et al., 2011). Some examples of these applications include roadside crisis telephones, grid-free homes, solvent extraction pumps, electric batteries, solvent extraction pumps, and remote sensing Using optical devices (typically mirrors) and Sun tracking systems, concentrating solar thermal (CST) systems concentrate a wide area of sunlight onto a smaller receiving area (Sezer et al., 2019). Solar energy can be converted into usable electricity in a number of different ways. Two of these ways involve the production of steam, which is then put to use in driving a turbine. These processes are referred to, respectively, as photovoltaics (PV) and collecting and concentrating solar power (CSP). The typical power plant draws its heat from concentrated solar energy, which is used to generate electricity. There are several different focusing technologies that can be utilized. The most important ones are as follows (Sezer et al., 2019):

- Parabola trough,
- Solar lenses,
- Linear Fresnels,
- Photovoltaic energy generating buildings.

Concentrating the sun's rays in this way has as its primary goal the production of enormous amounts of heat while maintaining a high thermal efficiency (Tahat et al., 2011). Below are two unnecessary hurdles of different solar systems:

- The resultant energy prices are regrettably not comparable with other sources of power.
- Renewable radiation is not always available whenever it is required.

Much studies have been conducted on methods which may assist in overcoming these limits; one such strategy is control (Tahat et al., 2011). Low Orbit around earth space-based operations are characterized by a large increase in electrical demand. It is projected that the space station would begin operations with 75 kW, in contrast to the 25 kW that will be used for other space projects (Tahat et al., 2011). Solar power is not a good option for installations of that magnitude because of its low conversion efficiency; also, the large absorbent surface area results in a considerable drag loss. In contrast, the batteries required for the storing of electric power are extremely heavy and have a limited life as reviewed by (Tahat et al., 2011). Utilizing higher thermal cycles to generate solar-powered energy is a preferable strategy. In this instance, the heat storage unit of the converter system is absolutely necessary for transitioning between the phases of the eclipse. The heat charge and discharge transient periods are on the scale of one hour, and the operational storage temperature ranges from 900 to 1200 Kelvin.

Thermal storage as latent heat in a solid-liquid phase transition has been demonstrated to be a desirable form of energy storage in two distinct methods (Tahat et al., 2011):

- Offers a large storage space, which is essential for any space-related projects.
- Due to the fact that heat is both stored and released at a temperature that is always the same, the thermodynamic cycle can benefit from temperatures that vary by only a little amount.

2.3. LORA TECHNOLOGY

LoRa (short for Long Range) is a wireless communication technology that allows devices to communicate over long distances with low power consumption (Qu et al. 2022). Integrating Lora technology with a monitoring system can provide a reliable and cost-effective solution for monitoring remote assets and transmitting data back to a central location (Sheng et al. 2020). To integrate Lora technology with a monitoring system, you will need Lora-enabled sensors and a Lora gateway. The sensors will collect data from the assets being monitored and transmit it using the Lora protocol. The LoRa gateway will receive the data from the sensors and transmit it over the internet or other network to the monitoring system (Sheng et al. 2020).

The monitoring system can be a cloud-based platform or a local server-based system. The data collected by the sensors can be analyzed and processed by the monitoring system to provide valuable insights and alerts (Ben et al., n.d.). For example, in an industrial setting, Lora sensors can be used to monitor equipment and detect abnormalities such as abnormal temperature or vibration levels, which can be used to trigger maintenance or repair activities (Sheng et al. 2020). When integrating Lora technology with a monitoring system, it's important to ensure that the sensors and gateway are configured correctly and that the network infrastructure is optimized for Lora communications (Ben et al., 2021). This includes selecting the appropriate frequency band, ensuring that there are no interference sources, and optimizing the placement of the sensors and gateway to maximize signal strength and minimize power consumption (Ben et al., 2021).

Table 2: Lora technology integration with the EMS.

ASPECT	DESCRIPTION
Sensors	Lora-enabled battery monitoring sensors are placed on each battery to collect data.
Gateway	A Lora gateway is installed in the battery room to receive and transmit data from the sensors.
Network infrastructure	The Lora network must be optimized to minimize interference and maximize signal strength.
Monitoring platform	A cloud-based monitoring platform is used to collect process and analyze the data.
Data collection	Data is collected on battery voltage, temperature, and other parameters.

Alerts and notifications	The monitoring system sends alerts and notifications when battery parameters fall outside set thresholds.

The binary data in LoRa is converted into a chirp signal, as illustrated in Figure 4. This signal representation consistently assigns a certain number of bits to each chirp, such as 7 bits in this case (Ben et al., 2021). When employing LoRa modulation in SF7, the bits are arranged into packets of SF bits, with each packet represented by a specific symbol chosen from two possible forms of symbols. Each chirp, composed of 10 bits, undergoes a transition from a high frequency to a low frequency. Consequently, the LoRa frame comprises a sequence of these chirps transmitted through the air (Ben et al., 2021).

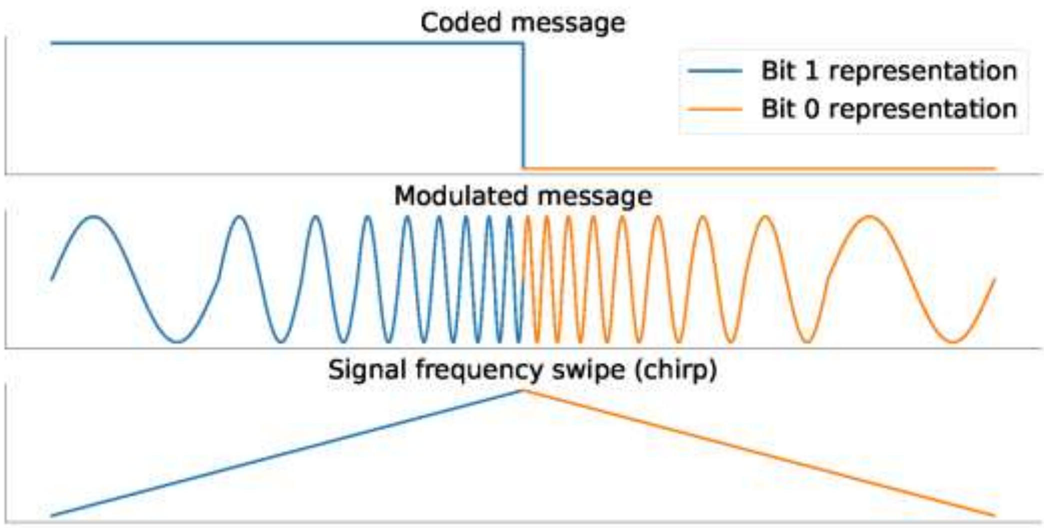


Figure 4. LoRa modulation of one and zero bit with chirps signals (Ben et al., 2021).

In LoRa, the duration of symbol transmission is contingent upon the selected spreading factor (SF), thereby associating each frame with a specific SF (Ben et al., 2021). Consequently, there exists a correlation among communication range, emission time, and the SF employed (Ben et al., 2021). As the SF increases, the transmission rate slows down, consequently extending the communication range (Ben et al., 2021). For instance, within a 125 kHz bandwidth, the emission time for an SF11 symbol is double that of an SF10 symbol, progressing in a similar manner up to SF12 for the same bandwidth (Ben et al., 2021). In LoRa transmissions, it is not solely data that is conveyed; rather, certain specifications must also be transmitted to frame the data (Ben et al., 2021). As a result, the frame consists of several components: a header used for synchronizing the transmitter and receiver, a payload containing user data, which can vary in size from 51 to 222 bytes based on the SF, and a cyclic redundancy check (CRC) to detect errors. This configuration is illustrated in Figure 5 (Ben et al., 2021).

Figure 5. LoRa frame (Ben et al., 2021).

The spreading code size directly influences the system's ability to transmit data effectively in noisy environments. Table 3 below illustrates the signal-to-noise ratios required to achieve successful transmission across various Spreading Factors (SF).

Table 3. Range of spreading factors (Ben et al., 2021).

Spreading factor (SF)	Spreading factor Chips/ symbol	Time on air by 10 bytes data packets	LoRa demodulator SNR
6	64	0.1 sec	-5 dB
7	128	0.1 sec	-7.5 dB
8	256	0.1 sec	-10 dB
9	512	0.25 sec	-12.5 dB
10	1024	0.25 sec	-15 dB
11	2048	0.5 sec	-17dB
12	4096	1 sec	-20 dB

LoRaWAN, a Low Power Wide Area Network (LPWAN) communication protocol standardized by the LoRa Alliance, utilizes the LoRa physical layer to facilitate long-range wireless connectivity. It is designed to enable the wireless connection of battery-operated devices to the internet across regional, national, or global networks (Ben et al., 2021). With a maximum data rate of 27 kbps, LoRaWAN allows only the gateway to gather data from multiple nodes deployed kilometers away (Ben et al., 2021).

This LPWAN technology has gained significant traction due to its long-range capabilities, low power consumption, and cost-effectiveness (Ben et al., 2021). With over 167 countries hosting LoRaWAN network deployments, involving 121 Public Telecom operators across 58 countries, its widespread adoption is evident (Ben et al., 2021). However, the varying frequency bands permitted for ISM applications in different countries pose a challenge, as sensors configured for one frequency band may not function on others without reconfiguration. LoRaWAN networks typically employ a star topology, simplifying network complexity and conserving battery life for connected devices. In this topology, each end-device communicates directly with gateways, eliminating the need for data propagation or forwarding among nodes.

Figure 6 illustrates the key components of a LoRaWAN network, including end-devices, gateways, network servers, and applications. End-devices utilize LoRa and LoRaWAN technologies for communication, while gateways transmit LoRaWAN frames from end-devices to network servers via higer-throughput back-haul interfaces such as Ethernet, 3G/4G, satellite, or Wi-Fi (Ben et al., 2021). The network server decodes packets from devices, performs security checks, and adjusts data rates as needed before generating packets to be sent back to devices. Finally, applications receive data from the network server, decode security packets, and use the information to inform application-specific actions (Ben et al., 2021).

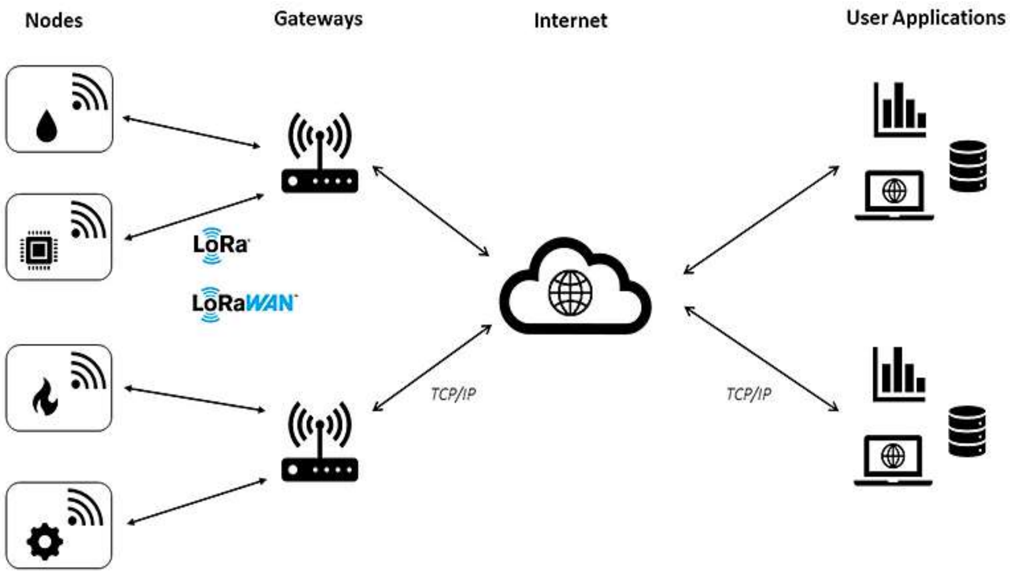


Figure 6. Architecture of LoRa WAN networks (Ben et al., 2021).

LoRa is a low-power wide-area network (LPWAN) technology specifically designed for Internet of Things (IoT) applications (Ben et al., 2021). It utilizes a unique modulation scheme called Chirp Spread Spectrum (CSS), which provides long-range communication, low power consumption, and robustness against interference (Ben et al., 2021). These features make LoRa a suitable option for remote and off-grid PV systems, where traditional wireless communication technologies like Wi-Fi and Bluetooth might not be effective (Ben et al., 2021).

2.2.1. System for Photovoltaic Conversion

A system for photovoltaic conversion is designed to convert sunlight into electricity using photovoltaic (PV) cells, which are semiconductor devices that generate electricity when exposed to sunlight. The basic components of a photovoltaic conversion system include:

- **Solar Panels:** These are the most visible component of a PV system, consisting of multiple PV cells connected together to form a panel. Solar panels can be either monocrystalline or polycrystalline, with monocrystalline panels being more efficient but also more expensive (Meral et al., 2011).

- **Mounting System:** This component holds the solar panels in place and is designed to optimize the angle and orientation of the panels for maximum sunlight exposure. Tracking systems can be added to adjust the angle of the panels throughout the day to follow the sun's path across the sky (Meral et al., 2011).
- **Inverter:** The inverter converts the direct current (DC) generated by the solar panels into alternating current (AC), which is the type of electricity used by most household appliances and the electrical grid (Meral et al., 2011).
- **Balance of System (BOS):** This includes all the additional components required for a functioning PV system, such as wiring, fuses, switches, and monitoring systems (Meral et al., 2011).
- **Energy Storage:** Some PV systems include batteries to store excess electricity generated during periods of high sunlight for use during periods of low sunlight or at night. Energy storage allows for greater energy independence and can increase the overall efficiency of the system (Meral et al., 2011).
- **Grid Connection:** If a PV system is connected to the electrical grid, it allows excess electricity generated by the system to be fed back into the grid, providing a source of income for the system owner. In some cases, this can offset the cost of electricity purchased from the grid during periods of low sunlight (Meral et al., 2011).
- **Monitoring and Maintenance:** Regular monitoring and maintenance are essential to ensure the optimal performance of a PV system. Monitoring can be done remotely using specialized software, while maintenance typically includes cleaning the panels and checking the overall health of the system components (Meral et al., 2011).

The variation of the acting forces is plotted as a function of the vehicle velocity. The graph was made considering that the vehicle is moving on a horizontal plane, where the slope is zero. From this graph, we can observe that about 2.0 kW is needed to overcome the aerodynamic drag and the rolling resistance frictions. It is also worth noting that aerodynamic drag friction does not have a significant effect on vehicle energy consumption and is mostly insignificant for lower velocities (up to

15 km/h). This is to expect because the velocity of this vehicle is relatively small (v_{max} = 43.2 km/h). Meanwhile, rolling resistance friction cannot be ignored, as it depends on the type of road, tires, etc., causing its contribution to be present in all ranges of velocity values (Meral et al., 2011).

The contribution of gravitational force is also investigated for various cases of road slopes. Looking at the figure 6, it becomes clear that gravitational force is the biggest contributing factor for energy consumption. For example, for the PV batteries on a flat plane, the total required power is within the range, while for an inclination of 5%, which corresponds to 2.86 degrees, about 8.8 kW is needed to overcome the acting forces in the PV batteries, etc. This is to be expected because the instantaneous power provided at the wheels increases with the increasing velocity (Meral et al., 2011).

2.4. PV SYSTEMS OF STAND-ALONE

Solar energy has a significant amount of untapped potential, and the direct conversion method that uses photovoltaics to generate electricity has several benefits, particularly in less populated areas. In this sense, one of the most important alternative energy sources is the photovoltaic (PV) system (Egido et al., 1992). PV energy generation is particularly attractive as a power source in rural areas with plentiful solar radiation throughout the year because it is clean, infinitely available, and very dependable (Egido et al., 1992).

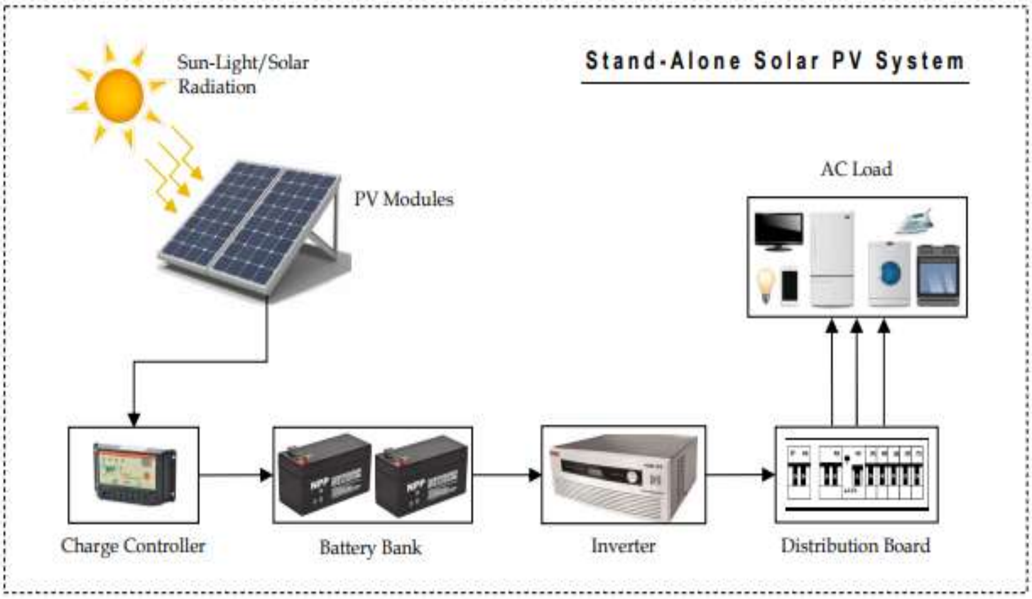


Figure 7. Diagram of a stand-alone Photovoltaics system (Ali et al., 2019).

A photovoltaic (PV) cell generates electricity using sunshine (Ali et al., 2019). The photovoltaic (PV) cell, often known as a solar cell, is the primary element of a PV system. In general, a single PV cell does not amount to very much. PV cells are joined to one another to create modules, which are then connected to one another in order to create arrays, which are bigger units. In order to meet the required electrical demand, these arrays are interconnected using both parallel and series configurations (Ali et al., 2019). Since PV arrays generate electricity only when exposed to light, it's common practice to incorporate a significant energy storage system, typically consisting of a bank of rechargeable batteries (Ali et al., 2019). PV arrays produce electricity only when they are illuminated. Charge controllers and converters are necessary for driving AC loads, preventing overchargingand over discharging of batteries, and preventing these circumstances from arising in the first place (Ali et al., 2019). When designing a freestanding photovoltaic (PV) system, one of the most important aspects of system design is determining the appropriate dimensions for the PV array, inverter, and battery bank (Ali et al., 2019). This section comprises details on solar irradiance for the proposed selected location, load and output for Photovoltaic cells, inverters, and battery, as well as data on the operational excellence of these equipment and their respective systems

(Ali et al., 2019). The schematic representation of a stand-alone PV system is shown in Figure 7 (Ali et al., 2019).

2.3.1. Basics and Analysis of Stand-Alone PV Systems

Photovoltaic modules are required for an autonomous PV system. PV module is the principal energy conversion element of a PV generator system as mentioned in (Ali et al., 2019; Egido et al., 1992). The link, which is not linear, between the output of a photovoltaic module's process and the amount of sunlight radiation and the temperature of the cell. They are not photovoltaic cells; rather, they are big area semiconductor diodes (Egido et al., 1992). The photovoltaic effect is the conversion of light's (photons') energy into electrical current. In the similar circuit for the simplest solar cell, the diode and source of current are linked in parallel. The amount of solar radiation received is directly proportional to the source current, and the PN junction of a photovoltaic array is represented by the diode (Ali et al., 2019). The perfect photovoltaic model can be expressed mathematically by the perfect photovoltaic equation (Sheik Mohammed-A, 2011), which can be written as:

$$V_T = \frac{kT}{q} \tag{2.1}$$

Where:

T = solar cell temperature (K);

k = Boltzmann constant, $1.38 \times 10^{-23}\ J / K$;

q = charge of electron, $1.6 \times 10^{-19}\ C$.

$$I = I_{ph} - I_0 \left[\exp\left(\frac{V}{n.V_T}\right) - 1\right] \tag{2.2}$$

Where:

I_0 = reverse saturation current (A);

I_{ph} = photocurrent (A)

V_T = thermal voltage, =29.5 mV at 25℃.

V= diode voltage (V);

n= diode ideality factor.

On the other hand, in order to calculate the thermal voltage, one can use the followingequation:

The temperature of the solar cell, as stated in (2), is described as:

$$T = 3.12 + 0.25G/G_{ref} + 0.899\, T_a - 1.3\, W_s + 273 \quad (2.3)$$

Where:

G_{ref} = reference irradiance intensity, 1000 W/m^2

G = irradiance intensity (W/m^2)

W_s = local wind speed m/s

T_a = ambient temperature;

The photocurrent, denoted by I_{ph}, in equation (1) is stated as being dependent on the irradiance intensity and the cell temperature in the following way:

$$I_{ph} = G/G_{ref}\, [I_{sc,f} + \mu_{I_{SC}}\, (T - T_{ref})] \quad (2.4)$$

Where:

$\mu_{I_{SC}}$ = the solar cell short-circuits temperature coefficient.

$I_{sc,f}$ = solar cell short-circuits current at reference condition

$G_{ref} = 1000\ W/m^2, T_{ref} = 25℃, Air\ mass = 1.5$

A photovoltaic system needs to have its development optimized for it to be able to satisfy the appropriate load demand at a certain degree of availability (Yang et al., 2008). The appropriate size of a freestanding photovoltaic (PV) system is highly dependent on meteorological data, such as the amount of solar radiation and the temperature of the surrounding environment (Yang et al., 2008). In determining the size of photovoltaic (PV) systems, which dictates their energy output, meteorological variables play a crucial role (Yang et al., 2008). Currently, efforts are underway to develop scaling methods for standalone PV systems. These endeavors aim to optimize the selection of PV modules, storage battery capacity, and inverter size for maximum efficiency (Yang et al., 2008). Comprehensive understanding of various factors including data sources, mathematical models of system components, sizing techniques, government energy policies, and user requirements is essential for achieving an optimal design for standalone PV systems. This knowledge ensures that system availability is maintained within a reasonable budget (Parida et al., 2011). Figure 7 illustrates the essential components of a standalone PV system, while Figure 8 demonstrates a DC-connected setup of an independent PV system alongside an AC-connected PV system design (Parida et al., 2011).

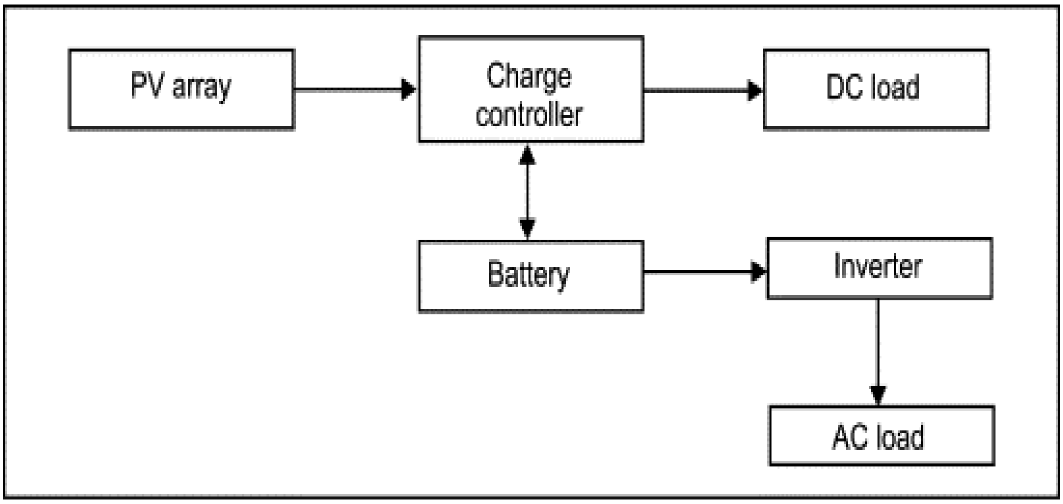


Figure 8. Components typical of a stand-alone Photovoltaics system (Ekren et al., 2008).

In order to effectively utilize solar radiation and temperature data in a specific area, it's crucial to categorize climatological measurements accordingly (Ekren et al., 2008). Meteorological data can be presented either as time series or statistical data. Time series data breaks down meteorological parameters into manageable intervals, such as hourly weather data for solar radiation and ambient temperature (Ekren et al., 2008). Time series data offers the advantage of revealing parameter variations, leading to more accurate performance assessments of PV systems. However, collecting on-site data in remote locations poses challenges due to limited connectivity. On the other hand, statistical meteorological data, also known as synthetic weather information, is derived from monthly average data or computed solar radiation and ambient temperature for a location using statistical techniques (Ekren et al., 2008).

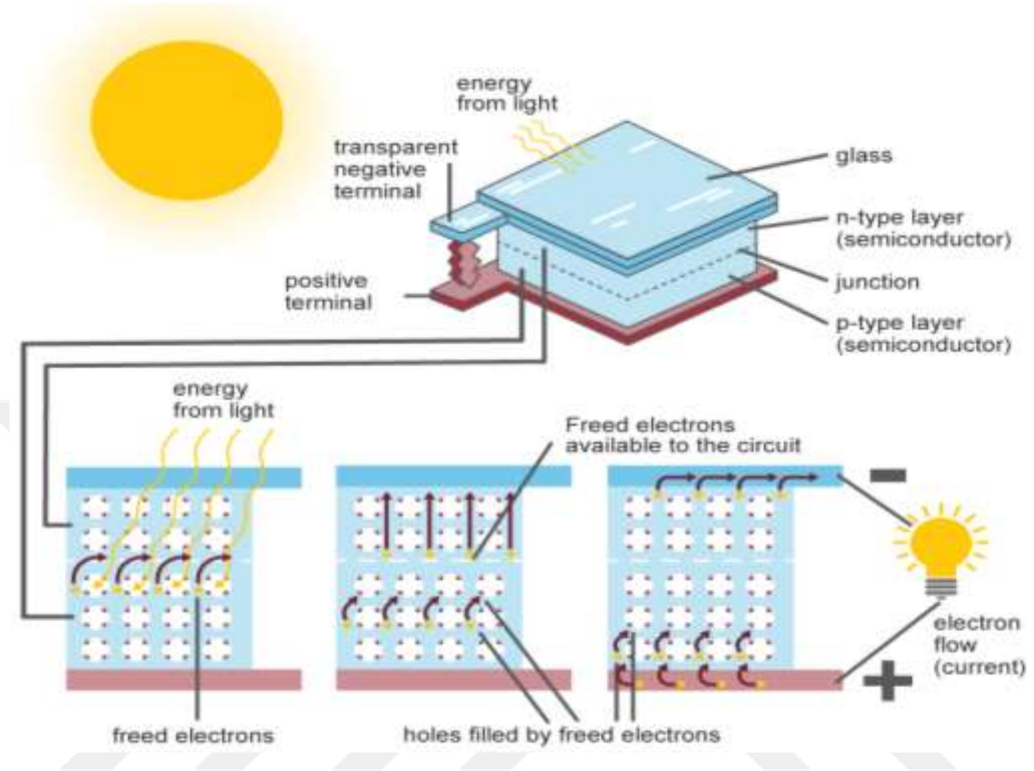


Figure 9. Number of steps required from sunlight to processing of PV based energy (Musa et al., 2015).

Using statistical weather information has the advantage to be used in place of data that is either inadequate or unavailable (Musa et al., 2015). This is one of the many benefitsof using such data, hence reducing the number of computer steps required for simulations. PV system performance is less sensitive to changes in these elements, which is a disadvantage (Musa et al., 2015). Figure 10 depicts the usual elements of a independent PV solar system, including solar cells generator, storage batteries, (DC-DC) converter, a charge controller, (DC-AC) inverter, and loads. A standalone PV plant is not connected to the utility grid (Musa et al., 2015). Typically, a photovoltaic generator is made up of a photovoltaic array, which is made up of multiple PV modules, each of which is made up of a significant number of solar cells (Rahman et al. 2018). When the output of the PV generator is greater than the needed load demand, energy is stored in the storage battery; conversely, when the output of the photovoltaic generator is inadequate, the battery discharges the energy that it has stored (Rahman et al. 2018). The load requirement of a standalone photovoltaic system may be a combination of AC and/or DC loads. By serving as a link between all the system parts, the power conditioning unit controls and safeguards the PV system (Chouder et al. 2012). Typical power conditioner unit components include the inverter, charge controller, and DC/DC converter (Hansen et al., 2000). In addition, the damping load is responsible for limiting the amount of excess energy generated whenever the production of the PV array is greater than the load needs and the storage cells are simultaneously charged to their max capability (Chouder et al. 2012).

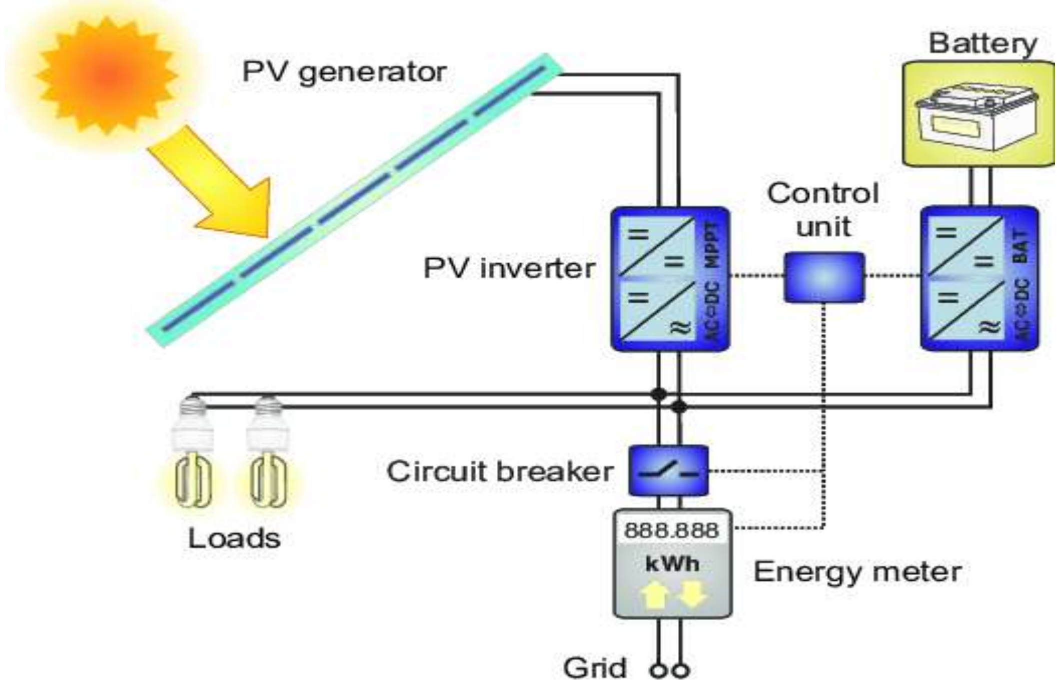


Figure 10. AC linked arrangement of an independent PV system (Weniger et al., 2014).

It is difficult to track the efficiency of a tiny PV system that is operating on its own, as these systems are often constrained by size and price limits due to the fact that commercial data loggers are prohibitively expensive relative to the total cost of the PV system, require specialized software, and must typically be constantly connected to a PC (Musa et al., 2015; Weniger et al., 2014). Additional development of precise, self-sufficient, and cost-effective data loggers is required for the monitoring of small, freestanding PV systems. Numerous studies have been conducted to develop an approach for sizing PV systems that is both user-friendly and extremely dependable (Musa et al., 2015). The majority of these strategies rely on a constant system load and govern the parameters that influence their dependability. In most cases, methods that are based on the idea of power supply throughout the course of a number of days spent operating independently are utilized (Musa et al., 2015). These straightforward steps ensure that the PV system will meet the essential reliability standards on a variety of days (Weniger et al., 2014). These solutions adjust the storage system so that it is appropriate for the load that is being carried. It is generally accepted that the capacity of the storage system can serve as an indicator of the reliability of a Photovoltaic. As a result, the number of days of autonomy serves as the criterion for reliability (Musa et al., 2015). When adopting these methods, there is no direct correlation between the amount of energy that can be stored in the system and the amount of energy that can be generated by the Photovoltaic system as mentioned by (Weniger et al., 2014). In addition, the total size of a solar photovoltaic system's PV array in conjunction with its battery bank is not always an acceptable measure. The evaluation and characterization of daily energy balances serve as the foundation for the development of a method (Posadillo et al., 2008). When these procedures are used, the results that are achieved are able tobe generalized further. Another method for building a freestanding PV system is one that is based on the ability of the load to receive energy in a reliable manner. This ability is frequently quantified by the probability of a power supply failure (LPSP), etc., and can be used as the foundation for building a freestanding PV system (Posadillo et al., 2008). This idea refers to the connection that exists between the energy shortfall and the demand for energy for theentirety of the system's operating lifetime. The LLP number is a statistical representation of the probability that the system will be unable to satisfy the demand for energy (Posadillo et al., 2008). Due to the unpredictable nature of solar energy, photovoltaic systems necessitate meticulous calibration to attain optimal performance concerning energy utilization and cost-effectiveness (Katzman et al., 1983). The cost associated with generating renewable energy plays a pivotal role in determining the efficiency of renewable energy systems

(Posadillo et al., 2008).Wind, solar photovoltaic (solar PV), small hydro (SH), and biomass were the four types of renewable energy technologies (RET) that were analyzed by Hernández et al. in their research on the development of RET in Spain over the past ten years. The findings of the study indicate that Spain is capable of meeting the objective for the generation of renewable energy (RE), but doing so would not be cost- effective (Posadillo et al., 2008). The measurements need to find a happy medium between affordability and durability in terms of sizing (Posadillo et al., 2008). Accurate sizing guarantees demand satisfaction and allows for future cost reductions. This will enable the incorporation of these systems into the market for renewable energy sources (Posadillo et al., 2008). When determining the size of a photovoltaic (PV) system, it is important to consider the capacity of the battery, which is defined as the total number of maximum current units it can hold (Posadillo et al., 2008). Due to the introduction of the Internet of Things (IoT) into solar measurement systems, it is nowpossible to undertake online monitoring of small off-grid photovoltaic systems (Posadillo et al., 2008). This improves both the functionality of the system and the quality of the service. The intelligent logger that was proposed has the capability of collecting data on electricity and climatic components, which provides information on daily energy use or output. Monitoring off-grid installations in a cheap, remote, and real-time manner is made possible by open-source software (Posadillo et al., 2008). The most important objective of this project is to make use of open-source software in order to show measurements of the electrical and climatic factors that are being tracked by the smart logger (Posadillo et al., 2008). Figure 11 is an illustration of a small-scale solar system that also includes a climatic station (Posadillo et al., 2008).

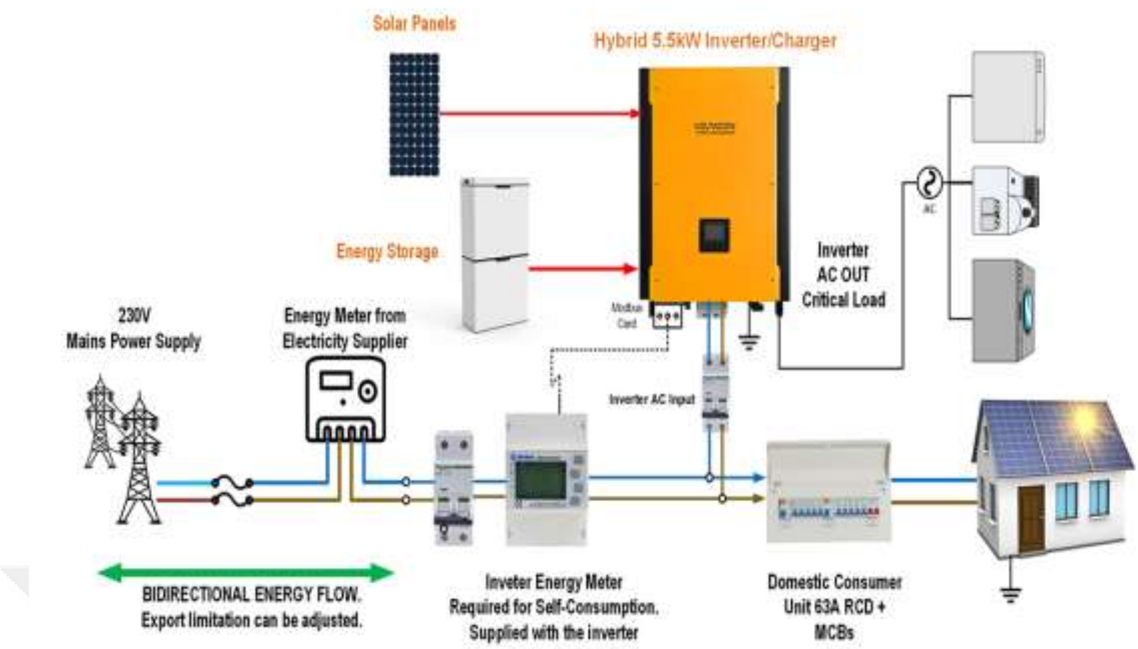


Figure 11. Block diagram of a PV based inverter attached with a battery (Posadillo et al., 2008).

2.3.2. Marketing and Advantages of Stand-Alone PV Systems

PV energy systems offer the advantages (Zeman, 2012):

1) They consist of no moving parts.
2) Do not generate any noise.
3) Need minimal or no service, are non-polluting.
4) Sustainable.
5) Quite modular and dependable.
6) May be deployed practically everywhere.

A set of interconnected components for converting solar irradiation into electricity is known as a freestanding photovoltaic system. These components typically include charge controller, Photo voltaic generator, battery, inverter, and the system load (Zeman, 2012).

Grid-off systems are PV power generation facilities that are separated from the utility grid. The following are the currently available designs for standalone PV systems:

1) The DC link voltage in solar household systems is connected to all of the consumers as well as the Photovoltaic generator (Zeman, 2012).
2) Mini AC local network with interconnected parts: This Photovoltaic technique was established as a result of the requirement to serve (minimal power) AC load with DC power and to charge the battery with DC from different sources. This PV technology was created as a consequence of the necessity(Zeman, 2012).
3) Multimodal AC connected systems: It is feasible to construct photovoltaic systems with modularizing designed components that are more flexible by coupling the PV generator to the AC and connecting all of the users(Zeman, 2012).

2.3.3. Stand-Alone PV Systems Monitoring

The adoption of open-source software has expanded dramatically and become trendy during the past decade. In recent years, the building of high-performance systems at low cost using open-source hardware (OSH) has been increasingly popular in recent years (LOpez-Vargas et al., 2018). As the Internet of Things (IoT) develops, it will become feasible to connect various pieces of apparatus and equipment and provide a cost-free option for appealing data storage (LOpez-Vargas et al., 2018). IoT makes it possible to remotely and inexpensively monitor the functioning of even the smallest stand-alone PV installations. Data is accessible via internet or mobile app (LOpez-Vargas et al., 2018). The standard for photovoltaic (PV) monitoring systems developed by the International Electro-Technical Commission (IEC) stipulates that the electrical values and meteorological values must both comply to strict accuracy standards. In the event of systems that operate independently, for example, the intelligent associated at least needs to comply with IEC61724 (LOpez-Vargas et al., 2018). Figure 12 depicts the suggested layout of the IoT-based monitoring system. The scalability of LoRa technology in the context of battery monitoring systems for PV applications is an essential consideration. examined the scalability of LoRa networks and their performance in different deployment scenarios. Their study concluded that LoRa networks can scale well, but proper network planning and management are necessary to ensure optimal performance (Bor et al. 2016).

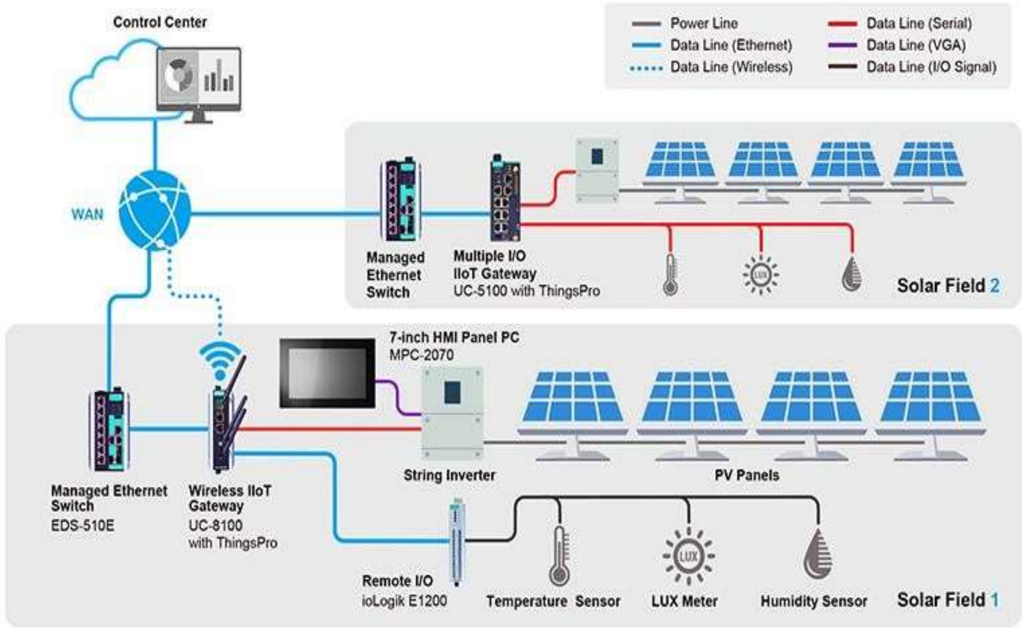


Figure 12. Architecture of an IoT-based monitoring system (Bor et al. 2016).

For many proposed methods, a web application was employed to provide online monitoring and control of remote installations. Furthermore, the grid operators receive detailed daily reports. Offline analysis of these data can be performed in order to provide statistical findings and energy performance metrics. Both the design of a SAPV system refit and the improvement of system performance can be accomplished through the examination of historical data. In order to determine whether or not the suggested remote surveillance system will be effective, the operation of a photovoltaic-powered outdoor refrigerator (Tina et al., 2014). In the case of applications that are temperature- sensitive, such as the storage of vaccinations or other things that are perishable, key control parameters have been discovered (Tina et al., 2014). These measurements were performed on a technology demonstrator that had been modified for outdoor operation with a horizontal PV module. Real-time monitoring from the standpoint of the design can uncover potential weaknesses in the design of the power supply, which enables the deployment of necessary precautions (Tina et al., 2014). In a nutshell, presented a real-time remote monitoring system that was built on Ethernet and was created specifically for PV-powered grid-off appliances (Tina et al., 2014). The system described in the study by Tina et al. (2014) is designed to monitor the primary electrical properties of a device under test (DUT) and record them in a database along with environmental factors. This system has the capability to automatically issue alerts in response to certain situations, thereby preventing DUT failure. Moreover, it incorporates a web-based application that can simultaneously monitor multiple devices located in different places. Authorized individuals can access real-time data remotely through the Internet. The investigation focuses on developing a data gathering system for remotely monitoring the operation of a photovoltaic (PV) appliance, which operates independently. Monitoring is essential for renewable energy systems to ensure their continued reliable operation. Early detection of failures leads to significant cost savings and increases the reliability of renewable energy sources. Additionally, the collected data can be used to optimize system performance. Users have access to various services such as control, monitoring, notification, reporting, and data export. Internet monitoring has proven beneficial in identifying operational issues, while post-processing of measured data validates the system's design and sizing. Manufacturers can use this information to improve their products by tailoring them to real-world conditions.

Remote monitoring significantly reduces reaction times for maintenance, repairs, and product enhancements, especially for solar-powered equipment in remote locations. Overall, remote monitoring has the potential to enhance system performance and reduce operational expenses over the PV device's lifetime.

Several technical papers and standards outline monitoring tactics to ensure that the performance data generated is reliable, objective, and representative. These monitoring strategies play a crucial role in ensuring the functionality and accuracy of the collected data.

2.3.4. MATLAB Simulink

The research involves examining, designing, and simulating a standalone photovoltaic system for a remote location. As part of this endeavor, it was deemed necessary to develop a series of simplified mathematical models for the load, wireless controller (used as a communication platform), battery, and PV generator components of the photovoltaic system (Thirumalaisamy et al., 2012). While MATLAB/Simulink was used to develop the model for the photovoltaic system components, existing research was relied on for the implementation and analysis of those components. The functionality of the photovoltaic system's components as well as their connections are evaluated (Thirumalaisamy et al., 2012).

In comparison to empirical methods of computation and sizing for the PV system, the MATLAB/Simulink program allows for modeling and sizing of complex PV systems. For an adequate evaluation of freestanding PV systems in terms of technical parameters and power performance, it is advisable to conduct short-term tests on two distinct types of days (clear sky day and partially cloudy sky day). Long-term economic evaluation of PV systems is possible, but investigating the behavior of the system's constituent components is difficult (Thirumalaisamy et al., 2012).

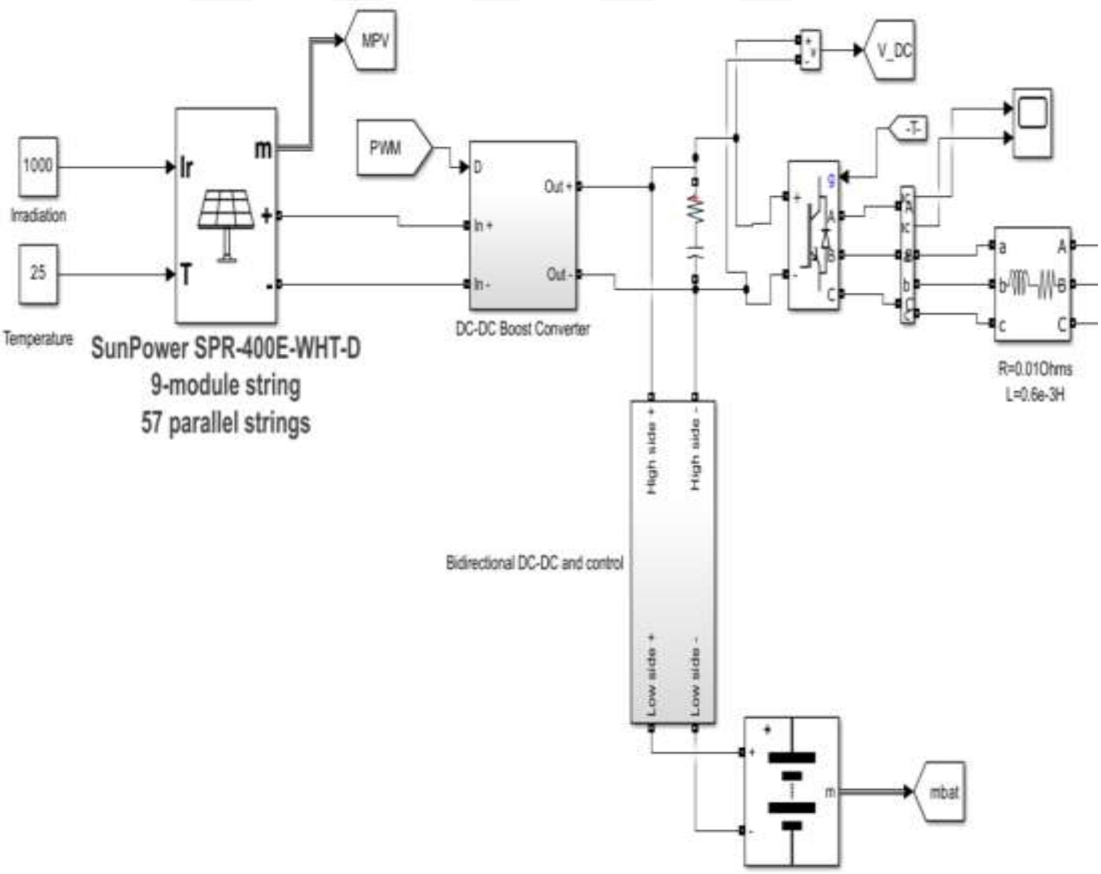
CHAPTER THREE

METHODODLOGY

The suggested system consists of two components, of which the first is the PV solar system comprising a solar cell arrays, MPPT, boost converter, battery bank, bidirectional converter, load, and controller. The second section comprises the LoRa communication and monitoring m-files simulation which are employed for transmitting and receiving significant system parameters, like voltages, current, power, and some other parameters.

3.1. The Photovoltaic (PV) solar system

Figure 13 depicts the PV system with monitoring system, which consists of boost controller, the PV array, MPPT controller and the load.



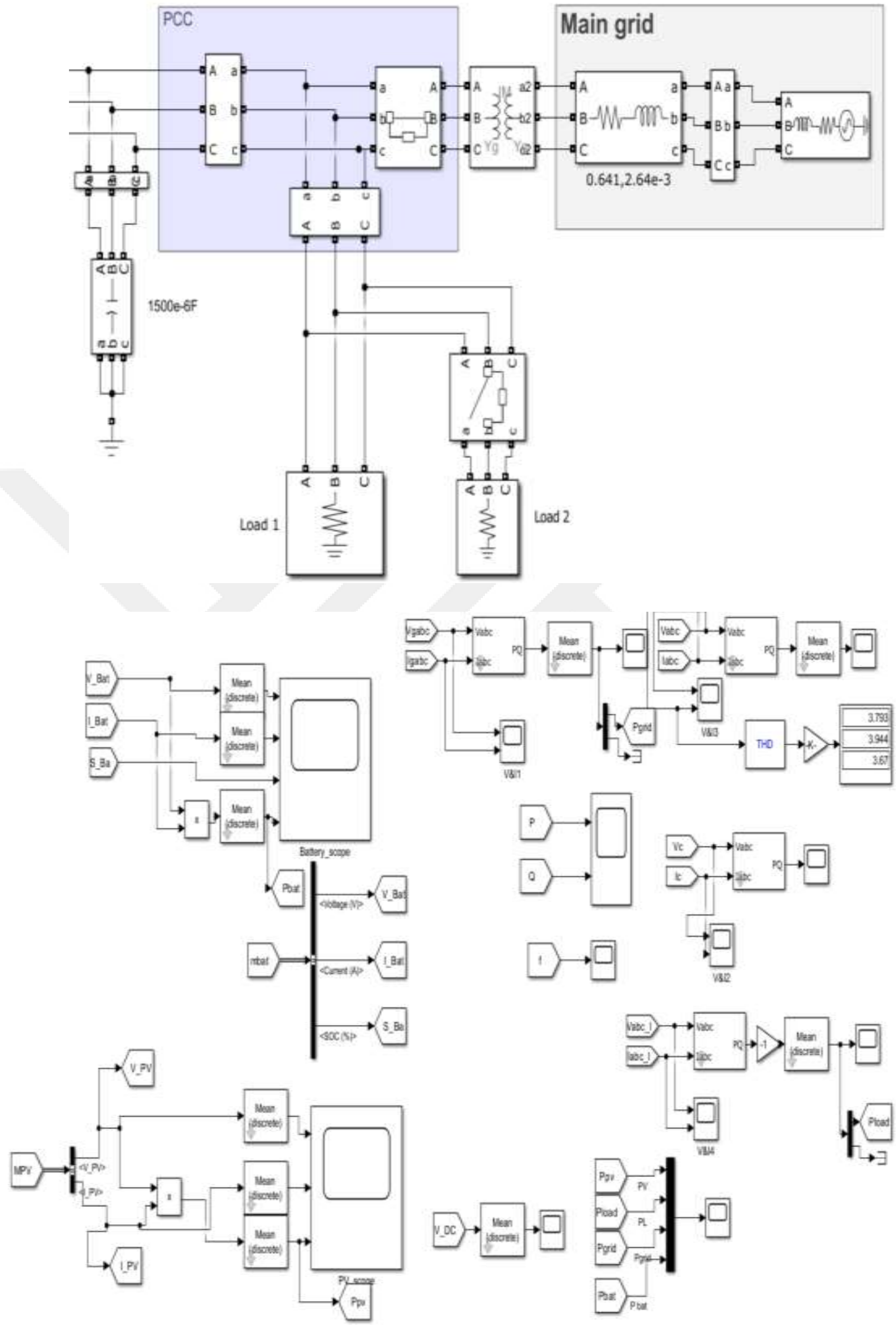


Figure 13. The PV system with the measuring system.

The proposed system outlines the configuration of complete grid connected photovoltaic (PV) three-phase AC power system with battery backup, facilitating the following objectives:

- Determine the required battery ranking depended on the connected load profile and the obtainable solar energy.

- Establish the optimal arrangement of panels, considering the number of connected series and parallel strings panels.

- Design a constant voltage three-phase AC supply.

- Choose appropriate values for the proportional gain (K_v) and of the PI controller and the phase-lead time constant (T_v).

Both the solar photovoltaic (PV) and battery storage components are capable of supporting grid-connected three-phase loads, with the load connected to a constant voltage three-phase AC supply. The solar PV system operates in two modes: maximum power point tracking (MPPT) and de-rated voltage control modes, employing a battery management system equipped with bi-directional DC-DC converters.

For MPPT of the solar PV system, the system utilizes the Perturbation and Observation (P&O) technique as one of the available MPPT techniques.

Various parameters can be specified within the system, including the average daily connected load profile, the daily available average solar energy in the region (measured in kWh), operating temperature of the solar PV system, day of autonomy, battery recharge time, output DC voltage, and specifications of the solar panels used. The determination of the number of PV panels required to meet the specified generation capability relies on data provided by the manufacturer of the solar panels.PI controller of the form $\frac{k_v(sT_v + 1)}{sT_v}$ is chosen to control the solar PV and battery management system.

3.1.1. Solar Plant Subsystem

The solar plant subsystem involves modeling a configuration with series-parallel connected strings of solar panels. Each solar panel is represented using the solar cell block sourced from the Simulink electrical library. In this illustration, the DC bus's output voltage, which varies based on temperature and irradiance, is used to estimate the number of solar panel strings connected in series. Similarly, the plant's power rating is employed to determine the number of solar panel strings connected in parallel.

It's important to note that connecting multiple panels may potentially slow down the simulation due to an increase in the model's element count. However, simulation complexity can be mitigated by assuming uniform irradiance and temperature across all solar panels. This allows for a reduction in solar elements by utilizing controlled current and voltage sources.

The specifications of the solar plant used in this study are detailed in table 4.

Table 4. Solar plant specifications details.

Parameters	**Value**
Short-circuit current Isc	5.9 A
Open circuit voltage Voc	85.3 V
Current at maximum power point Imp	5.49 A
Voltage at maximum power point Vmp	72.9 V
The maximum power of each panel	400 W
Dimensions	1686×1002 mm
Weight	18.5 kg

Figure 14 shows the Simulink model for the solar plant with their voltage and current sources devices.

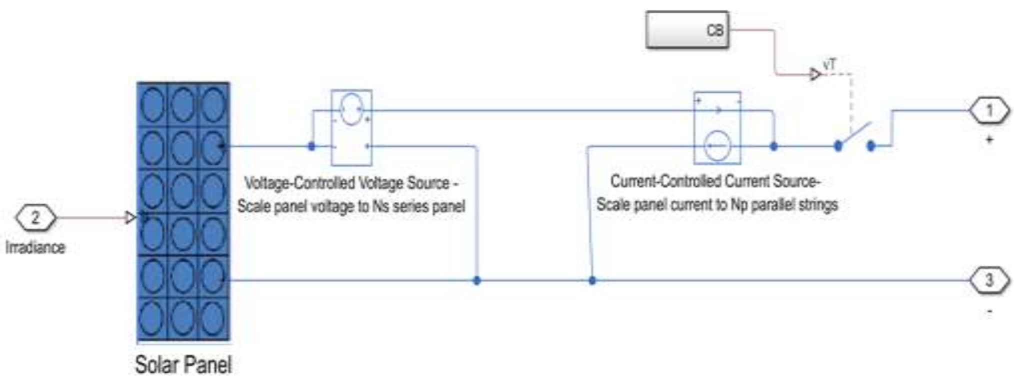


Figure 14. The solar panel subsystem

The total number of the arrays for (250 kW) and the maximum power of "SunPower SPR-400E-WTH-D" = 400W for each array are provided by:

$$N = \frac{Total\ required\ power\ (watt)}{Maximum\ power\ for\ each\ panel\ (watt)} \qquad (3.1)$$

$$N = \frac{200\ kW}{400\ W} = 500\ array\ matrix$$

The layout of PV (photovoltaic) array farms necessitates arranging parallel and series arrays in a specific configuration to meet the desired voltage and current as per the design specifications. The variables N_p and N_s denote the number of parallel and series arrays, respectively. This arrangement can be mathematically expressed as follows:

$$N_T = N_p \times N_s \qquad (3.2)$$

Here, N_p represents the number of parallel arrays, N_s represents the number of series arrays, and the total number of PV arrays is the product of these two values. This expression helps define the overall layout and connectivity of the PV array system to meet the electrical specifications outlined in the design process.

The total number of arrays in series N_s can be calculated from [53]:

$$N_s = \frac{Boost\ input\ Vdc}{pv\ array\ V_{mpp}} \qquad (3.3)$$

Where,

$$V_{L-L} = 0.612\ m \times (Vdc)_{\text{inverter}} \qquad (3.4)$$

Where m is the modulation index and is set to 0.85 and the V_{L-} is 380V, the inverter Vdc of is 800V, the inverter Vdc is chosen to be 800 V. The boost converter duty cycle is 0.5. The output voltage of PV is the input voltage of the boost converter=650v.

$$N_s = \frac{650}{72.9} = 9\ strings$$

The total series number of arrays N_s is 9, and by applying Equation (3.2), the total parallel number of arrays N_p is [45]:

$N_p = \frac{500}{9} = 56\ strings$

The voltage, current, and power of the proposed PV solar system can be calculated as:

$V_{PV} = N_s \times V_{mppt}$ = 9 ×72.9 = 656 V

$I_{PV} = N_p \times I_{mppt}$ = 56× 5.49 =307.44 A

$P_{PV} = V_{PV} \times I_{PV}$ = 656 × 307.4 ≈ 200 kW

The specifications of the proposed PV system is shown in Table 4.

Table 5. The proposed PV system Specifications Details.

Parameters	**Value**
Series Panels No. (N_s)	9
Parallel Panels No.(N_p)	56
Total Panels No. (N)	500
MPPT Voltage of PV System	656 V
MPPT Current of the PV System	307A
Total Power	201.6 kW

Figure 15 depicts the I-V and P-V curve characteristics of the chosen PV of 9 series modules and 57 parallel strings at a constant temperature of 25°C with the irradiance levels of 1000W/m^2.

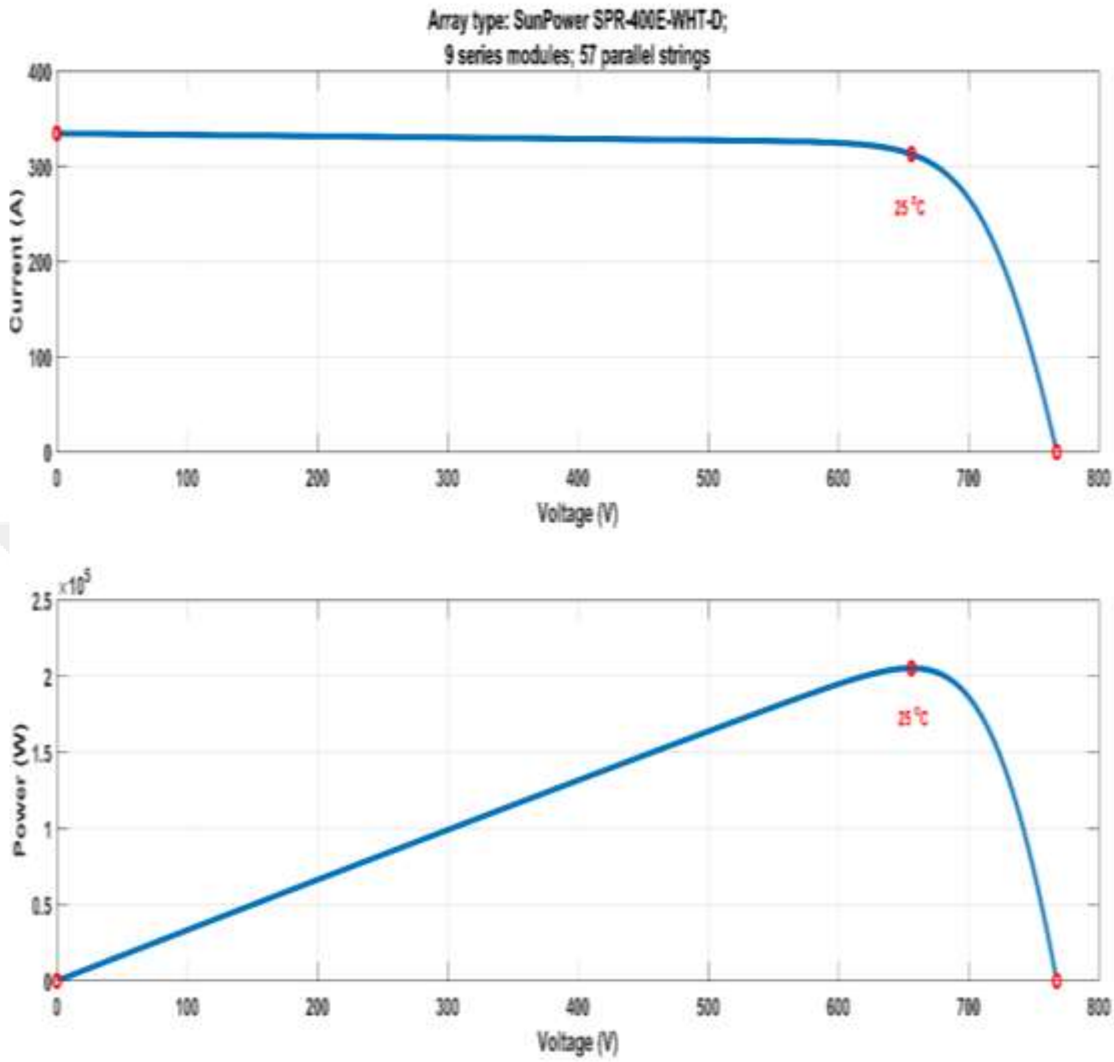


Figure 15. I/V and P/V characteristic curves at temperature of 25°C with 1(kW/m^2)

3.1.2. Boost DC-DC Converter

The Boost DC-DC converter plays a pivotal role in regulating the solar PV power system. Specifically, when the battery hasn't reached full charge, the solar PV plant operates in the maximum power point mode. In this mode, the system optimizes power output. Conversely, when the battery achieves full charge and the load demand is lower than the PV power generated, the solar PV system seamlessly transitions to a constant output DC bus voltage control mode. This operational mode ensures stability and control over the DC bus voltage, adapting the system to varying conditions and demands. Figure 16 shows the Simulink model for the boost converter, while the converter parameters are listed in table 5.

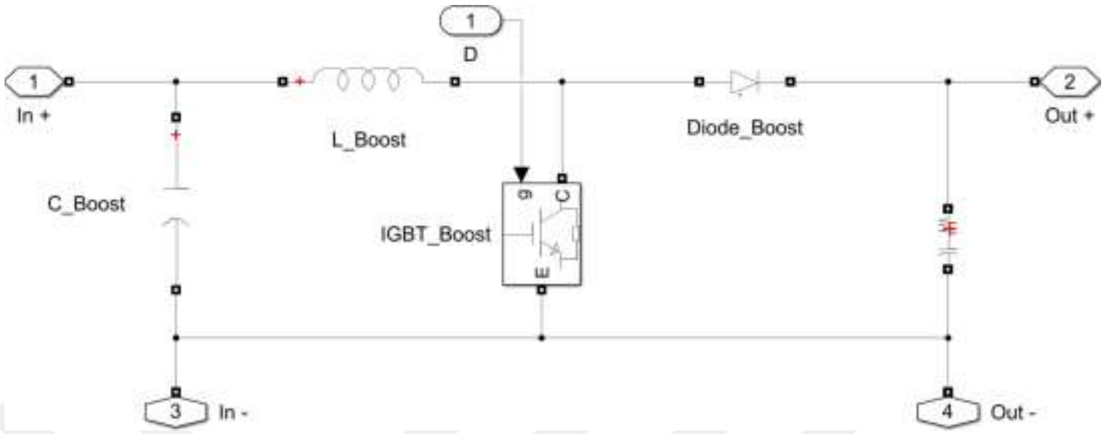


Figure 16. DC-DC Boost or Up Converter

Table 6. Boost or Up converter parameters

Inductor	Resistor	IGBT	Diode	Capacitor	Freq.
0.0118H	0.1061Ω	Forward V: 0.8V On-resistance: 0.001 Ω Off-conductance: 1e-51/ Ω Threshold voltage: 2.5	Forward V: 0.8V On-resistance: 0.3 Ω Off-conductance: 1e-81/ Ω	1mF	20 kHz

It should be noted that, in the proposed system, P&O MPPT technique is implemented that can be used using the variant subsystem.

3.1.3. Bidirectional Battery Management System

For developing a suitable management system for the charging or discharging the battery, a bi-directional or two-way DC-DC converter, as shown in Figure 17, takes center stage. Employing a buck converter configuration facilitates the charging of the battery, while the boost converter configuration handles the discharge process. This dual-mode operation enhances battery performance and prolongs its life cycle, emphasizing the importance of controlled charging and discharging. To ensure optimal battery functionality, this proposed system imposes restrictions on the maximum charging and discharging currents for contributing to an extended battery life and improved overall system efficiency. Notably, the maximum charging power aligns with the solar plant capacity under standard test conditions. In an effort to expedite the battery recharge process, the chosen maximum charging power exceeds the user-specified battery recharge time. This strategic decision aims to enhance the system's responsiveness to user requirements and expectations. For precise control, distinct controllers manage the charging and discharging operations. The Battery Management System controller features two essential loops: an outer voltage loop and an inner current loop with PI controller. This dual-loop configuration optimally regulates the charging and discharging processes, ensuring the battery operates within specified parameters.

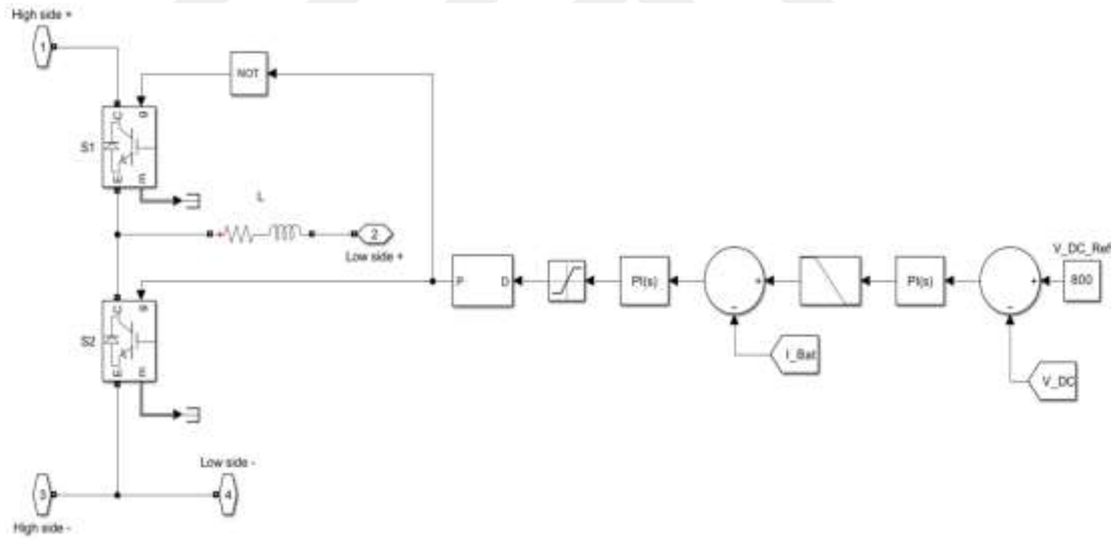


Figure 17. Bi-directional converter EMS

3.1.4. Three-Phase Grid AC Power Supply

The unswerving provision of a constant AC voltage to the interconnected intricate loads is facilitated by the three-phase constant voltage AC power supply with range of

(380-400)V (RMS voltage). Illustrated in Figure 18, a three-phase with pulse width modulation (PWM) inverter transforms the boosted DC voltage from the converter into sinusoidal three-phase AC voltage supply. The generated sine waves are transferred through a transmission line that represented by RL-circuit with (R=0.01Ω, L=0.6mH) for ensuring a seamless AC supply to the load, the model incorporates an LC filter with C=1.5mF to guarantee a refined and stable output.

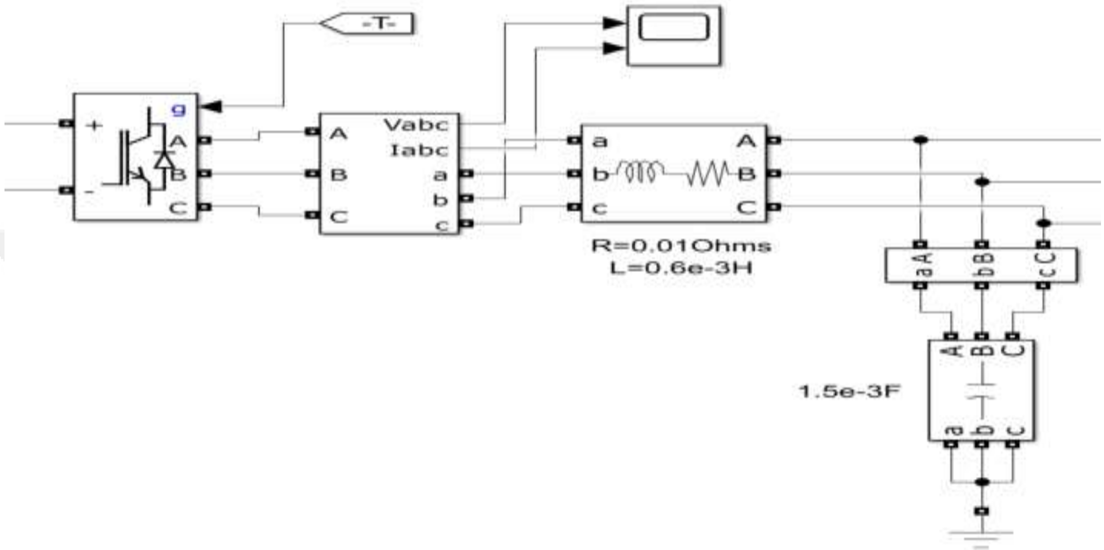


Figure 18. DC/AC inverter with LC filter

3.1.5. Load

A RL load is connected to the AC inverter's output. The load power varied between 1 and 2.5 kW with constant AC voltage power supply with RMS voltage of 380V as shown in figure 19.

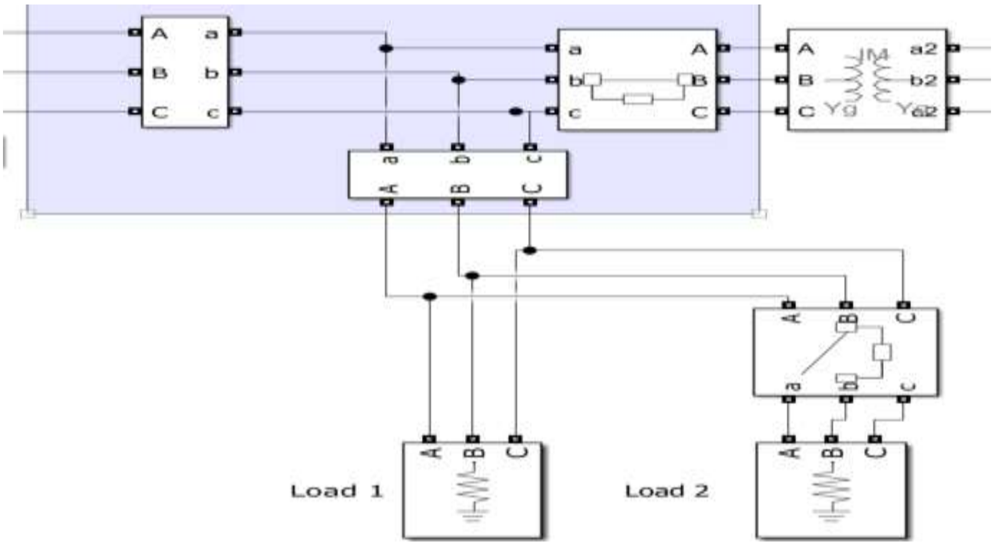


Figure 19. A varying RL load

3.1.6. Main grid

The grid can generated sine waves that are transferred through a transmission line that represented by RL-circuit with (R=0.641Ω, L=2.64mH) for ensuring a seamless AC supply to the load as shown in figure 20.

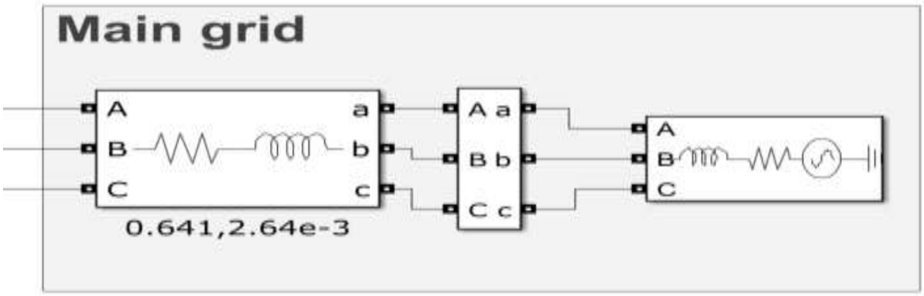


Figure 20. The main grid

3.1.7. Solar Irradiance

To simulate the solar operation its required to make solar radiation varied from zero to 1000 W/m^2, with STC temperature with T=25°C. Figure 15 shows the used solar radiation parameters.

3.2. LoRa Simulation

An m-file MATLAB file code used to simulate LoRa transceiver to calculate BER and required transmission power and SNR. LoRa simulation based on the m-file code published by (Al Homssi et al., 2021). The published code used to simulate LoRa communication system for “Multiple-Frequency-Shift-Keying (MFSK)” modulation in both coherent and none-coherent techniques, and also the system simulated for two types of noise: AGWN and Rayleigh noises. The LoRa overall model is shown in figure 21.

The solar plant voltage, current, irradiance and power are transmitted over LoRa communication system and monitored in the remote-control room. The proposed system simulated for all possible operating cases. The simulation results are discussed in chapter four. Proposed system flow chart is shown in figure 22.

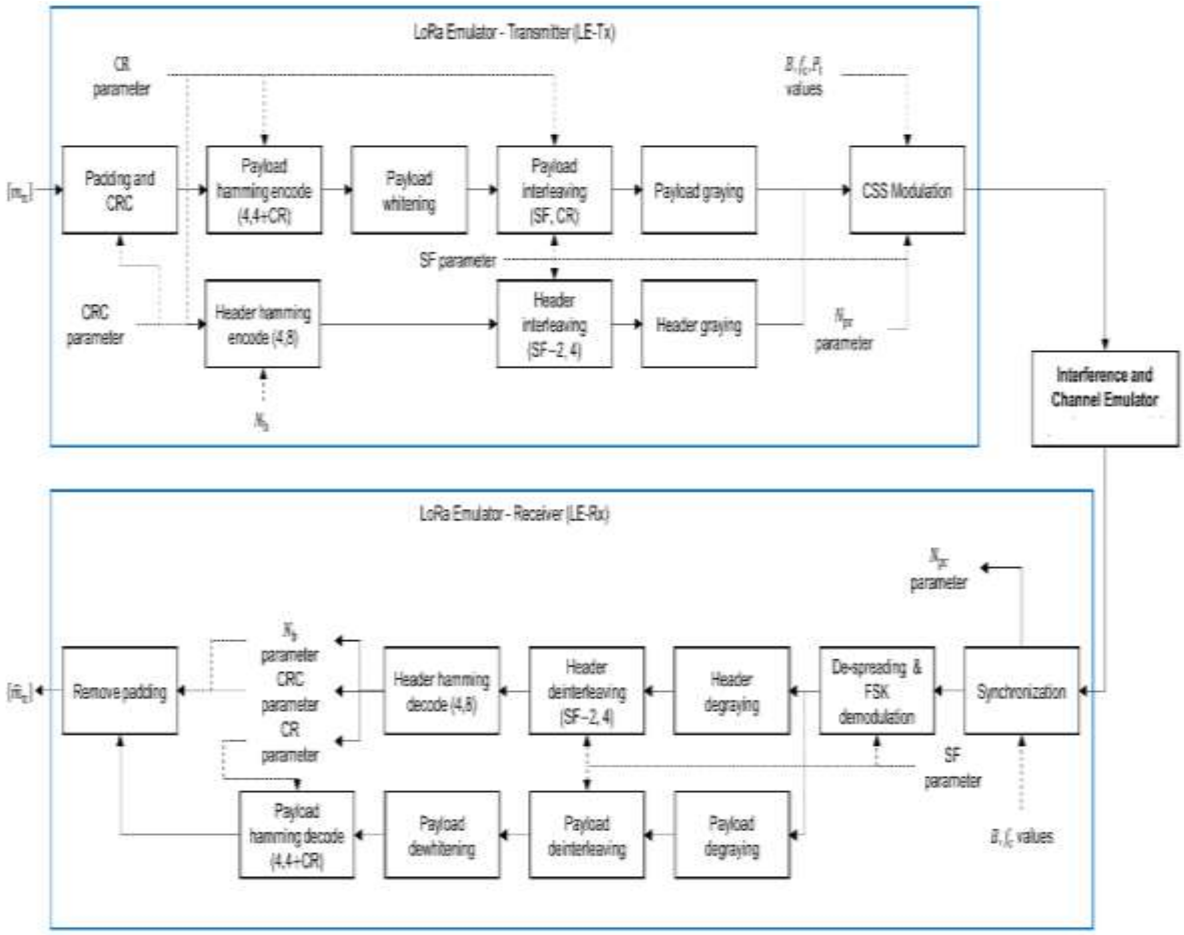


Figure 21. LoRa application model (Al Homssi et al., 2021)

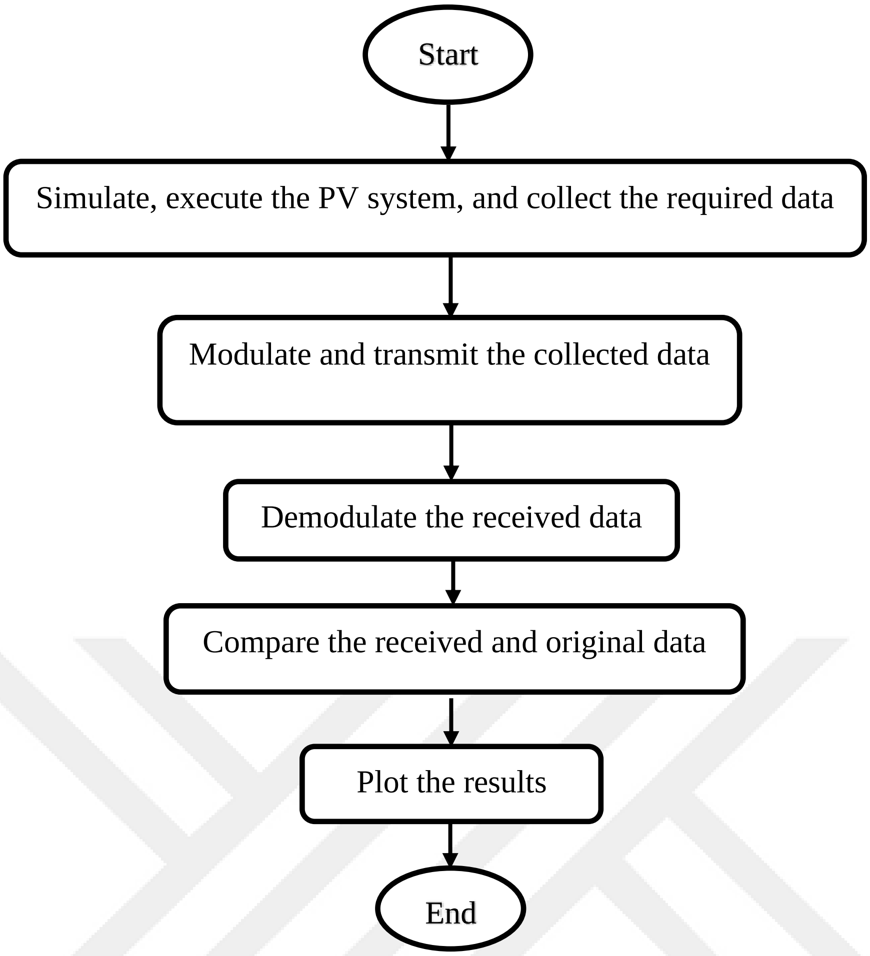


Figure 22. Proposed system flow chart

3.3. LORA Protocols

In the context of a battery monitoring system, LoRa technology can be used to implement the Medium Access Layer (MAC) protocol for wireless communication. The MAC layer is responsible for managing the transmission of data between devices in a network, and Lora technology provides a reliable and efficient method for wireless communication between battery monitoring devices. In the context of a battery monitoring system using Lora technology, the MAC layer can be implemented using the following steps:

- **Establishing a Network:** The first step in implementing the MAC layer is to establish a network. This involves setting up a Lora gateway, which serves as the central communication hub for the battery monitoring devices. The gateway is responsible for receiving data from the battery monitoring devices and forwarding it to the appropriate destination.

- **Defining Communication Channels:** Once the network is established, communication channels need to be defined. Lora technology uses a spread spectrum modulation technique to transmit data over multiple frequency channels. By defining communication channels, the battery monitoring devices can communicate with the gateway without interfering with each other.
- **Implementing the MAC Protocol:** With the network and communication channels defined, the MAC protocol can be implemented. The MAC protocol manages the transmission of data between the battery monitoring devices and the gateway. It defines the rules for accessing the communication channels, handling collisions, and ensuring reliable communication.
- **Transmitting and Receiving Data:** Once the MAC protocol is implemented, data can be transmitted and received between the battery monitoring devices and the gateway. The battery monitoring devices collect data on the battery voltage, current, and temperature, and transmit it wirelessly to the gateway using LoRa technology. The gateway receives the data and forwards it to a central database or user interface for analysis.

Figure 23 illustrates a simplified LoRa frame, featuring the addition of a LoRa protocol header. This LoRa header is crucial for transmission and consequently prolongs the transmission time, despite the number of useful bits remaining unchanged. As a result, the effective transmission throughput is reduced.

Figure 23. LoRa technology MAC Frame.

In the context of utilizing the LoRa protocol, various protocol layers have been introduced. Each layer provides specific services, with the upper layers being closer to the user, while the lower layers pertain to the transmission medium. As illustrated in Figure 24, the LoRaWAN protocol consists of two main layers: the application layer and the Medium Access Control (MAC) layer. These layers form the basis of the LoRaWAN protocol, which facilitates transmission over the internet via gateways. As the frame passes through the gateway, a different header is appended to the frame to enable transmission over the internet. This new header, known as the IP header, allows the frame to be transmitted over the internet while preserving the content of the original LoRaWAN frame. Thus, the content of the LoRaWAN frame remains intact throughout the transmission process.

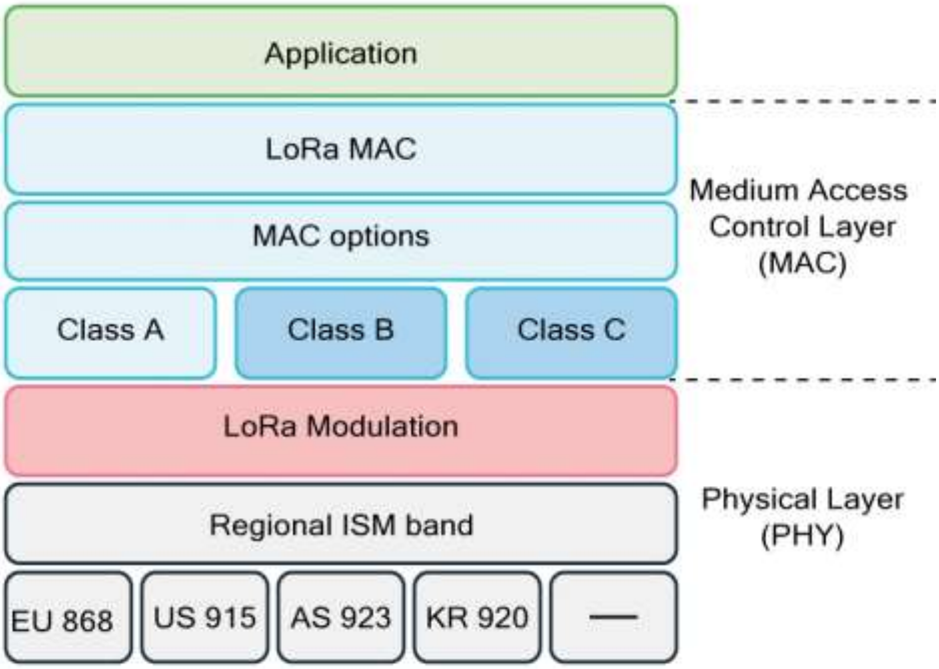


Figure 24. LoRa MAC protocol layers for the design of EMS (Kim, 2019).

In the utilization of the LoRa protocol, additional protocol layers have been incorporated, with each layer providing specific services. As the data is transmitted through the frame, it undergoes encapsulation in each lower layer, effectively adding details to the transmission process. The composition of the entire LoRa frame, including the information encapsulated at each layer, is illustrated in Figure 25, where the LoRa spreading frame is as depicted in Figure 26.

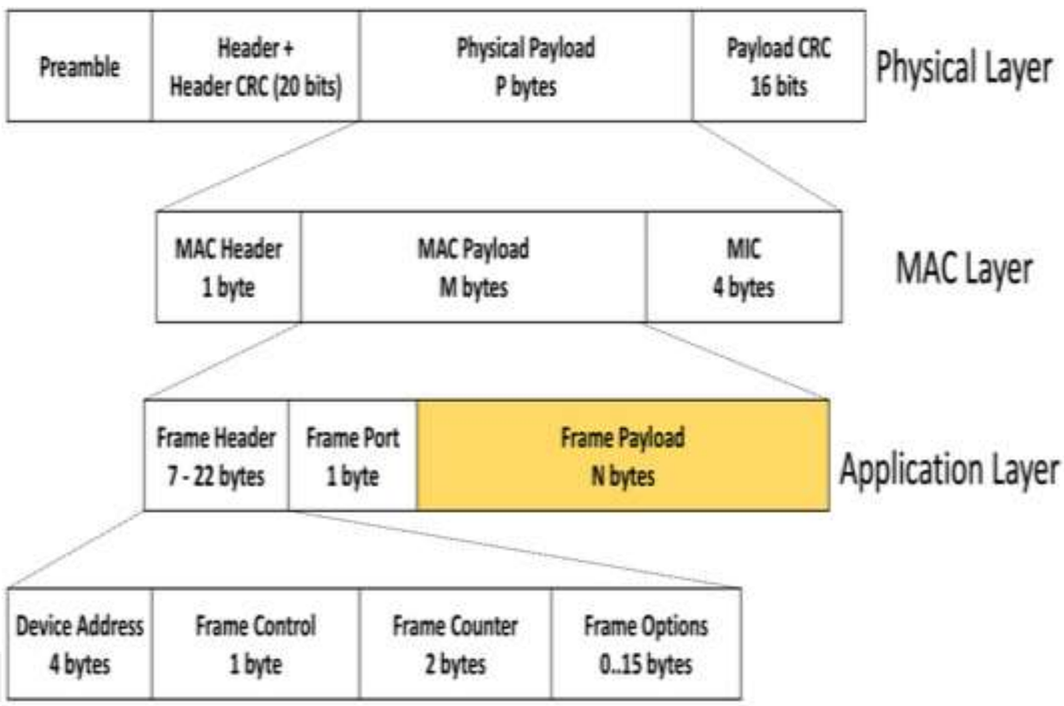


Figure 25. Frame of the LoRa different layers (Sales Mendes, 2020).

Before encapsulating user data in the Application layer, they undergo encryption using the Application Session Key (AppSKey) to ensure the security of the transaction.

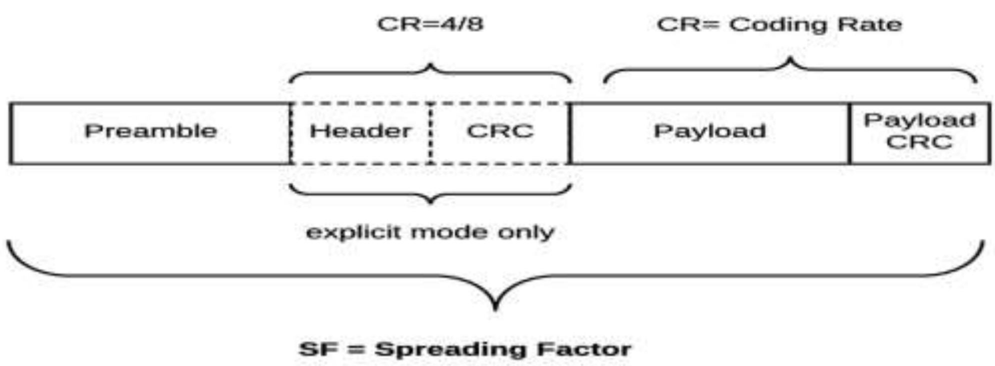


Figure 26. Spreading factor LoRa frame for EMS PV application (Sales Mendes, 2020).

CHAPTER FOUR

SIMULATION RESULTS

4.1. LoRa Simulation

In this work the communication system simulated in specific conditions to check its performance. Figure 27 shows the BER for coherent and non-coherent FSK modulation and noises with respect to the SNR, the simulation outcomes compared for AWGN noise.

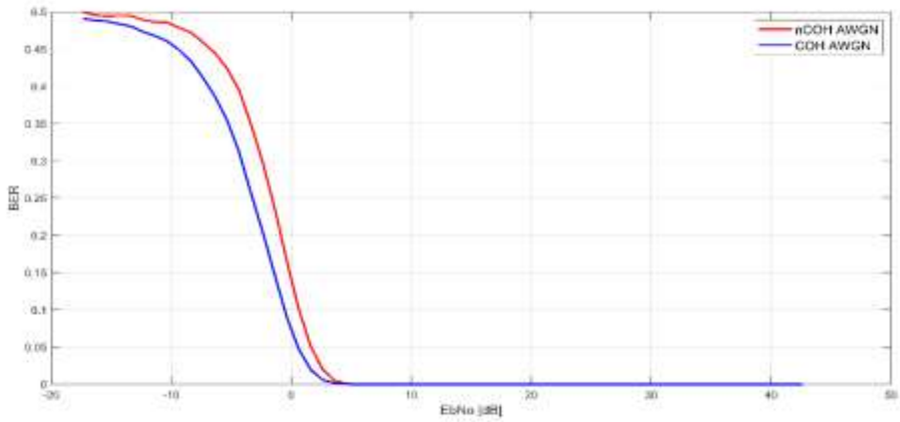


Figure 27. BER for LoRa in coherent and noncoherent FSK for AWGN noise effect

While the system response in case of Rayleigh noise is shown in figure 28.

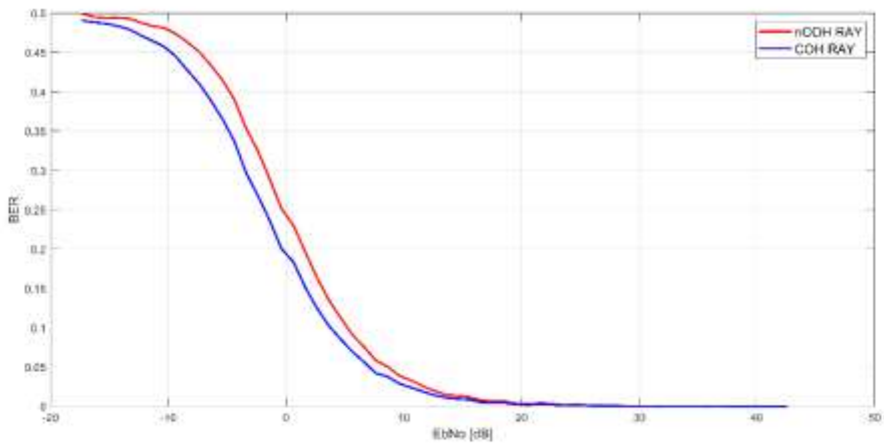


Figure 28. BER for LoRa in coherent and noncoherent FSK for Rayleigh noise effect

The power/frequency curve is shown in figure 29.

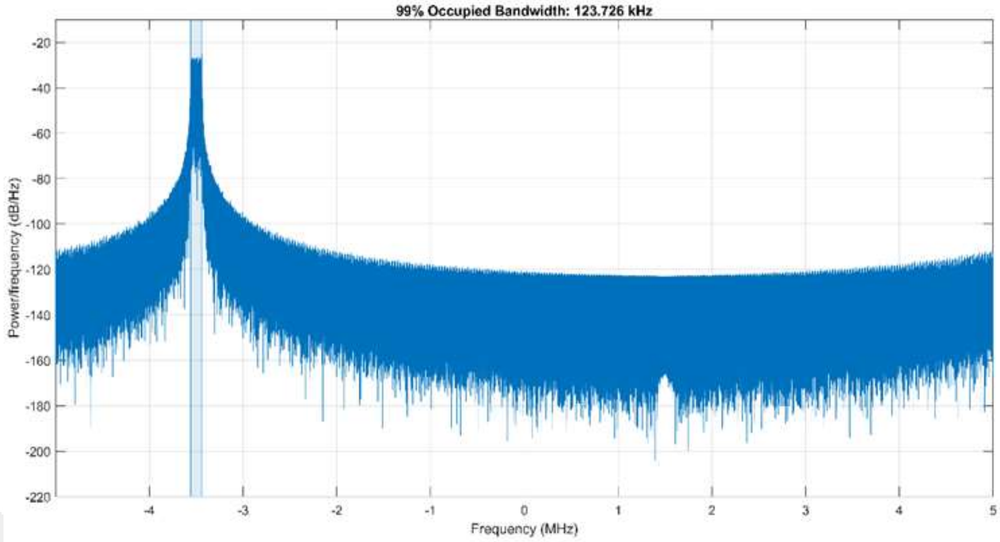


Figure 29. Occupied bandwidth

While figure 30 is showing the spectrum density for the LoRa communication system.

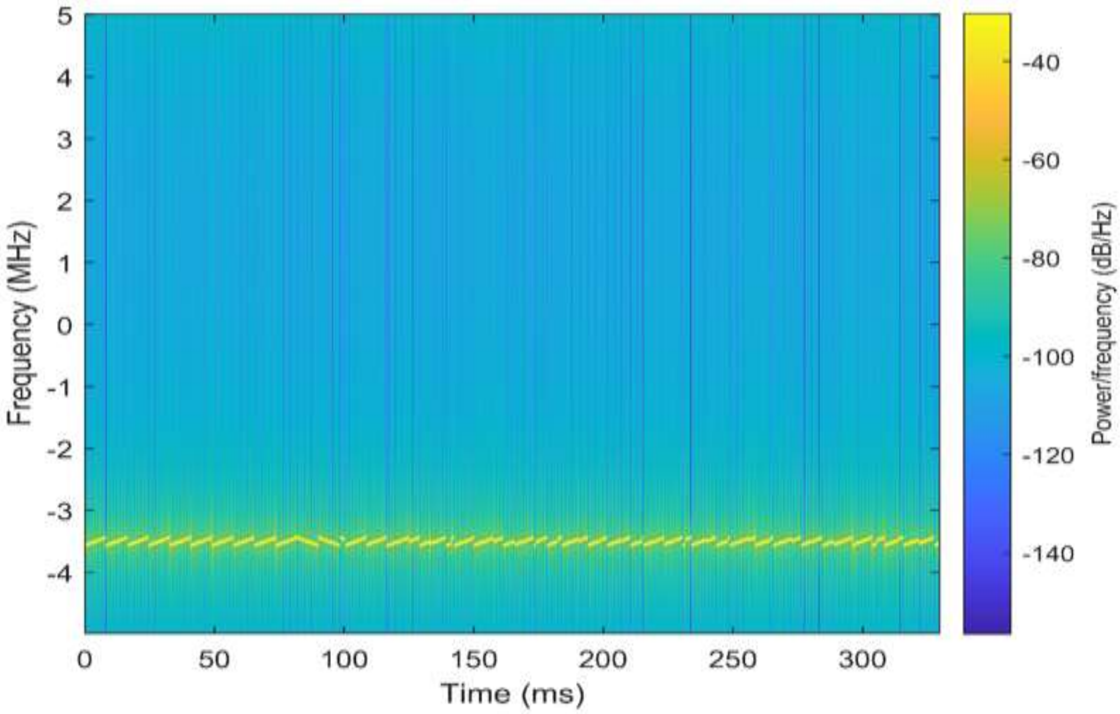


Figure 30. Spectrogram for LoRa communication system

4.2. THE PV SOLAR SYSTEM

The PV solar system is simulated for all expected operating conditions (solar irradiance level, loading, MMPT, Constant voltage). Use the following sets and the generated results are as an example:

****

**** For the given Solar Panel and PV Plant Parameters ****

Required PV Power rating = 200 kW

Minimum number of panels required per string = 8

Maximum number of panels connected per string without reaching maximum voltage = 10

Minimum power rating of the solar PV plant = 1.80 kW

Maximum power possible per string without reaching maximum DC voltage = 400 W

Actual number of panels per string = 9

Number of strings connected in parallel = 57

Actual solar PV plant power = 200 kW

****

**** For the Battery Charging/Discharging Parameters ****

Rated amp-hr of the battery = 400 Ah

Battery nominal voltage = 400 V

Fully charged voltage = 465 V

Reference battery charging current = 45.24 A

Nominal (Average) discharge current = 43.48 A

Maximum battery discharging current = 43.47 A

Initial state-of-charge (%) = 70 %

Maximum battery charging Power ≈ 18 kW

Maximum battery discharging Power ≈ 16 kW

The battery discharge parameters can be concluded with the following figure 31.

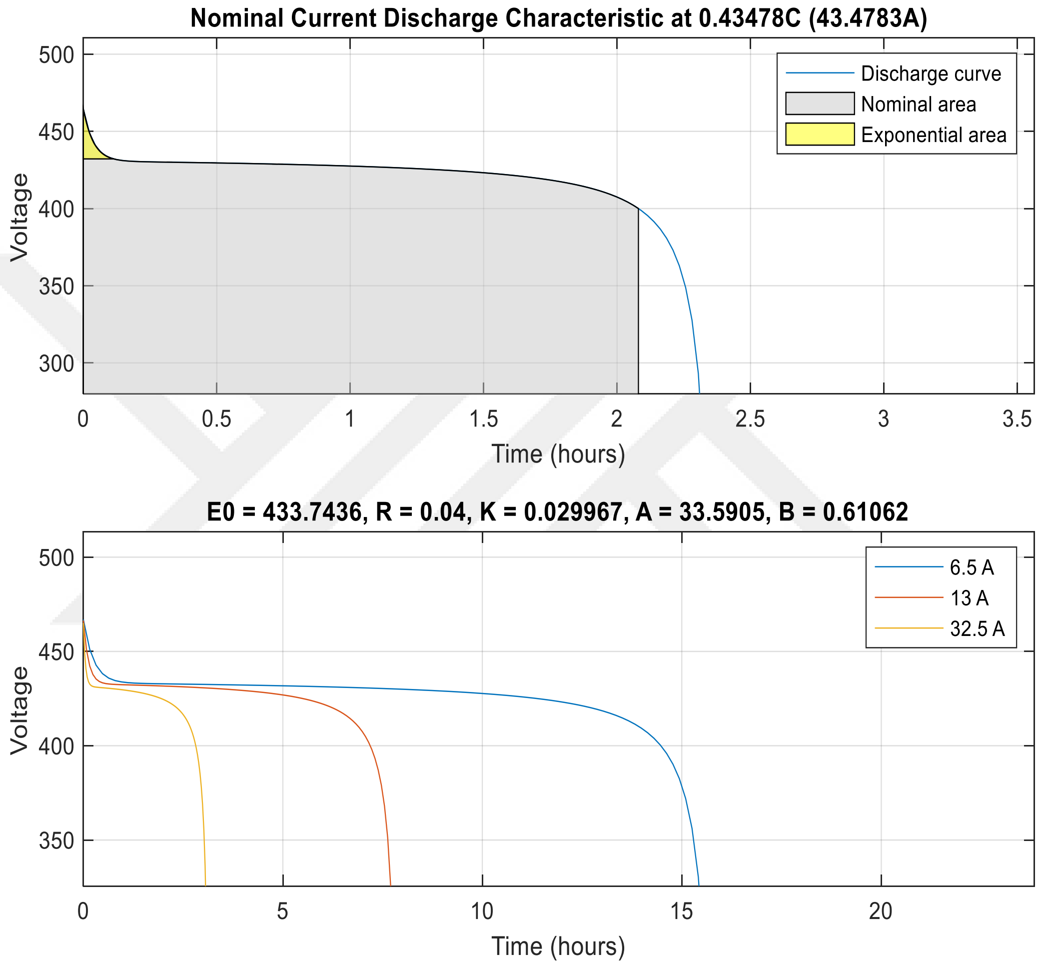


Figure 31. Battery discharging parameters (voltage, current, time)

To understand the system behavior with the monitoring, it can take the normal operating case with irradiance of G=1000W/m^2 and STC temperature with T=25C°. The PV voltage (V_{PV}), current (I_{PV}), and the power (P_{PV}) are shown in the figure 32.

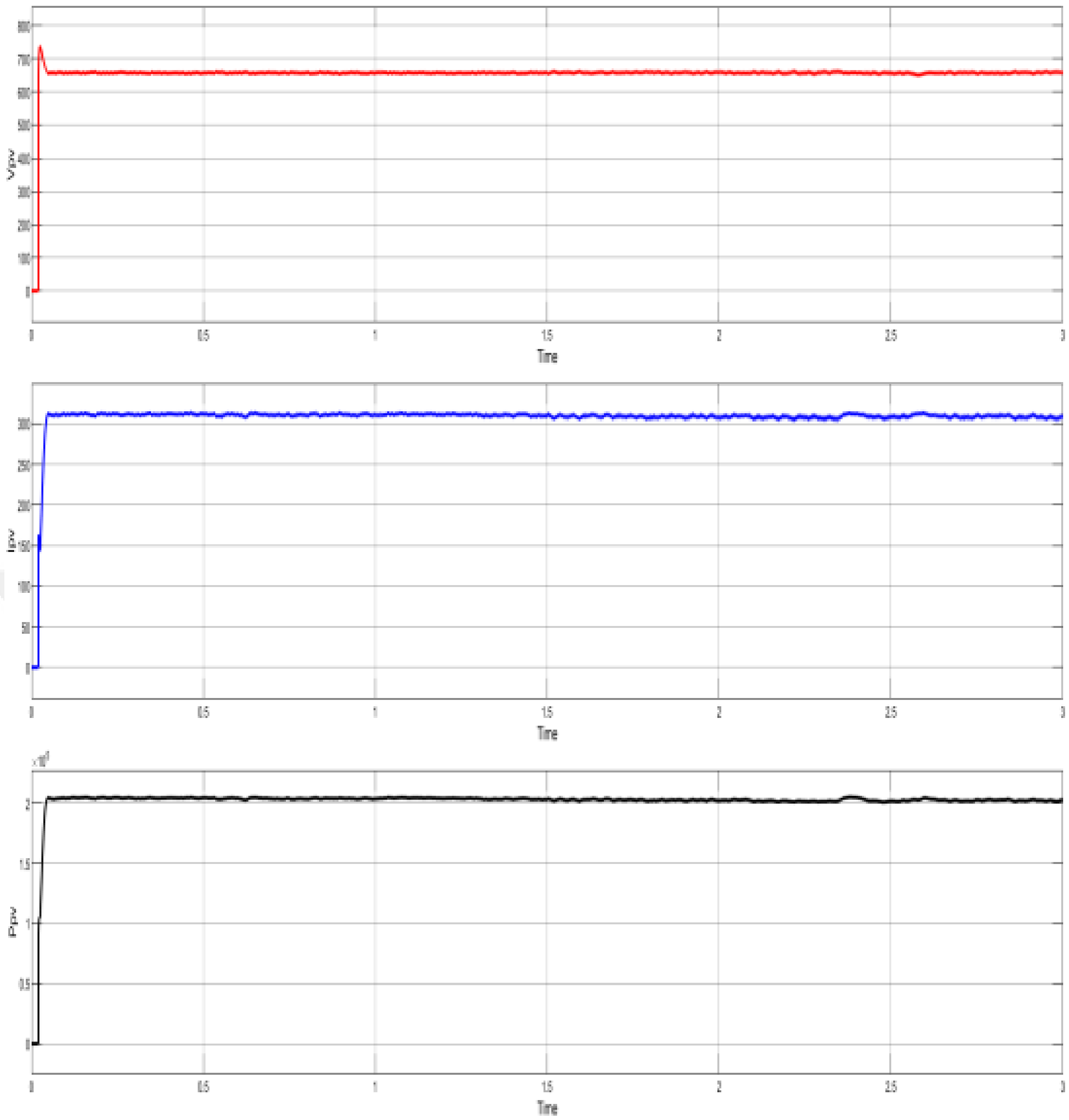


Figure 32. PV voltage, current, and power under a 1000W/m^2 results

As the irradiance is constant along the whole period, so the PV voltage, current, and power are of fixed values that are related to our system configuration. Also for continuous controlling the system, it clear from figure 33 that the real power (P) is varied according to the control state and the reactive power (Q) is always zero to keep the unity power factor for the PV system.

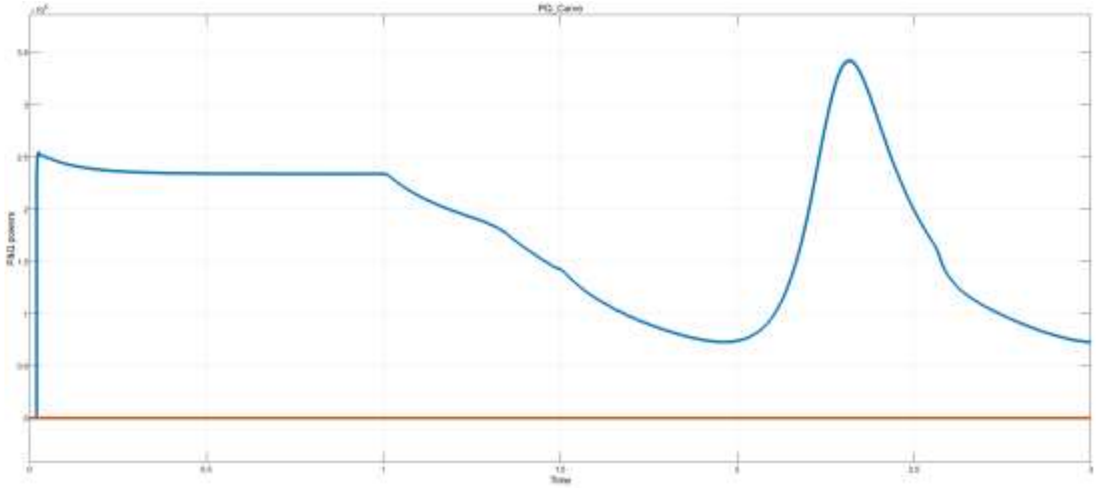


Figure 33. The real power (P) and the reactive power (Q) for the PV part

As illustrated in figure 34, the three phases voltage (Vabc) and current (Iabc) that are supplied to the PCC and hence to the load or the grid are pure sine waves and with appropriate values.

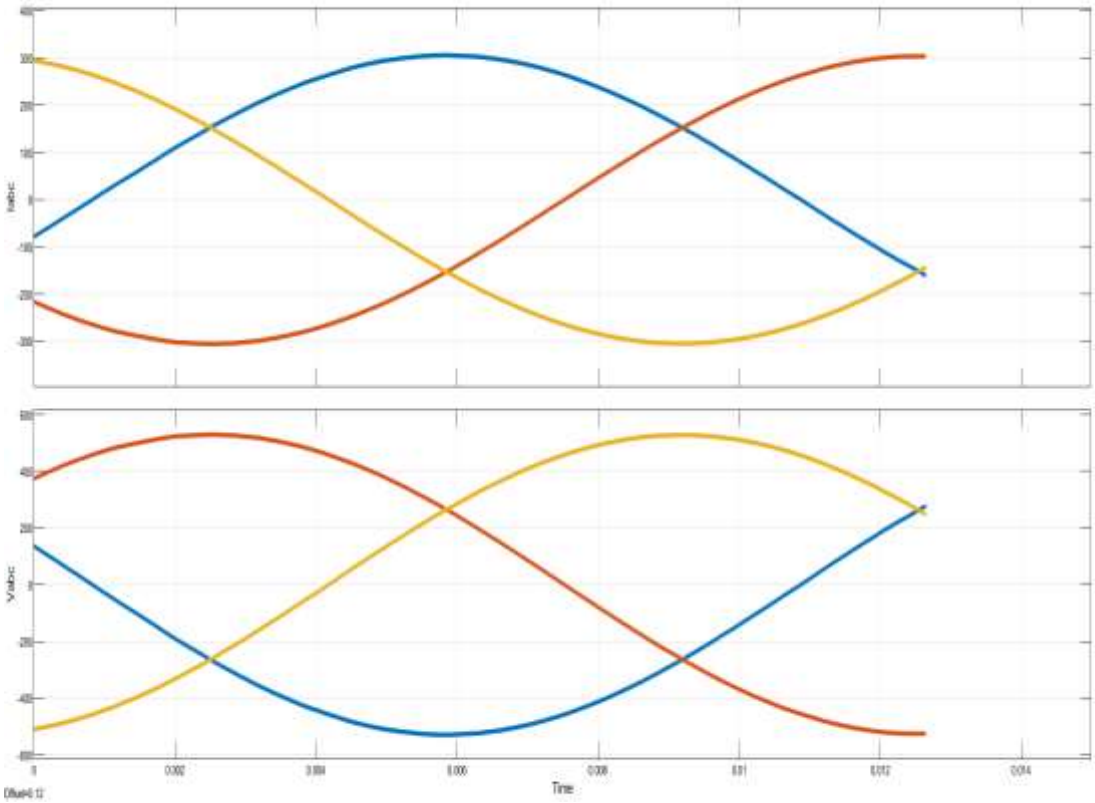


Figure 34. The three phases voltage (Vabc) and current (Iabc)

The load types in the reality system are inductive load type, so there are generated real power (P_L) and reactive power (Q_L) that are both greater than zero. Figure 35 depicts the load powers.

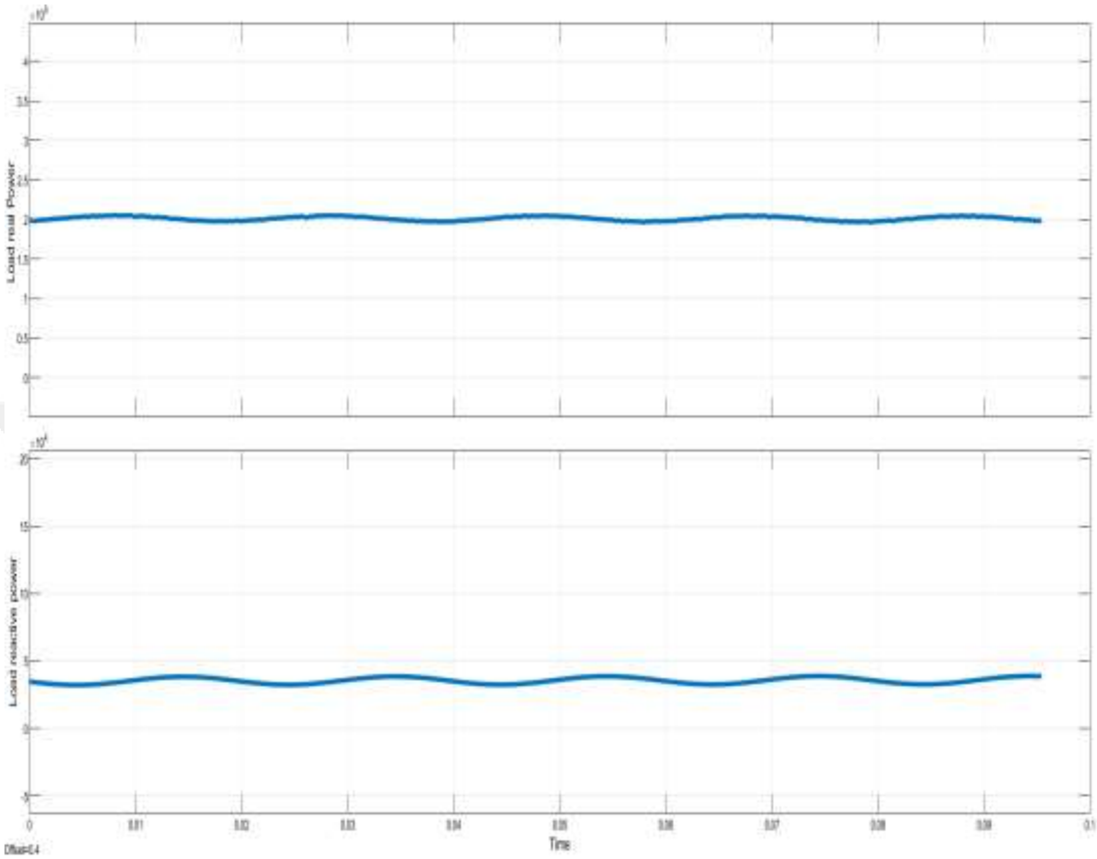


Figure 35. Real power (P_L) and reactive power (Q_L)

The load demand (PL) is varied during the period, as a result the battery and grid powers (Pbat & PG) are varied also depending on the load variation. Figure 36 explains the load variation effect on system performance.

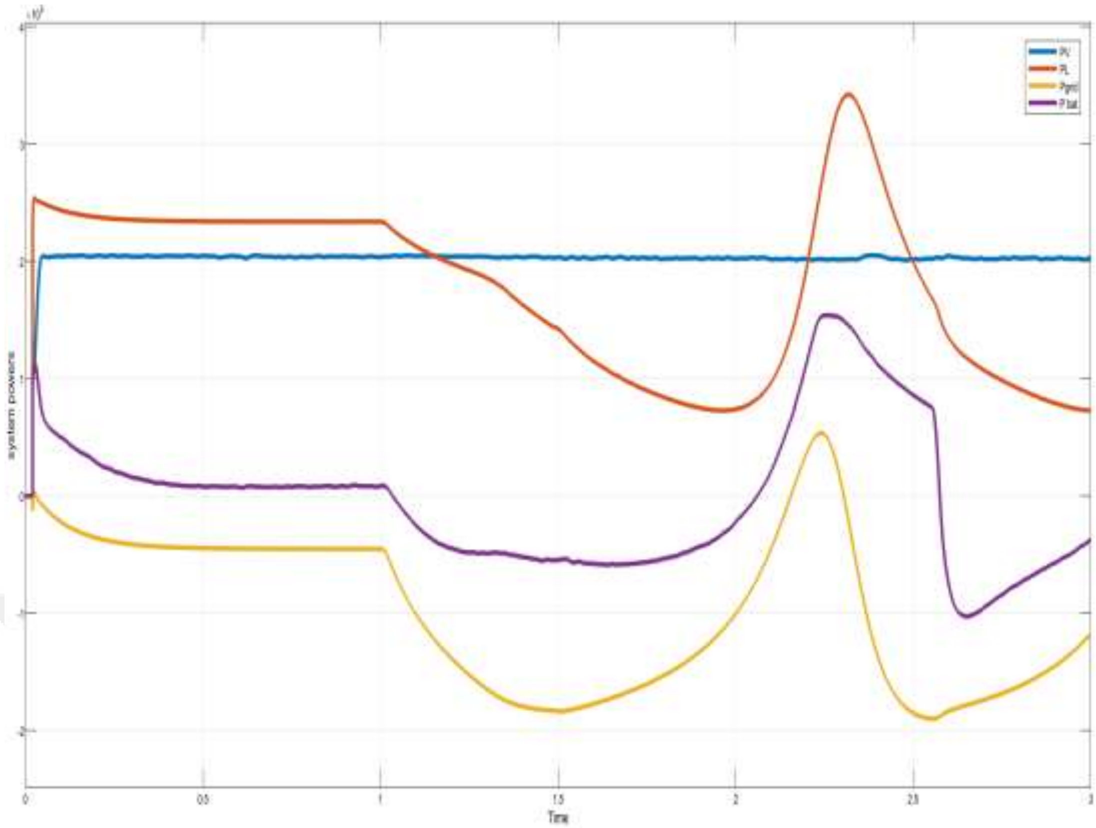


Figure 36. Load variation effect on system performance for 1000W/m2

It can divide and test the validity of the proposed PV system during its operations periods as:

From (0-1)sec, the P_L is greater than P_{PV}, so the battery can compensate the difference and the P_G is near to zero.

From (1.1-2.2)sec, the P_L is lower than P_{PV}, so the battery can be in idle state and the difference between P_{PV} and P_L is transferred to the grid as a P_G.

From (2.2-2.5)sec, the P_L is overstated to high power value and the P_{PV} with the P_L can't provide the load demand requirement, as a result the grid power P_G can compensate the system by the required power.

From (2.5-3)sec, again the P_L is lower than P_{PV}, the battery is of good charging level, the difference between P_{PV} and P_L is transferred to the grid as a P_G.

The state of the battery operation under the case study is as shown in figure 37.

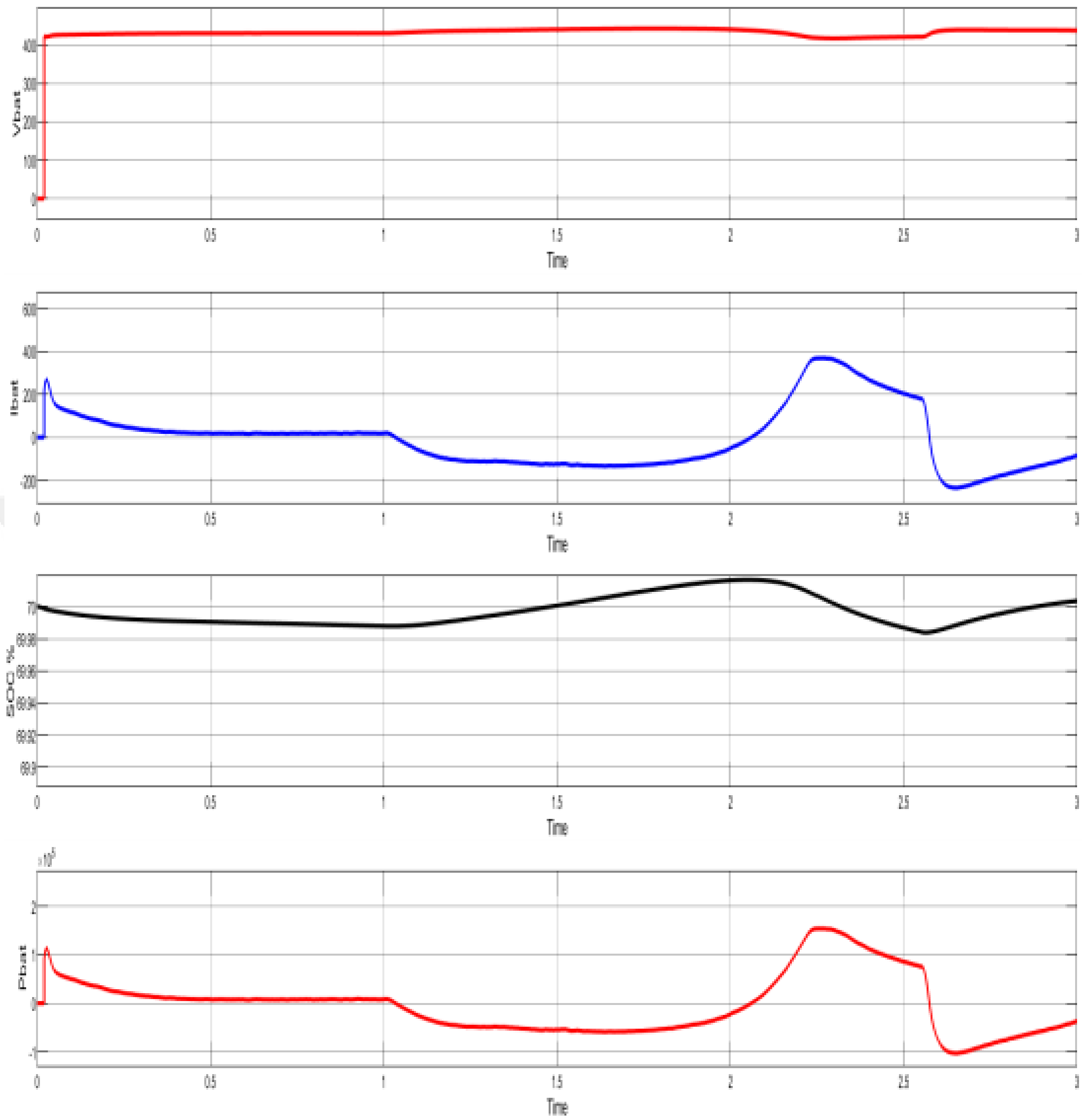


Figure 37. The battery voltage, current, SoC and power curves for 1000W/m^2

It is clear the battery state curves that the battery voltage V_{bat} can keep its value with constant along the whole period, while the battery current I_{bat} and power P_{bat} is varied depending to the system working and with three levels: high to charge the battery, low when discharging the battery, and constant when no needing to the battery power. The state of charge (SoC) is varied according to battery operating modes, however, in the case under study the SoC is near to nominal setting value which is 70%.

In our research, we aim to develop a comprehensive monitoring and data acquisition system for a photovoltaic (PV) solar power system integrated with battery storage, load, and grid connection. The primary objective is to ensure efficient operation and management of the system by continuously monitoring key parameters such as PV voltage, current, and power; battery voltage, current, power, and State of Charge (SoC); load voltage, current, and power; as well as grid voltage, current, and power.

In our operational modes and throughout the entire duration, we continuously monitor previous states and values by displaying results using Matlab/Simulink interfaces. For each parameter, we transmit four values: the maximum (max.), minimum (min.), mean, and variance. The max. value signifies the highest recorded value, while the min. value indicates the lowest. The mean value represents the average, and the variance reflects the deviation from the mean, representing the standard deviation. These measurements are taken for significant parameters including:

- Photovoltaic (PV): Voltage (VPV), current (IPV), and power (PPV).

- Battery: Voltage (Vbat), current (Ibat), power (Pbat), and State of Charge (SoC).

- Load: Voltage (VL), current (IL), and power (PL).

- Grid: Voltage (VG), current (IG), and power (PG).

Subsequently, LORA technology is utilized to continuously transmit and receive the aforementioned values, saving them as a worksheet or Excel file for further analysis.

By continuously monitoring these parameters, we can assess the performance of each component within the system and identify any anomalies or deviations from expected values. This real-time monitoring capability enables us to optimize system operation, detect and diagnose faults or failures promptly, and make informed decisions regarding system maintenance and performance improvement.

Furthermore, by transmitting the monitored data using Long Range (LoRa) communication technology, we can remotely access and analyze the system's performance data in real-time. This remote monitoring capability is particularly valuable for off-grid or remote solar power installations, where on-site inspection and maintenance may be challenging or impractical.

Overall, our goal is to develop a robust and reliable monitoring system that provides valuable insights into the performance and operation of PV solar power systems, facilitating efficient management and optimization of renewable energy resources.

Now, if the radiation is 800 W/m^2 and STC temperature with T=25C°, the PV voltage (V_{PV}), current (I_{PV}), and the power (P_{PV}) are shown in the figure 38.

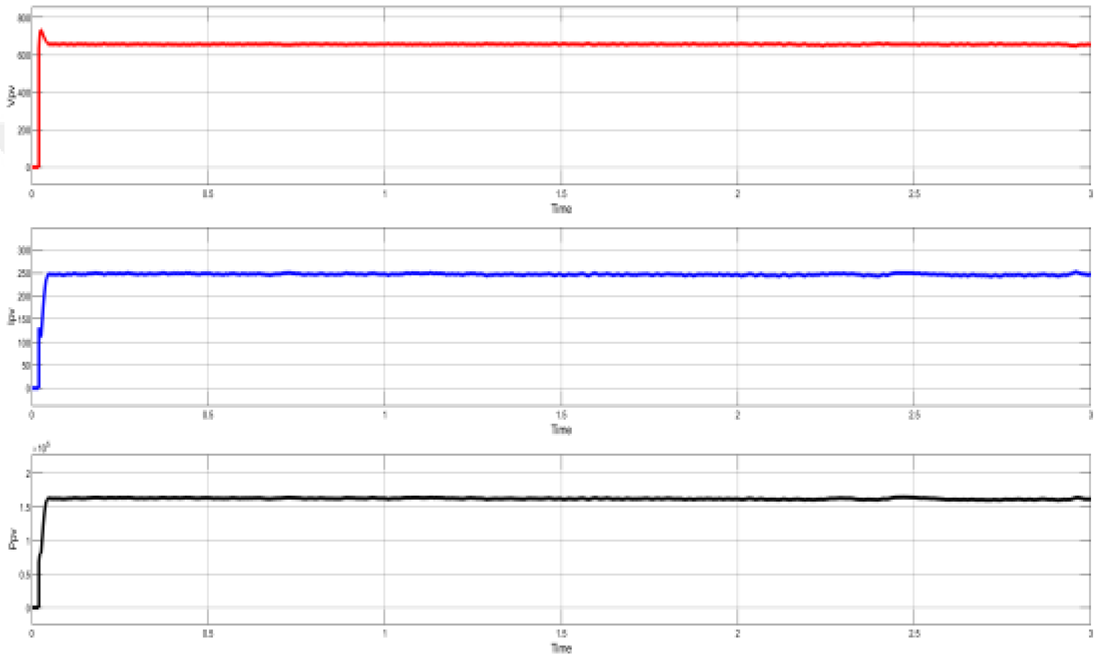


Figure 38. PV voltage, current, and power under 800W/m^2 results

Figure 39 explains the load variation effect on system performance.

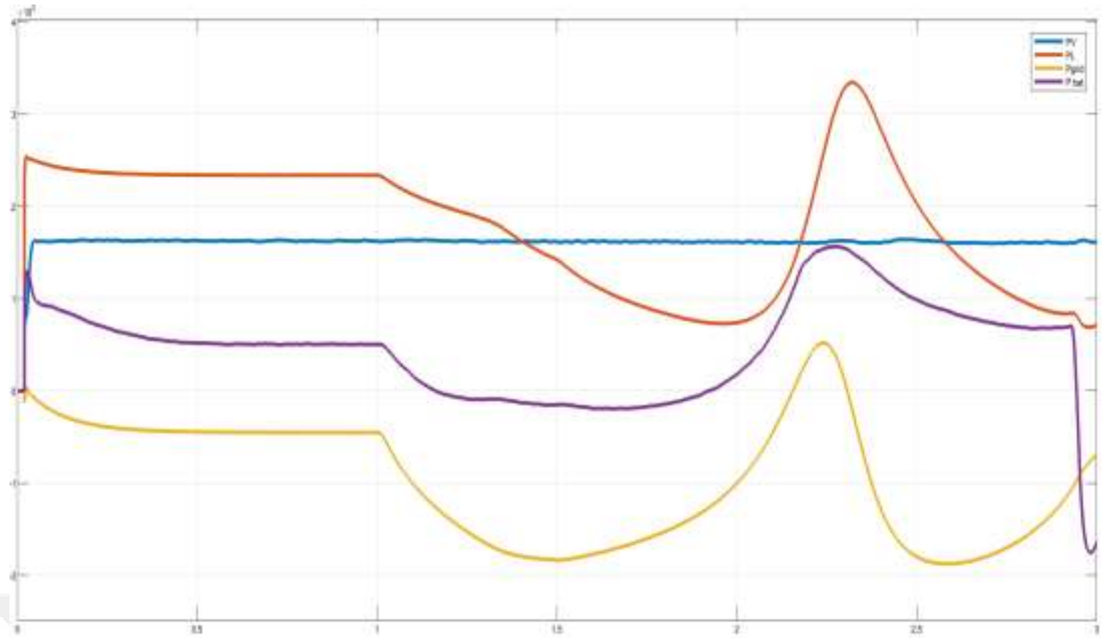


Figure 39. Load variation effect on system performance for 800W/m^2

The state of the battery operation under the case study is as shown in figure 40.

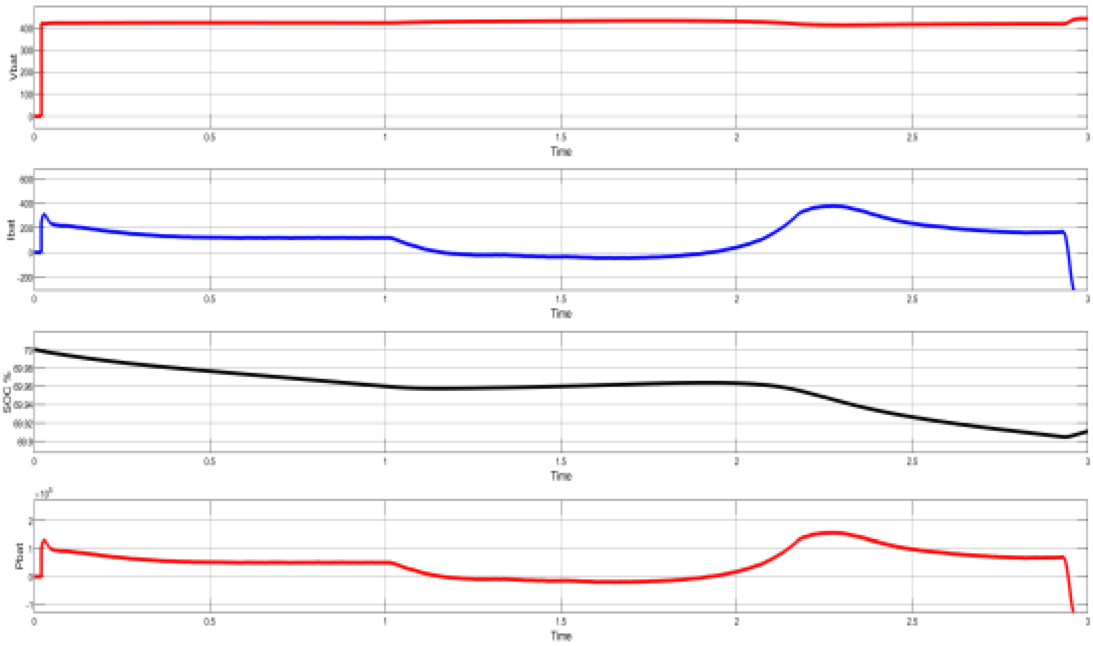


Figure 40. The battery voltage, current, SoC and power curves for 800W/m^2

CHAPTER FIVE

CONCLUSIONS AND FUTURE WORKS

5.1. Conclusions

PV solar array systems are widely used in many applications and always installed in far places, therefor such systems need remote monitoring process with suitable communication tool that can easily transceiver the commands and data. In this work, an IOT application for remote monitoring of grid-off /grid-connected solar PV array systems supplied with variable load is installed. The communication system used for data transmission is LoRa based. The solar power system works in two modes depending on the connected load, MPPT mode and constant voltage mode.

Data collection and processing play a critical role in monitoring systems tailored for Photovoltaic (PV) applications. It outlines the types of data collected by the system, encompassing various parameters such as PV performance metrics, battery status indicators, load characteristics, and grid-related parameters. To facilitate efficient transmission, this data will be transmitted using LoRa technology, ensuring secure communication channels while integrating robust security measures to safeguard the integrity of the transmitted data.

Solar power system simulated using MATLAB/Simulink software for all expected operating cases such as solar irradiance variation and load variation. LoRa communication system also simulated using MTLAB software for many types of modulation and SNR.

The system readings (voltages, currents, and powers) are transmitted and received in the remote monitoring room. The transmitted and received data are compared to show the system performance. For all simulated cases the data accuracy is very high.

The PV system operates in different modes, which are influenced by factors such as solar irradiance, generated solar power, connected load, battery state of charge (SoC), and maximum battery charging/discharging current limits. To optimize the system's performance and track the maximum power point (MPP) of the solar PV, two maximum power point tracking (MPPT) techniques can be employed: Incremental Conductance (INC) or Perturbation and Observation (P&O).

Several parameters need to be specified, including the average daily connected load profile, the region's daily available average solar energy (kWhr), solar PV system operating temperature, day of autonomy, battery recharge time, AC supply availability, and solar panel specifications. The determination of the number of PV panels required to meet the specified generation capability is based on data provided by the solar panel manufacturer.

Among numerous variables, the DC bus voltage level (V_{dc}), solar irradiance (G_{rad}), and battery state of charge (SoC) are crucial in determining the appropriate operating mode through supervisory control.

5.2. Future works

- The studied system can be implemented using physical components that can verify the system performance from networking site of view.
- The examined system can be instantiated using real time components like microcontrollers, networking adaptor and attachable devices.
- A double control room system may be a good solution for both communication lose or to overcome the local controller failure, to make the system more stable.
- In a viability of Wi-Fi system, it can depend on more accurate and friendly communication protocol like the ThinkSpeak environment protocol.

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