Modeling, Analysis, and Implementation of a DC micro grid Energy Management System

By

Fannie Isaac Masango

Submitted in partial fulfillment of the requirement for degree

Master of Engineering in Electrical Engineering

in the

Department of Electrical Engineering

FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

Tshwane University of Technology

Supervisor: Prof. J.A. Jordaan

Co-Supervisor: Dr A F Nnachi July 2024

ACKNOWLEDGMENTS

I wish to convey my heartfelt appreciation to Prof JA Jordaan, my supervisor, for his positive outlook and invaluable guidance, as well as to Dr. AF Nnachi, my co-supervisor, for his mentorship, patience, and expertise. Under your supervision, I have gained immeasurable insights and knowledge.

To My Teachers:

I extend my appreciation to the faculty members at Tshwane University of Technology eMalahleni campus, particularly Mr. P Ehlers, Dr CG Richards, and Mr. Manana for their dedication to fostering my academic growth and intellectual curiosity. I would like to express my gratitude to the faculty members at Tshwane University of Technology eMalahleni campus, with special recognition for Mr. P Ehlers, Dr. CG Richards, Mr. Manana, Dr AO Akumu and Dr PF LeRoux. Their unwavering commitment to nurturing my academic development and sparking my intellectual curiosity is greatly appreciated.

For all those whose names I may have omitted but who have played a part in my academic journey, I express my heartfelt gratitude. This thesis is a testament to the collective efforts and encouragement of all these individuals and entities. Your belief in me has been a driving force behind my accomplishments, and I am profoundly grateful for your unwavering support.

ABSTRACT

Microgrids (MG) are small-scale power subsystems that incorporate distributed generation, energy storage, local loads, system control, and coordination. Energy Management Systems (EMS) play a crucial role in fortifying the resilience of microgrids, ensuring their stability and continued operation even when energy supply is constrained. EMS enables centralized monitoring and control of energy consumption across various building systems. It is designed to collect, store, and analyze power consumption data from residential and industrial appliances. To achieve a fully automated and stable grid with plug-and-play capabilities, an agent-based EMS is proposed for use in a DC microgrid. This paper introduces an energy management system utilizing a systems-of-systems approach. We model and simulate an energy management system for a PV/Composite Storage DC microgrid in MATLAB. The primary aim of this paper is to enhance the performance of the DC Microgrid by integrating an existing grid with an energy management system at the residential level. The control system's objective is to ensure prolonged operation of loads by maintaining the local battery's charge until the PV modules cease power generation. Four scenarios of varying load demand were tested. The results obtained from both scenarios demonstrate the effectiveness of this control system design approach.

NOMCLEMATURE

RES	-	Renewable Energy Resources
DC	-	Direct Current
AC	-	Alternative Current
MG	-	Direct Current Microgrid
DCMG	-	Maximum Power Point Tracker
MPPT	-	Energy Storage System
ESS	-	Distributed Energy Resources
DER	-	Energy Resources
ER	-	Energy Resources
EMS	-	Energy Management System
AFE	-	Active Front End
CGMS	-	Central Grid Management System
REMCS	-	Residential Energy Management and Control System
SoSs	-	System of Systems
SoC	-	State of Charge

Contents

List of Tables

List of Figures

NOMCLEMATURE

RES	-	Renewable Energy Resources
DC	-	Direct Current
AC	-	Alternative Current
MG	-	Direct Current Microgrid
DCMG	-	Maximum Power Point Tracker
MPPT	-	Energy Storage System
ESS	-	Distributed Energy Resources
DER	-	Energy Resources
ER	-	Energy Resources
EMS	-	Energy Management System
AFE	-	Active Front End
CGMS	-	Central Grid Management System
REMCS	-	Residential Energy Management and Control System
SoSs	-	System of Systems
SoC	-	State of Charge

Chapter 1

Introduction

1.1 Statement of research problem

The utilization of renewable energy resources (RES) is on the rise, as many countries are making efforts to transition away from non-renewable energy sources due to their contribution to carbon emissions in the atmosphere. Microgrids combine distributed energy resources, energy storage, and load management. They have found applications in electrifying off-grid rural villages and remote regions. DC Microgrids (DCMG) have gained widespread use in aerospace, automotive, marine, and other industries. They serve as crucial components for integrating DERs (Distributed Energy Resources), especially since most renewable energy sources generate DC power. A nano grid, on the other hand, is designed for power distribution in a single house or small building [11]. A DC nano grid typically includes DERs, MPPT (Maximum Power Point Tracking), and ESS (Energy Storage System).

The use of renewable energy resources (RES) continues to grow. Numerous nations are seeking to transition from non-renewable energy sources as a result of the carbon emissions released into the atmosphere. A microgrid combines distributed energy resources, energy storage, and load. They have been used in the electrification of off-grid rural villages and remote areas. DC Microgrids (DCMG) have been widely used in aerospace, automotive, marine, and other industries. They are the critical components in integrating DERs since most renewable energies produced are in DC form. A nano grid is a power distribution system for a single house/small building. A DC nano grid consists of a DER, MPPT, and ESS.

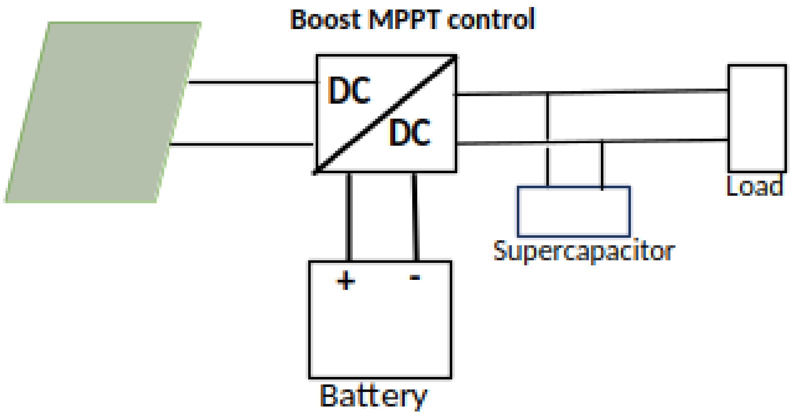

Figure 1.1: DC nano grid

Nano grids are connected to form a microgrid cluster. The units in a microgrid can share resources. When the resources are shared in a Microgrid, substantial load variations and changes in generating capacity and storage will occur. In order to guarantee a stable Microgrid, a control system is required to maintain bus voltage at a constant level for as long as possible when load demand exceeds generation.

1.2 Background to the research problem

Intermittency of Renewable Energy Sources (RES) poses a significant challenge in standalone DC Microgrids (DCMG). Additionally, variations in load, changes in generating and storage capacities, and unstable bus voltages further complicate microgrid stability. DCMGs are characterized by power-sharing, where Energy Resources (ERs) are distributed across the grid and connected via a bus line. DC-DC converters are essential components, adjusting source voltages to match the bus voltage.

In residential distribution systems (RDS), such as those using DERs like PV panels, load demand varies considerably based on usage, necessitating generation and load forecasting to manage these fluctuations effectively. The intermittency of RES adds complexity, making it challenging to manage constant load removal, power supply, and the balance between power production and demand. Hence, there's a clear need for a robust Energy Management System (EMS).

An EMS offers centralized and monitoring and control of energy usage across building systems, capable of recording, storing, and processing power consumption data from major household and industrial appliances. This research proposes an agent-based energy management system, which, when employed in a DC microgrid, can achieve a fully automated and stable grid with plug-and-play capabilities. Hierarchical control in a DC microgrid enhances grid efficiency by introducing load-shedding and minimizing downtime.

1.3 Objectives of the research problem

This research will mainly benefit communities in areas that experience severe power outages as a result of old failing infrastructure and utilities not being able to meet the ever-increasing energy demand. Energy management systems can help improve the robustness of microgrids ensuring that the grid remains stable and operational for a long time when energy is very limited. Implementing DC microgrids in residential areas presents unique technical challenges that require specific solutions. Studies have been conducted for the energy management and control of DC microgrid systems for many reasons including power flow management, voltage regulation, and load balancing, to ensure reliable and efficient operation. The control strategies vary depending on MG structure; AC, DC [12] or hybrid also the communication between the units [41]. This study aims to provide insights into integration of Distributed energy resources into residential areas with the focus on DC MG optimisation by resource sharing algorithm.

1.4 Delimitation of study

This study does not cover the AC interface of a DC microgrid. AC-DC interface requires rectifications, usage of Active Front End (AFE) and special Topologies [21]. Therefore, the microgrid will fully operate in islanded mode. protection systems and devices are inherently more challenging, and the typical loads in residential buildings are not yet compatible with dc voltages. [37]. Protection systems are not discussed in this paper.

1.5 Research Methodology

The methodology employed in this study is primarily quantitative. Input data parameters are processed through a Matlab simulation model, allowing for comprehensive analysis. Software simulations are conducted to determine optimal system parameters, and these simulations involve the creation of a simulated model of a DC microgrid using computer software.

Within this simulated model, various parameters, mainly the battery state of charge (SoC), temperature, irradiance and load demand are systematically adjusted to create different scenarios and assess their impact on the grid's performance. These scenarios are designed to represent a range of potential real-world conditions and challenges.

Furthermore, to complement the digital simulations and provide real-life validation, a physical representation of the DC Microgrid (DC MG) is constructed. This physical system allows for hands-on analysis and experimentation, facilitating a deeper understanding of the data generated in the simulation phase.The combination of digital simulation and physical experimentation ensures a comprehensive and robust assessment of the DC microgrid's behavior and performance under varying conditions.

1.5.1 Research Design

The DC microgrid Energy Management System proposed in this paper is based on the Systems of Systems. Figure 2 shows four houses connected to the CGMS (Central Grid Management System). Each house is represented by a block in the Matlab Simulink model. These four houses represent four different scenarios serving as input parameters for the CGMS.

1.5.1.1 Residential unit types

(1) A node with a storage system capable of both storing and sourcing energy for the microgrid.

(2) A node with only a storage system, without the capability to source energy.

(3) A node without a storage system, able to source energy only when sunlight is available.

(4) A node on the system that neither stores nor sources energy.

The blocks are combined to form a microgrid that connects to the CGMS.

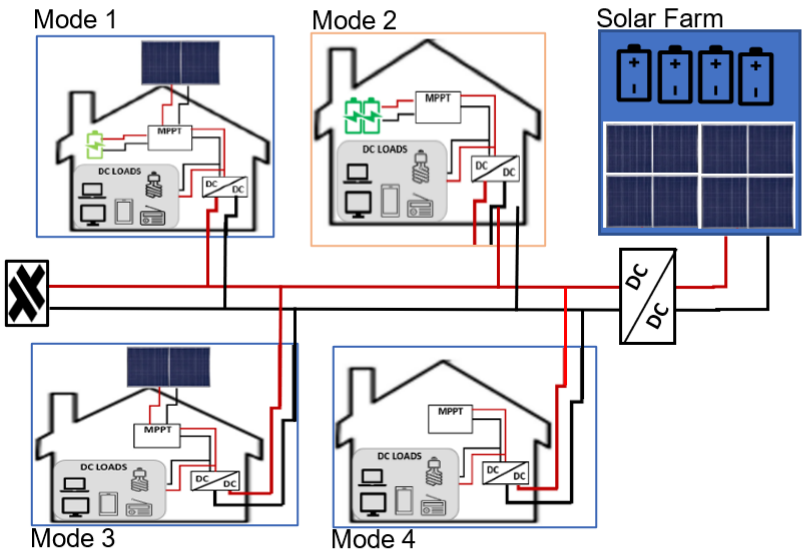

Figure 1.2: Residential unit operation modes.

Nano grids are connected to form a microgrid cluster. The units in a microgrid can share resources. When the resources are shared in a Microgrid, substantial load variations and changes in generating capacity and storage will occur. In order to guarantee a stable Microgrid, a control system is required to maintain bus voltage at a constant level for as long as possible when load demand exceeds generation.

1.5.2 Component technology.

DC microgrid systems utilize renewable energy technologies like Photovoltaic (PV) modules and wind turbines. Among these, PV modules are particularly common and readily available at affordable prices for consumers. In this research, PV modules will be exclusively employed as the energy source.

The primary objective of this study is to test the energy management system algorithm under various scenarios. This will be achieved by adjusting the system's resources in a manner that triggers all possible operating states. Specifically, energy storage capacity and loads will vary for each unit tested.

1.5.3 Simulation and optimisation

The performance of the designed DC microgrid is modeled and simulated using Matlab/Simulink software. The simulation results are utilized to optimize system configurations, control strategies, and component sizing. This process aids in identifying potential improvements, evaluating system resilience, and validating the design.

1.5.3.1 Software parameters required for load shedding regulation include:

(1) Defining Load Sizes: Since each household may have different loads connected to the system, and considering the limited grid energy, an algorithm will be developed to determine the allowable power consumption for each household based on their contribution.

(2) State-of-Charge (SoC): SoC is a crucial parameter describing the remaining capacity of a battery. It is essential to monitor SoC during battery discharge to ensure efficient energy management.

(3) PV Irradiance Input: Irradiance levels vary with weather and day/night conditions. This parameter provides information about the available solar energy that can be used to charge the batteries.

(4) Connecting and Disconnecting of Loads: The system must be able to detect and react to changes, recalculating load shedding when significant loads are connected or disconnected.

1.5.4 Implementation

A DC MG test bed will be constructed as described, incorporating key components such as DERs, energy storage systems, power converters, and control systems.

Chapter 2

Literature Review

2.1 Introduction

In the landscape of modern energy systems, generation technologies play a crucial role in shaping the way we harness and utilize power. From traditional fossil fuel-based methods to cutting-edge renewable sources, Generation technologies encompass a wide spectrum of solutions that drive the transition toward sustainable and efficient energy production. This section delves into the diverse range of generation and storage technologies, exploring their mechanisms, advantages, and challenges, while highlighting the pivotal role they play in shaping our energy future. Microgrids integrate these diverse renewable energy sources and storage into a functional system. Furthermore, Strategies for efficiently integrating RES and ES are also discussed and finally the proposed study on the energy management system is presented.

2.2 Generation Technologies

The first form of electricity generation was demonstrated by Thales when he rubbed amber with animal fur, although he attributed the objects to having some sort of soul [38]. William Gilbert was the first person to use the term 'Electricity' in the late 1600s, over a lot of other invention related to electricity took place. In the early years of the 19th century that the works of Alessandro volta, Benjamin Franklin, Michael Faraday and Andre Ampere that really contributed to the electricity generating technologies we use today.

2.2.1 DC and AC generation

The development of Alternator and Dynamo paved the way for electricity power industry. The dynamo which produces DC electricity was developed by Werner Siemens and Charles Wheatstone in 1867. Electric motor, rotary converter and an alternator which generates AC electricity are all based on Dynamo.

Today it is common knowledge that alternators, commonly referred to as generators are preferred for electricity generations over Dynamos because alternating current distribution of power over large distances is more efficient than direct current. The first power station to have been built was in Bavarian town in 1878, it used steam to drive dynamos and the first power station to use an alternator was built in the United Kingdom in the town Godalming. Other technologies that we used to drive the generator soon followed, this includes, Hydropower, ignition engines, wind power, nuclear power etc.

In the recent years there have been an increase emphasis on renewable energy as the non-renewable sources will not always be available, and their direct role they play in global warming crisis make them not viable option for future generation of electricity. The growth of solar and wind power has caused a rise in distributed generation systems such as microgrids.

However, the PV output power is also affected by environmental factors such as clouds, rainy conditions, deposition of snow or dust on the panel surface and the geographical location of the PV plant where the plant is installed. In the absence of solar radiation or in the nighttime, the battery bank in a PV system is used as a power backup to the connected load. The batteries have their constraints, such as short lifetime and replacement requirements during project lifetime [34].

2.2.2 DC Generation Technologies

Direct current is produced by generators with commutators, fuel cells, rectifiers and photovoltaic cells. DC generators are rarely used in power plants due to extensive use of AC over DC in transmission lines. [26]. Photo voltaic arrays generate DC electricity in the presence of adequate sun radiation, in case where the sun radiation is inadequate, wind generation is utilized by using rectifiers. M.S. Keerthana et al. [27] demonstrated a dual source DC Microgrid by using wind and solar.

2.2.2.1 Photovoltaic Panel

When sunlight (photons) strikes the photovoltaic cells, it releases energy that frees electrons from the semiconductor material, generating an electric current. The flow of electrons creates a direct current (DC) electricity within each photovoltaic cell. Multiple cells are connected in series or parallel to achieve the desired voltage and current levels. The generated DC electricity from the individual cells is combined within the panel using wiring and junction boxes. These components connect the cells and allow the collected electricity to be routed to the panel's output terminals. A Matlab/Simulink model of a PV cell equivalent is shown in figure below.

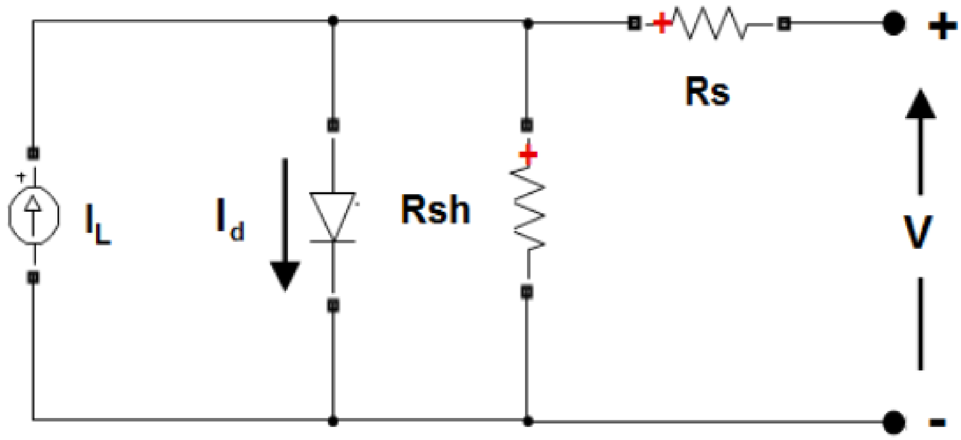

Figure 2.1: A Matlab/Simulink model of a PV cell

The voltage-current characteristic equations for the model above are defined as:

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

$$V_T = \frac{k_t}{q} * nl * NCell \tag{2.2}$$

Where:

I_d = Diode current(A)

V_d = Diode voltage(V)
I_o = Diode saturation current(A)
nl = Diode ideality factor
k = Boltzman constant: 1.3806e-32 J.K-1
q = Electron charge: 1.6022e-19C
T = Cell temperature (K)
$Ncell$ = Number of cells connected in series in a module

The PV cells capture the energy of the sun and convert it into electricity. There are three main categories of PV panel options: Mono-crystalline solar panels, Poly-crystalline solar panels and thin-film solar panel.

2.2.2.2 Poly-crystalline Panel

Polycrystalline PV panels are made up of polycrystalline silicon produced from numerous mono-crystals. They are characterised by a light blue colour and distinctive crystal edges. Poly-crystalline photovoltaic panels are considered less efficient and more vulnerable to high temperatures. They are popular due to being less expensive than mono-crystalline Panels.

2.2.2.3 Mono-crystalline Panel

These panels use single-crystal silicon cells and are known for their high efficiency.

2.2.2.4 Thin-film Panel

Thin-film panels use various semiconductor materials deposited in thin layers on a substrate. They are flexible and can be used in diverse applications, but they typically have lower efficiency compared to crystalline panels.

In the assessment of various photovoltaic technologies, the researchers in [5] determined that the performance of Mono-crystalline PV systems outperformed other technologies in terms of configuration. However, thin film systems have showed a slightly better performance in specific yield per installed capacity (1693 kWh/kWp) in comparison with Mono-crystalline (1678 kWh/kWp) due to its low temperature coefficient. Nevertheless, it is crucial to acknowledge that the effectiveness of a PV system is dependent upon a range of factors, including geographical location, installation angle, shading, maintenance, and cost considerations [33], [29].

2.2.2.5 Thermoelectric generators (TEGs)

Thermoelectric generators convert heat into electricity by using the Seebeck effect. When there is a temperature difference between the two sides of the thermoelectric material, it creates an electric potential difference (voltage) between them. Electrons flow from the hot side to the cold side, generating an electric current. The generated electrical power is proportional to the temperature difference and the efficiency of the TEG.

TEGs have a very low efficiency and high cost [28] which limits their application only in special areas. Search has been done to improve the TEG efficiency for applications in other areas such as [40]. Unlike most DC generators, increasing (Thermal Energy Modules) TEMs does not linearly increase power generation capacity as stated by the authors in [43].

2.2.2.6 Wind Turbine

A wind turbine is a device that converts the kinetic energy from the wind into mechanical energy and then transforms it to electricity. Wind turbines harness the power of the wind, and it is considered clean energy because no greenhouse gases are emitted during its operation.

A typical wind turbine consists of rotor blades, a tower, and a nacelle. The wind makes the blades spin and rotate a shaft connected to a generator [22]. Wind turbines are inherently alternating current by nature. For use with other renewable energy sources such as PV, wind turbines must be converted to DC.

2.3 DC Distribution

The DC distribution is the preferred topology for microgrid distribution systems. Nandini K.K. [18] listed the following advantages of DC distribution system over AC:

- The power factor is not necessary for calculating distribution loss in a DC system.
- The power losses associated with capacitance charging and discharging are eliminated.
- There is no requirement to consider utility grid synchronization or reactive power in the DC system.
- Battery converter primarily regulates the DC bus voltage using linear feedback.

DC has its own disadvantages which include the lack of standardisations for LVDC distribution networks which were noted by, Katar et al [19]. DC transmission lines has two basic distribution structures, the unipolar and bipolar system. In a unipolar system figure 2.2, electric energy is carried over two voltage lines, the Vdc and 0Vdc for reference.

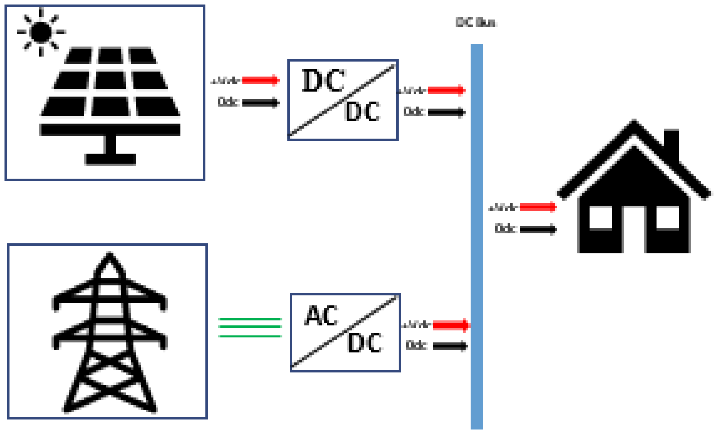

Figure 2.2: Uni-polar grid

The bipolar distribution system figure 2.3.2 carries three voltage lines, the +Vdc, the reference and the -Vdc.

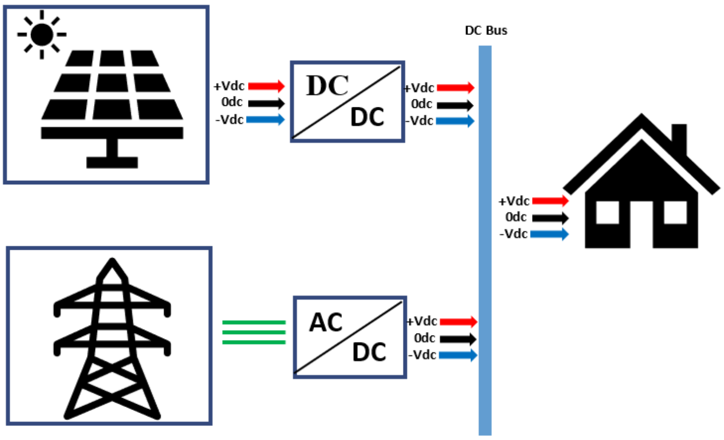

Figure 2.3: Bi-polar grid

2.4 Energy Storage Technologies.

Due to the intermittent nature of RES, which off-grid MG heavily relies upon, energy storage systems are used to power the grid when there is not enough sunlight for PV or wind speed to output the required energy to meet demand. There a many energies storage type, and each type can be further sub divided into categories. Table 2.1 below shows different types of energy storage systems:

Batteries represent the most prevalent form of energy storage and belong to the category of electromechanical storage solutions [2]. Electromechanical storage involves conversion of chemical energy into electrical or vice versa through reduction-oxidation(redox) reactions. Batteries are electromechanical devices that store and release electrical energy through redox reaction.

A range of battery varieties are employed for energy storage purposes, encompassing lead acid batteries, lithium ion, sodium nickel chloride, nickel cadmium battery, etc. These batteries vary in their respective characteristics and application.

Renewable energy storage relies on various battery types to store excess energy generated from renewable sources like solar and wind. Lead acid battery are the oldest rechargeable batteries [3]. They are well suited for application where reliability and cost are primary considerations. On the other spectrum Lithium ion is very costly however the make up in cost by their high energy density, efficiency, and life cycle.

Table 2.1: Types of energy storage.

Type of Energy Storage	Description and Applications
Batteries	- Lithium-ion: Portable electronics, EVs - Lead-Acid: Automotive, backup power, renewables - Nickel-Metal Hydride: Hybrids, stationary - Flow Batteries: Grid-scale, scalability - Sodium-Ion: Grid-scale, emerging alternative
Pumped Hydroelectric Storage	- Water pumped to higher reservoir during low demand, released for peak
Compressed Air Energy Storage	- Compressed air stored, released through turbines
Flywheel Energy Storage	- Energy stored in rotational motion of flywheel
Thermal Energy Storage	- Heat or cold stored in materials for space heating, cooling
Hydrogen Energy Storage	- Electrolysis of water to produce hydrogen for power, transportation
Superconducting Magnetic	- Energy stored in superconducting coils, rapid discharge
Thermochemical Energy Storage	- Energy stored in chemical reactions, releases energy on demand
Electrochemical Capacitors	- High-power, quick charge and discharge
Gravitational Energy Storage	- Lifting weights for potential energy storage, releases for electricity

2.4.1 Electromechanical Storage

2.4.2 Hydrogen Energy Storage (HES)

Hydrogen energy storage uses hydrogen gas as a means to store and release energy. A fuel cell is used to store hydrogen energy. In a fuel cell hydrogen and oxygen react to form water to produce electricity. This method has gained attention as a versatile and potentially sustainable solution for addressing energy storage and distribution challenges.

their high energy density, efficiency, and life cycle.

2.4.3 Mechanical Storage

Mechanical storage is the process of storing energy in mechanical systems and converting it back to usable energy when needed. The types of mechanical storage include pumped hydroelectric storage (PHD), Compressed Air Energy Storage (CAES), Flywheel Energy Storage, Gravitational Energy Storage. These types of energy storage have geographical and environmental constraints.

2.4.4 Mechanical Storage

Supercapacitors use polarized liquid layers between conducting ionic electrolyte and conducting electrode to increase the capacitance. They have a very high energy density and power. Supercapacitors have a very low stage of charge compared to other electromechanical storage systems [32]. They can be used to suppress power fluctuations in Wind and PV systems, they are generally combined with a battery system in a hybrid storage system.

2.4.5 Thermal Energy Storage (TES)

Thermal energy storage is a method of storing thermal energy by heating or cooling and releasing it when needed. TES systems can also be used to mitigate the intermittent of renewable energy sources, by storing heat in water tanks, molten salts, or another material.

2.5 Operational Strategies for DC Microgrids

There are two basic modes in which DC MGs are operated: Grid-connected and Off grid. Grid-connected in this instance means that the DC MG is connected to the utility, converters are used to convert from AC from the utility to DC used in DCMG transmission lines. EMS are integrated into MGs to improve efficiency and to maintain grid stability. In the absence of EMS control strategies for converters are used to improve grid performance.

Unlike the AC's bus control systems which controls the AC bus voltage and frequency, The converters in DC microgrid have just one parameter to control, which is the DC bus voltage. [10] discussed three control schemes used in DC microgrids: Constant-current control, constant voltage control, and droop control.

2.5.1 Constant-current control

The constant-current control aims to keep the bus current at constant level and change in demand may greatly affect DC bus voltage. Energy storage systems can utilize the constant-current control strategy to help recover bus voltage in a short time.

2.5.2 Constant-voltage control

This strategy aims to keep the voltage stable. Ultra-capacitors are used to reduce the fluctuations caused by changes in load demand.

2.5.3 Droop control

The Droop control strategy is used to stabilize the voltage and solve the load sharing problem. [10]. [6] explained droop voltage using DC system voltage-current characteristic line (V-I characteristic line). The load demand will cause a change in the output current of converters, which will lead to the drop of bus voltage. The droop control scheme is the same as that of voltage-control, with the difference being reference voltage is replaced by droop voltage.

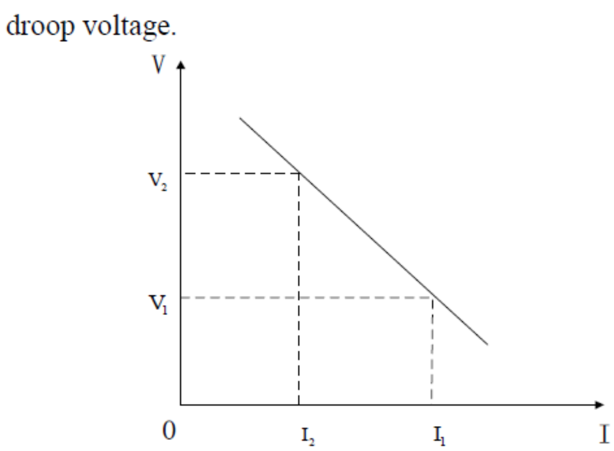

Figure 2.4: DC voltage-current characteristic line

2.6 Operational Strategies for DC Microgrids

Mohammed A.A et al [1], describes hierarchical control in their DCMG systems as consisting of three level; primary, secondary, and tertiary control.

(1) Primary control deals with voltage/current regulation, and control of local power-sharing.
(2) Secondary control works on the top of primary control dealing with voltage compensation, power quality regulation, microgrid synchronization with any external grid, etc.
(3) Tertiary control is the highest level and is responsible for optimization, power management, economic dispatch, and overall system regulation.

A communication less decentralised power-sharing method for composite storage devices developed by [7], their strategy allows plug and play of multiple batteries and ultracapacitors by implementing a master-slave control on additional batteries. This paper does not guarantee full equalisation of SoCs. Equalisation is highly dependent on load and power generation.

2.7 EMS-integrated DC MG

Energy Management Systems are used in MG to improve grid performance, reduce operational costs, and increase efficiency [8]. Different algorithms for EMS have been proposed for different MG topologies.[24] proposed a 4-level DC-based home management system to meet voltage levels of home appliances and devices. The EMS proposed in [20] improves efficiency and power management by introducing three modes of operation: power mode, deficit, and power balance mode.

2.8 Multi-level approach

Multi agent systems in microgrids are made up of units called agents. From the MG perspective, agents are HEMS connected to it. The agent on the MG can be configured in two ways, centralised multi-agent coordination and de-centralised agent coordination. Figure 2.5 below illustrates the centralised multi-agent coordination described by [15], the coordinator is the central agent, it is responsible for commination between the agents.

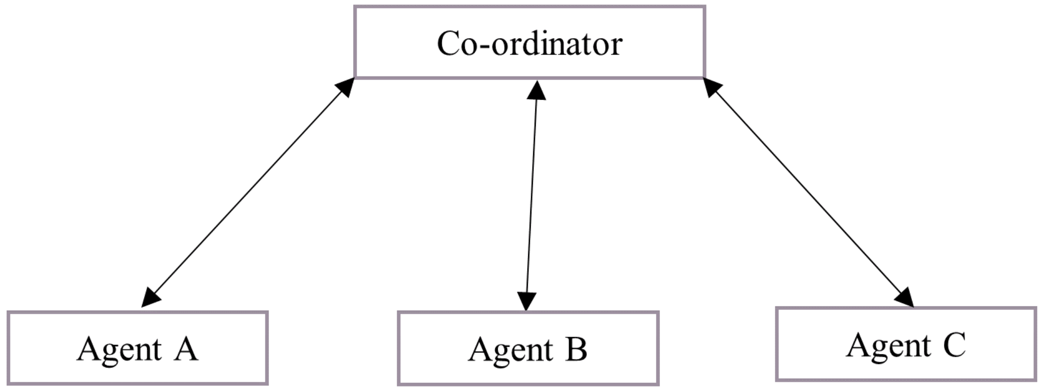

Figure 2.5: Centralised multi-agent coordination

A de-centralized multi-agent co-ordination is shown below. In this architecture, the agents work independently, they communicate to each other to determine the status of other agents so they can perform the same task by associated motives.

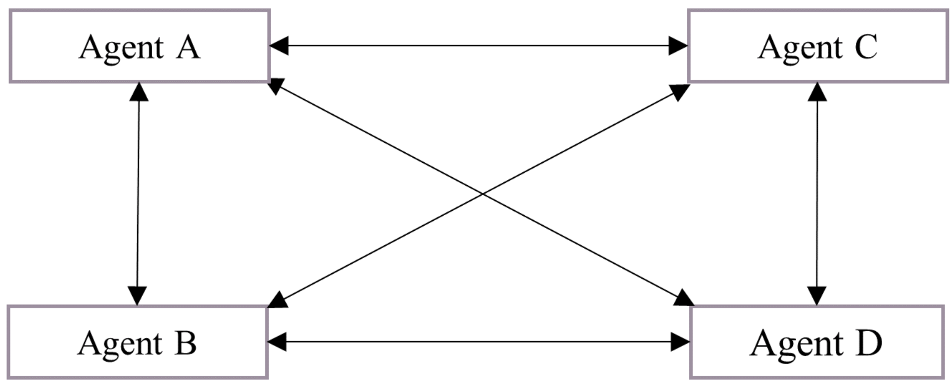

Figure 2.6: De-centralized multi-agent co-ordination

2.9 Proposed study

A microgrid can be defined as power cluster of distributed generation, load, and energy storage device accumulated together in the vicinity to each other [25]. The most used distributed generation in residential areas are PV [36]. The flexibility of the proposed

EMS allows for residential units to be configured as DG, ESS, load, or any combination, depending on the resources available in the unit [35].

2.9.1 Introduction

Ahmad Alzahrani et al. [35] described as a Systems of Systems (SoSs). SoSs are integrated systems that are diverse and autonomous but work together to achieve common goals. The systems can work together or independently. Table 1 below shows some characteristics of SoSs.

Table 2.2: Systems of Systems characteristics

Characteristic	**Definition**
Operational Independence	All subsystems work independent and have no interference with other subsystems
Evolutionary development	Flexible to adding new subsystems
Emergent behaviour	The overall system works as collective unit to accomplish a big task
Geographic distribution	The subsystems are sequentially distributed to facilitate the flow of information
Managerial independence	The subsystems are in control of their own operation.

From a microgrid layout, REMCS (Residential Energy Monitoring and Control systems) are systems that connect to another system such as CGMS (Central Grid Management system). REMCS subsystems capable of operating independently without any input or interference from CGMS.

2.9.2 Modelling the microgrid for the EMS using SoSs

The SoSs have characteristics that allow easy integration of the EMS into the microgrid, with each system working independently, failure of one system will have little impact on the overall operation of the grid. Figure 5 below shows the DC microgrid connected to RES, loads and storage systems.

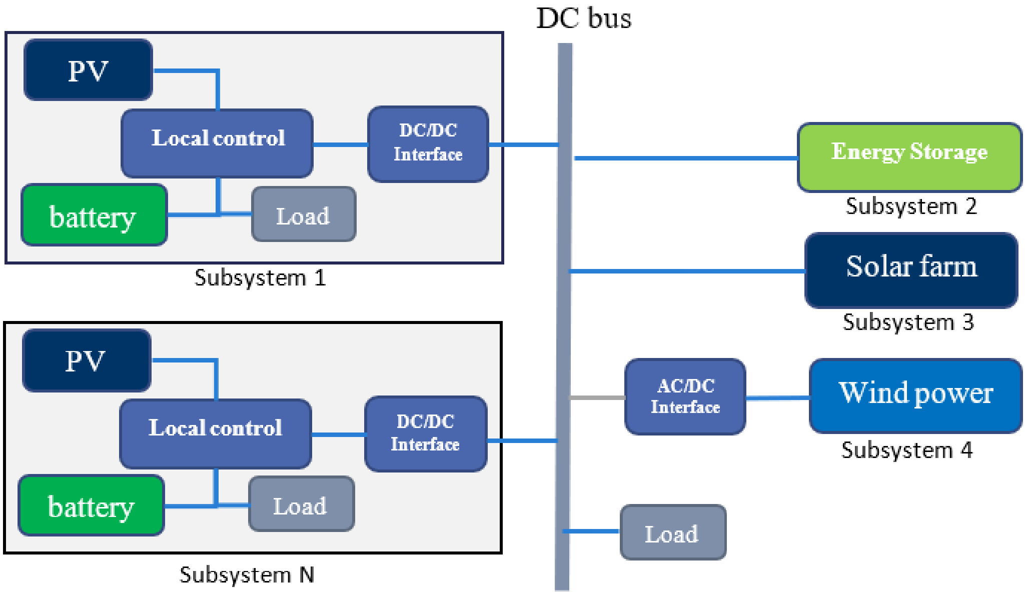

Figure 2.7: DC MG Systems of Systems

2.10 Conclusion

This this section, energy generation, storage and distribution methodologies were reviewed to determine the best solution for DC MG application. From the studies above and taking account of all the cited references, energy management systems differ greatly due to grid attributes, such as centralised and decentralized, voltage regulation, frequency control, etc.

The current study proposes the adoption of a decentralized energy management system for the DC MG, characterized by a non-communicative framework. This approach capitalizes on the power sharing concept elucidated in reference ,while additionally introducing a System of Systems framework to enhance control mechanisms and operational efficiency.

Chapter 3

Theoretical considerations

3.1 Introduction

This chapter presents feasibility study and planning, power balancing and control mechanisms, and battery energy storage systems. Additionally, model development of the DC microgrid and a discussion on the state chart model for the Energy Management System (EMS) are provided. By systematically examining these aspects, the objective is to establish the grid structure to be utilized in the simulation.

3.2 Feasibility study and planning

The objective of this study is to implement an energy management system in a DC microgrid with the aim of enhancing overall system performance. The feasibility studies for the EMS are closely reliant on the feasibility study of the DC microgrid, given that they constitute an addition to the DC microgrid. The feasibility of DC MG is studied in this chapter.

The viability of DC MG in residential areas is evaluated in comparison to the ac grid in terms of conversion efficiencies in [14]. The author concluded that DC systems with local generation and storage encounter less conversion losses, this was supported by [30], they developed AC and DC models for comparison and concluded that when AC power system is supplied by a DC source, further losses can be expected resulting in further benefits of a DC distribution system. The highest efficiency is attained when

DC sources supply DC loads, and AC sources supply AC loads. The positive outcome demonstrated in [17] has established the feasibility of directly supplying appliances with DC voltage.

3.3 Resource Assessment and Design

3.3.1 Battery Energy Storage System

The battery SOC level determines the duration of use of electrical energy after sunset [4] and if the battery capacity is too low the grid is likely to shut down. For the EMS to effectively keep the grid stable the SoC of the battery must always be known. The charging/discharging effect on SoC can be represented by the following equation [23];

$$SoC_{bat,t} = SoC_{bat,t-1} + (\eta_c P^{c}_{bat,t-1} - \frac{\eta_c P^{dc}_{bat,t-1}}{\eta_d}) \tag{3.1}$$

$$SoC_{bat,min} \leq SoC_{bat,t} \leq SoC_{bat,max} \tag{3.2}$$

Where:

$SoC_{bat,t}$ = Battery SoC at time t
η_c = charging efficiency
η_d = discharging efficiency
$P^{c}_{bat,t-1}$ = charged power at time t-1
$P^{dc}_{bat,t-1}$ = discharged power at time t-1

The BESS minimum and maximum charging and discharging power constraints at time t can be written as:

$$P^{c}_{bat,min} \leq P^{c}_{bat,min} \leq P^{c}_{bat,min} \tag{3.3}$$

$$P^{dc}_{bat,min} \leq P^{dc}_{bat,min} \leq P^{dc}_{bat,min} \tag{3.4}$$

The scalability and quietness of solar panels allow for easy integration into residential areas. Battery storage systems ensure energy independence for residential units and grid stability. compared to the other energy storage systems studied in this paper, battery storage systems can be modular, allowing for incremental capacity additions.

3.3.2 Power Balancing and Control

The power balancing strategies are classified as: centralized, decentralized and distributed. In centralized control, the central controller acquires system information for control, decisions, and schedules tasks. The decentralized control operates on local quantity measurement. A distributed control uses DC bus signaling in which bus voltage is the communication carrier to decide operation modes [13].

A modified distributed control is used in this paper. A web-based communication protocol is used to communicate bus voltage and other parameters to the main control, nodes can still operate individually. The type of control used by the nodes operates the same across all nodes. The equation below measures the power available to the load on a specific node.

$$P_{LOAD} = P_{GRIP} + P_{PV} + P_{BAT} \tag{3.5}$$

Where P_{PV}, P_{BAT}, and P_{GRID} function as input power to local load. P_{LOAD} is power drawn by the load.

DC bus voltage shifting from charging mode to discharging mode.

$$P_{BAT} = P_{LOAD} + P_{PV} + P_{GRID} \tag{3.6}$$

In the case of more radiation, the battery gets charged, however, overcharging the battery is avoided. Excess power is shared with the grid. The central control ensures grid stability by making decisions for the nodes connected to the grid. In this control, there are N number of nodes. $P_(GRID)$ is obtained from equation 3.7

$$P_{GRID} = P_{PV} + P_{BAT} + \Sigma_{i=1}^{N} P(i) \tag{3.7}$$

Where:

P_{PV} = is the solar farm PV
P_{BAT} = solar farm battery storage

3.3.3 Energy Management System

Figure 2 below shows the proposed state machine control strategy for residential unit 1. Load demand is determined using probabilistic load demand for the renewable energies proposed in [9] . This control strategy prioritises battery charging while there is still power being generated from RES. The unit enters a power sharing state when there is surplus energy from the PV panels.

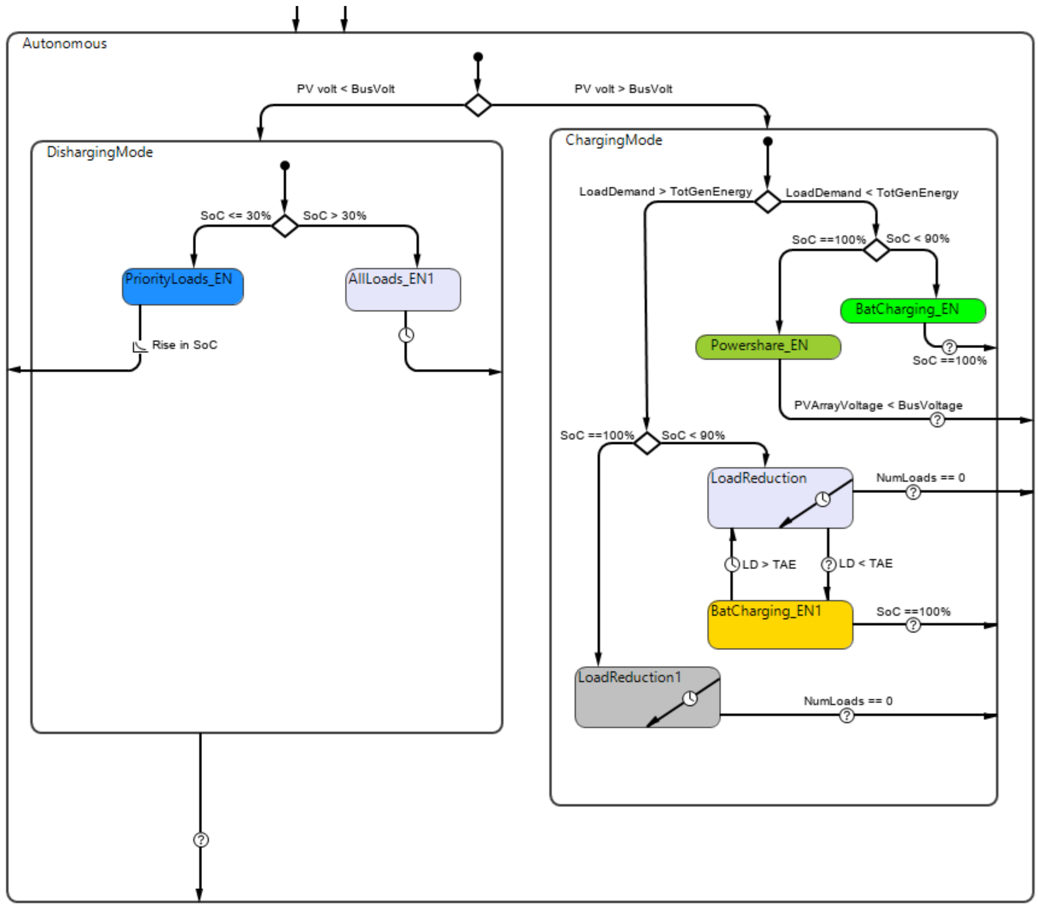

Figure 3.1: Operating mode 1 strategy

Figure 3.1 illustrates the control strategy for mode 2 operation, where the unit functions as a battery storage due to the availability of battery capacity. In this mode, priority is given to battery charging, ensuring that the load can continue to operate long after sunset. When there is insufficient energy from the grid to charge the battery and meet the load demand, the system activates the load reduction state.

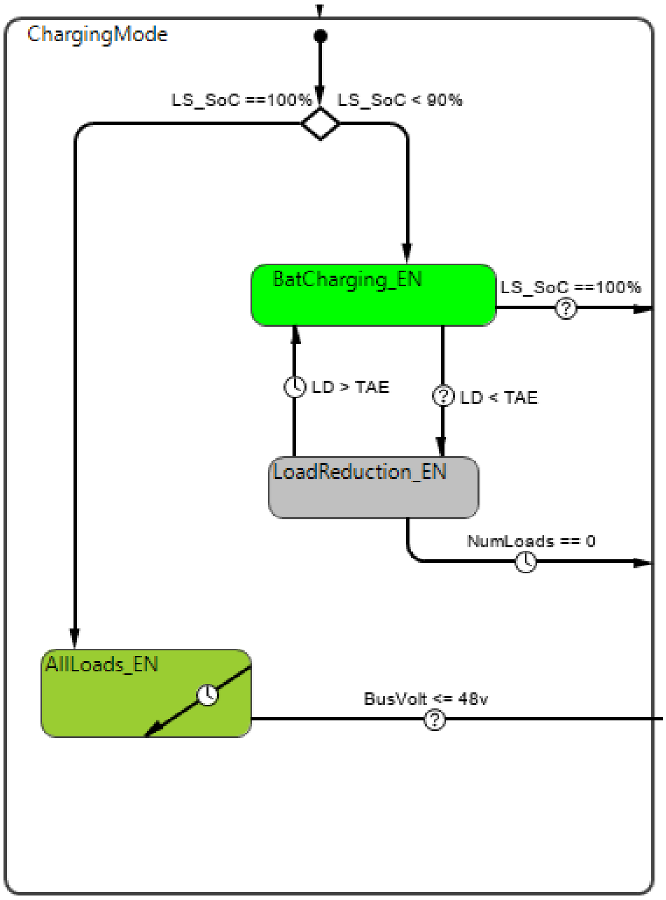

Figure 3.2: Operating mode 2 strategy

Mode 3 characterizes a residential unit that generates power but lacks a storage system. Figure 3.3 illustrates the state machine for this unit. The system enters a power-sharing state when the PV array generates sufficient power to meet the local demand. The State of Charge (SoC) of distributed energy sources can be estimated with reasonable accuracy using the filtered terminal voltage method proposed in in [42]. This estimation allows the residential unit to contribute energy to charge the Energy Storage System (ESS) on the grid.

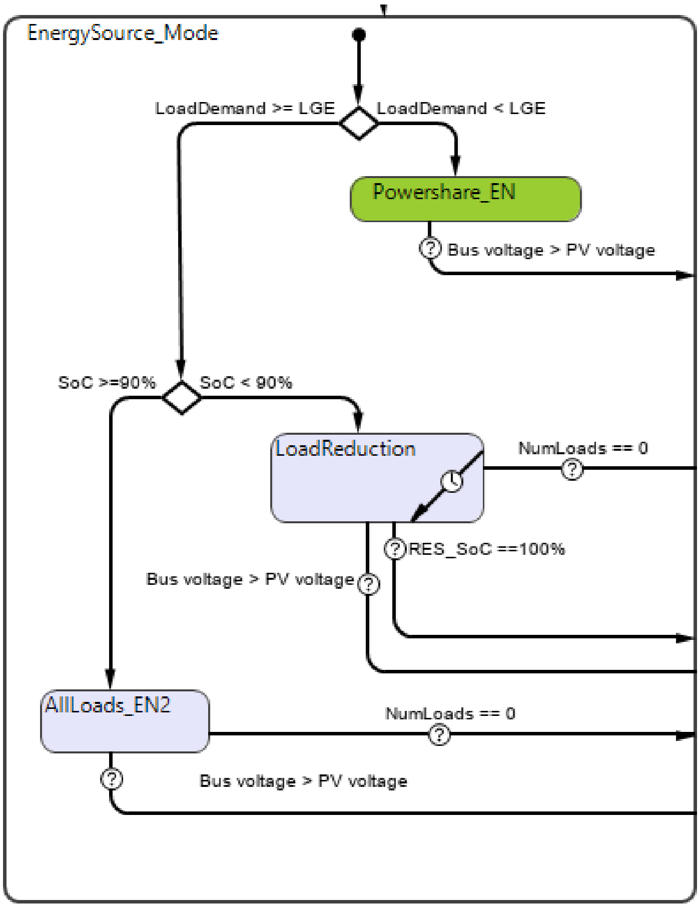

Figure 3.3: Operating mode 3 strategy

The control strategy for modes without any energy source or battery storage is simple: load reduction is triggered when the solar farm State of Charge falls below 10%. This system solely relies on external power sources.

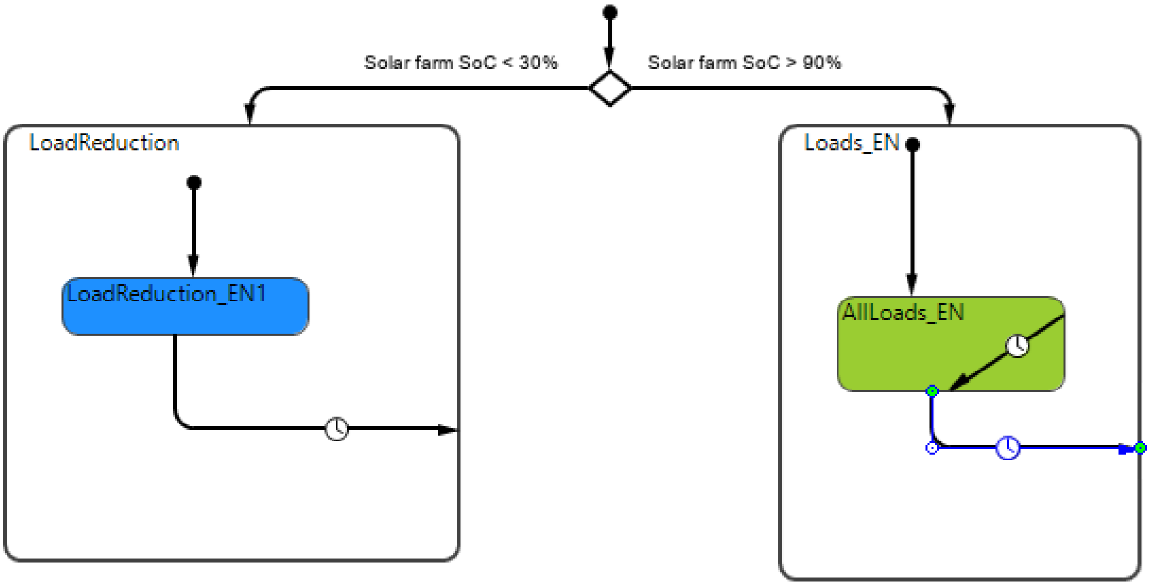

Figure 3.4: Operating mode 4 strategy

3.4 Conclusion

In this chapter, we conducted a feasibility study of the Energy Management System (EMS) and the DC Microgrid (MG) as a whole. Several authors have demonstrated the feasibility of DC MGs for residential use, with the EMS serving as an enhancement to the DC MG. We also explored power balancing and control strategies for managing units connected to the MG. The MG can be configured to operate in both centralized and decentralized (autonomous) modes. Additionally, state charts for the units were developed.

Chapter 4

Methods and materials

4.1 Methods and materials

4.1.1 Introduction

System Overview The aim of this paper is to introduce a Direct Current (DC) microgrid Energy Management System (EMS) utilizing system of systems (SOSs). The proposed system involves the integration of renewable energy sources, energy storage, and demand management within a microgrid framework. The Matlab Simulink environment is employed to model and simulate the system.

4.1.2 Microgrid configuration

The microgrid comprises four houses, each symbolizing a unique scenario. As depicted in Figure 4.1, these houses are interconnected with the Central Grid Management System (CGMS) via a microgrid. In the Matlab Simulink model, each house is represented as a distinct block

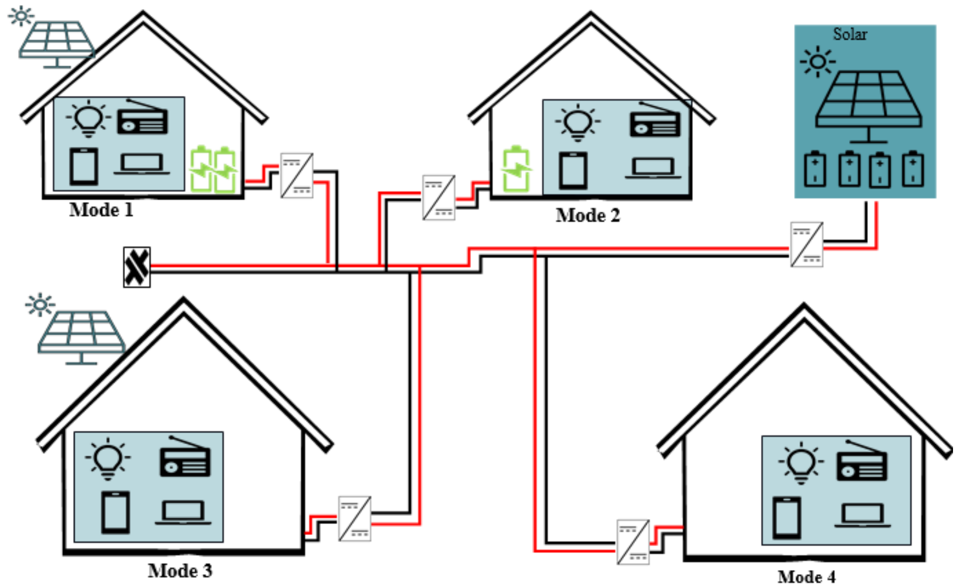

Figure 4.1: Residential unit operation modes.

4.1.3 Scenarios for diverse inputs

The four houses in the microgrid allow for the simulation of various scenarios that serve as input parameters for the CGMS:

Scenario 1: Node with Storage System In this scenario, a node within the microgrid is equipped with an energy storage system. This system can both store and source energy, providing flexibility in managing energy demand and supply.

Scenario 2: Node without Storage System This scenario involves a node that lacks an energy storage system. Energy can only be sourced from renewable sources (e.g., solar panels) during periods of sunlight.

Scenario 3: Node with Only Storage System Here, a node in the microgrid is equipped with an energy storage system but does not possess the capability to generate energy. It can only manage energy based on stored reserves.

Scenario 4: System Node with No Energy Interaction This scenario represents a node in the microgrid that neither stores nor sources energy. It serves to demonstrate the impact of non-participating nodes on the overall energy management system.

4.2 Matlab Simulink Model

The proposed microgrid EMS and scenarios are implemented using the Matlab Simulink platform. Each scenario is modeled as a separate block, with appropriate connections to represent energy flow, storage, and interaction with the microgrid.

4.3 Validation and Verification

The proposed microgrid EMS's validity is confirmed by conducting comparisons with a laboratory model and benchmark scenarios. Sensitivity analysis is conducted to assess the system's robustness to varying parameters.

4.4 Microgrid Formation

By combining these individual house blocks, a comprehensive microgrid is formed. This microgrid is integrated with the CGMS, allowing for centralized energy management and coordination across the various scenarios. In the absence of CGMS, the microgrid can still operate under systems of systems rule. The formation of a microgrid involves the integration of four distinct units, each of which presents a unique scenario for analysing the response of the energy management system.

4.4.1 Photo Voltaic Solar Panels

In the evaluation of the system, two series of interconnected PV modules with parameters as specified in Table 4.1 are employed. The output voltage and current of these PV modules are calculated by applying irradiance and temperature data sourced from [39], utilizing the following equation:

$$I_d = I_o(\exp(\frac{V_d}{V_T}) - 1) \tag{4.1}$$

$$V_T = \frac{k_t}{q} * nl * NCell \tag{4.2}$$

Table 4.1: PV array parameters

Parameter (Unit)	Solar Farm PV	Solar Farm PV
Maximum Power(W)	330	330
Open circuit voltage(V)	36.84	48
Short-circuit current Isc (A)	100	19.896
Voltage at maximum power point Imp (V)	100	22
Current at maximum power point Imp (A)	55.87	55.87

Figure 4.6.1 displays the irradiance and temperature data intended for use as input parameters in the PV simulation block. Given their close proximity, it can be inferred that the irradiance will be consistent across all units

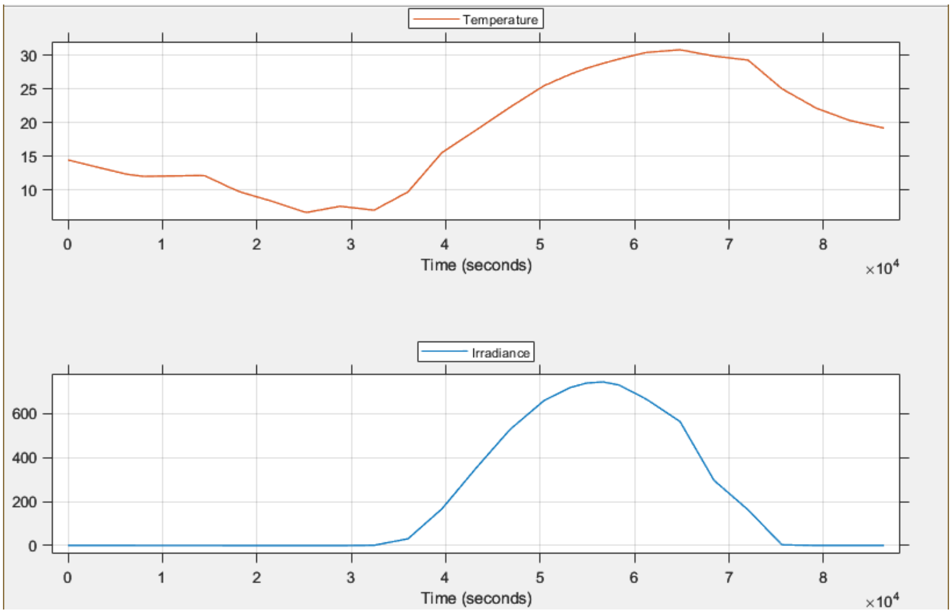

Figure 4.2: Photo Voltaic Generation Irradiance and Temperature 8/16/2020[39]

The battery's capacity rating, as illustrated in Table 4.2. Shows two battery capacities used in this paper, The solar farm energy storage system (SF ESS) and Residential energy storage system (RE BSS). The Solar farm battery storage boasts a substantial maximum capacity of 100 ampere-hours (Ah), enabling it to store a significant amount of electric charge. With a nominal voltage of 48 volts (V), SF ESS maintains a consistent grid operating voltage while it is charged. RE BSS is a specialized energy storage solution operated by a REMCS in a MG, it is designed to complement SF ESS.

The energy storage block in Simulink offers a versatile configuration that can ac-

Table 4.2: Energy storage parameters

Parameter (Unit)	SF ESS	RE BSS
Maximum capacity (Ah)	100	22
Nominal voltage(V)	48	48
Nominal capacity (Ah)	100	19.896
Rated capacity (Ah)	100	22
Fully Charged Voltage (V)	55.87	55.87
Cut-off voltage (V)	36	36

commodate a wide range of battery storage options. In the context of this research, the selected energy storage technology is lithium-ion batteries. Lithium-ion batteries are chosen for their well-established performance characteristics, high energy density, and suitability for various applications. Their adaptability within the Simulink framework ensures that they can be used effectively in the context of the research project.

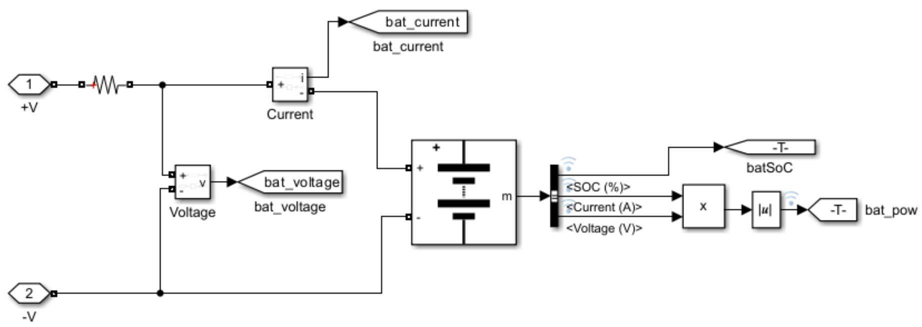

Figure 4.3: Battery Storage System

4.4.2 Load Profile

Internally, most of the appliances operate on DC [16]. With the improvement in technology such as USB power delivery (USB-PD) standards, appliances such as LCD TV, laptops and monitors can be powered directly from USB connection. The load profile provided in figures 4.3 – 4.7 are utilised to model various load conditions experienced by the units over a 24-hour period.

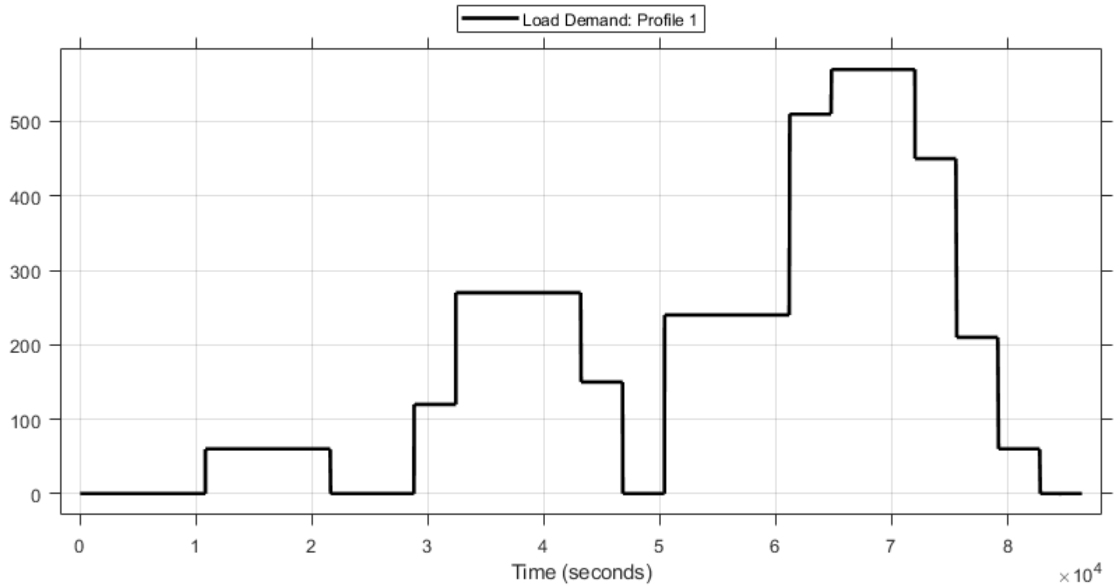

Figure 4.4: Load demand: Profile 1

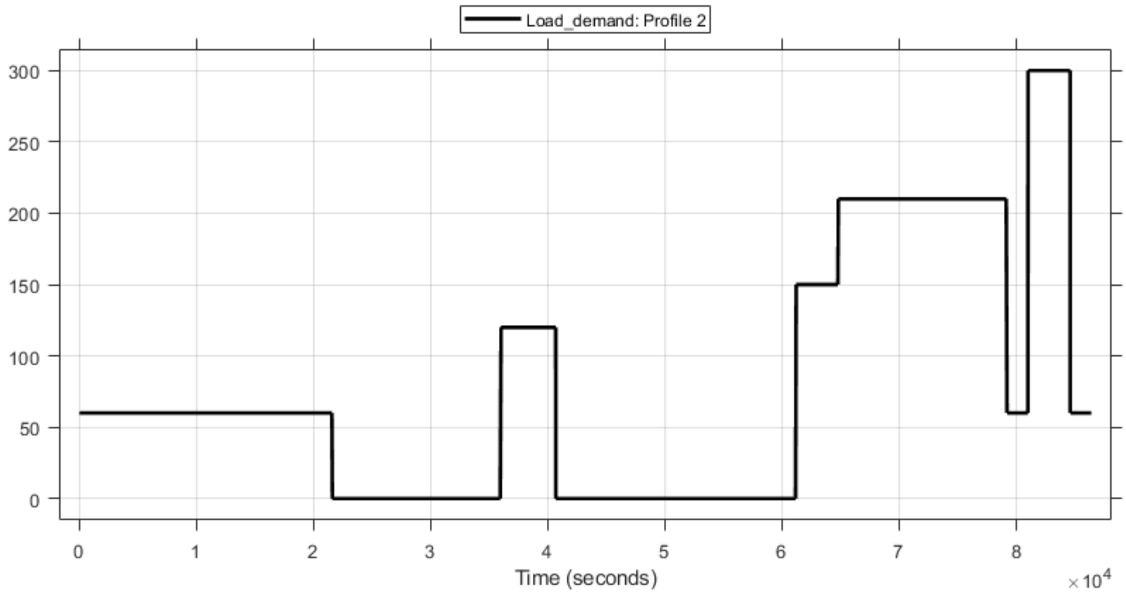

Figure 4.5: Load demand: Profile 2

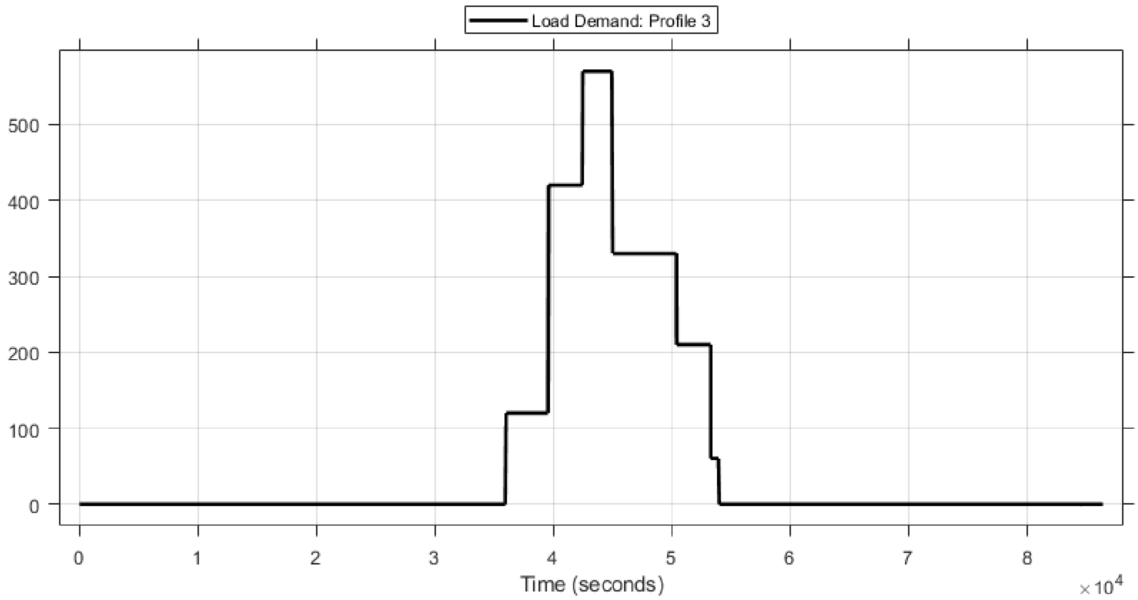

Figure 4.6: Load demand: Profile 3

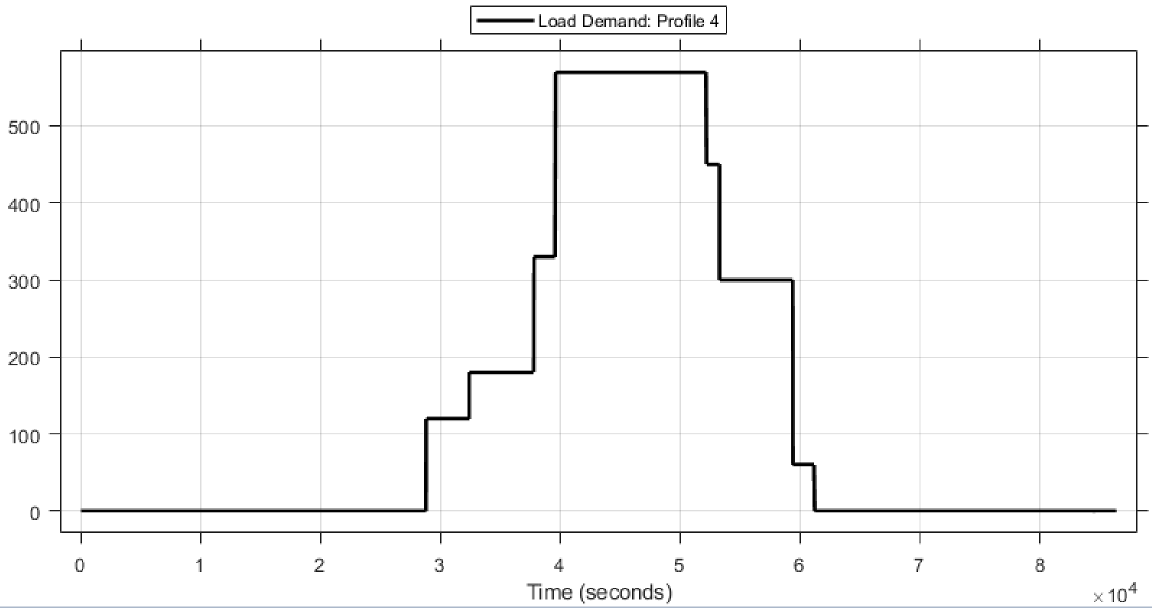

Figure 4.7: Load demand: Profile 4

Matlab Signal editor block is used to produce load profiles during simulation time.

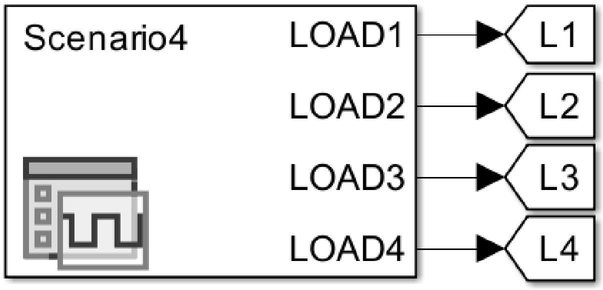

Figure 4.8: Load profile waveform selector

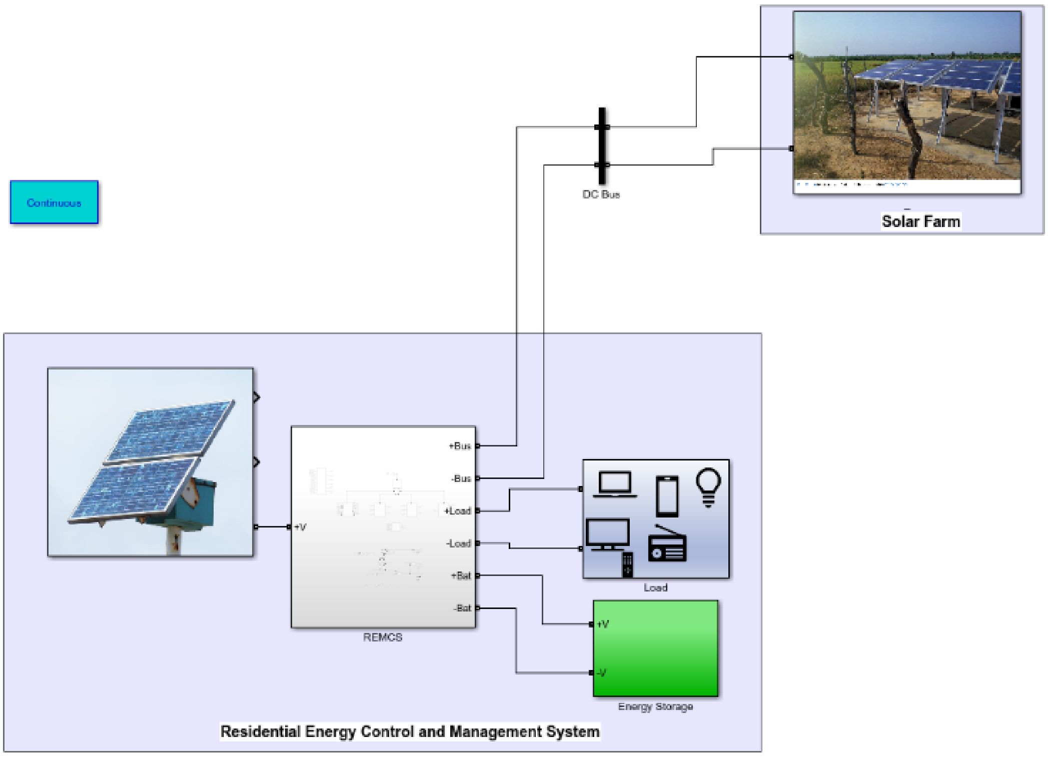

Figure 4.9: REMCS unit Matlab overview

Figure 4.9 displayed above illustrates a Matlab/Simulink representation of an REMCS unit connected to a solar farm through a DC MG. Units' configuration can be modified by addition and or removal of ESS and BSS. In the REMCS block, an MPPT system interfaces with the PV module, and a bidirectional DC-DC converter connects to the external Grid. Several switches are employed to control the grid. The load block consists of four distinct resistive loads that are turned at different interval to produce the load profiles discussed.

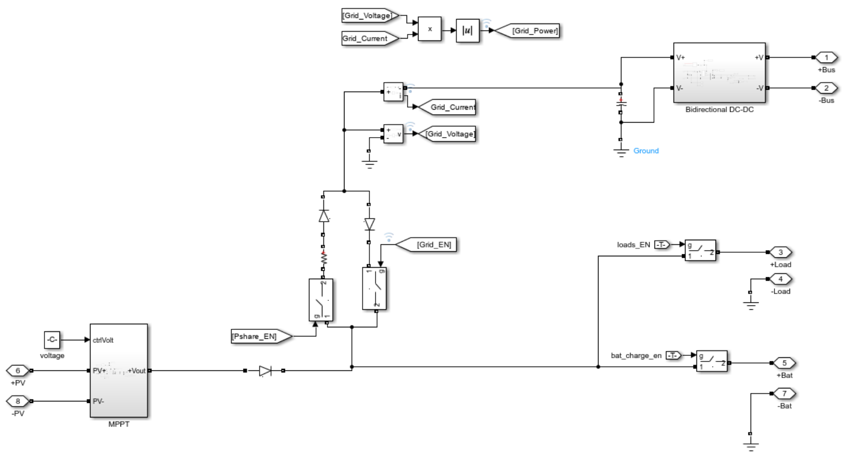

Figure 4.10: REMCS nano grid

The load block consists of four distinct resistive loads that are turned at different interval to produce the load profiles discussed.

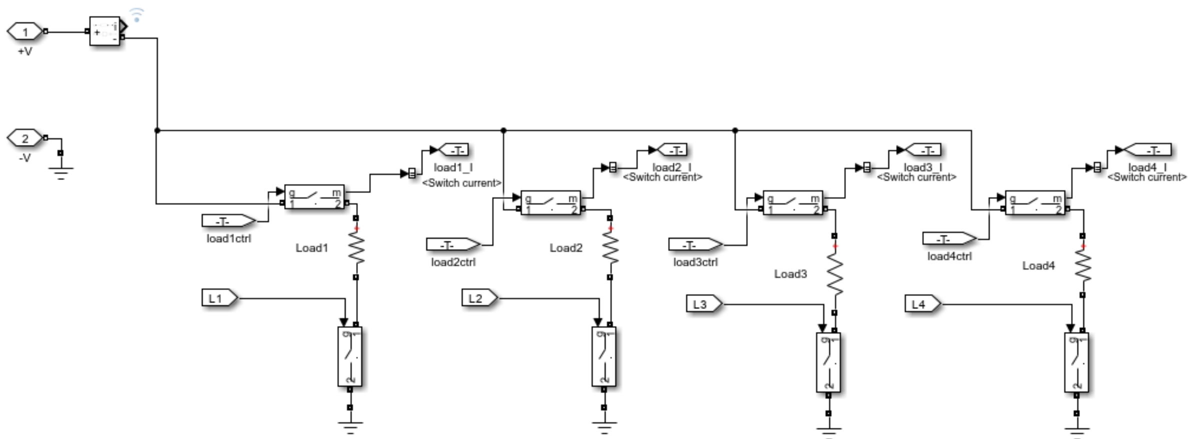

Figure 4.11: Loads control circuit

The load demand for the load profiles is determined by adding up the total power consumption of all activated loads as depicted in the figure below.

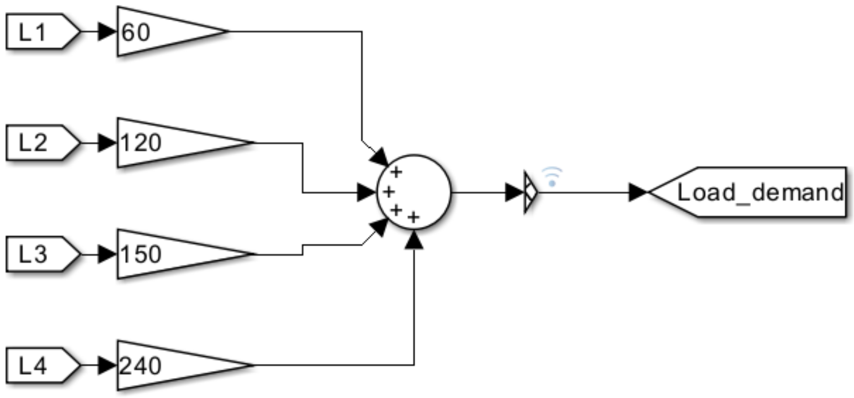

Figure 4.12: Load demand block

4.5 REMCS Design Logic

4.5.1 State Observer

The Systems of Systems framework allows REMCS units operate fully independent without direct communication to other units in the grid. The state observer REMCS, using power flow and voltage measurements can determine the state of the grid and respond accordingly.

The Systems of Systems philosophy empowers REMCS units to operate as self-contained entities, operating independently without the necessity for direct communication with other units interconnected in the grid. Instead of relying on constant coordination or centralized control, these REMCS units are designed to function autonomously, ensuring flexibility and robustness in the overall system.

Within this framework, a state observer is integrated into the REMCS. This observer uses power flow and voltage measurements to assess and monitor the state of the grid. By continuously analysing these key parameters, the state observer can determine the health, performance, and stability of the grid at any given moment.

This capability provides several advantages. First, it enables each REMCS unit to make informed decisions in real-time, optimizing its own operations based on the grid's condition. Second, it enhances the grid's resilience since REMCS units can respond to changes or disturbances independently.

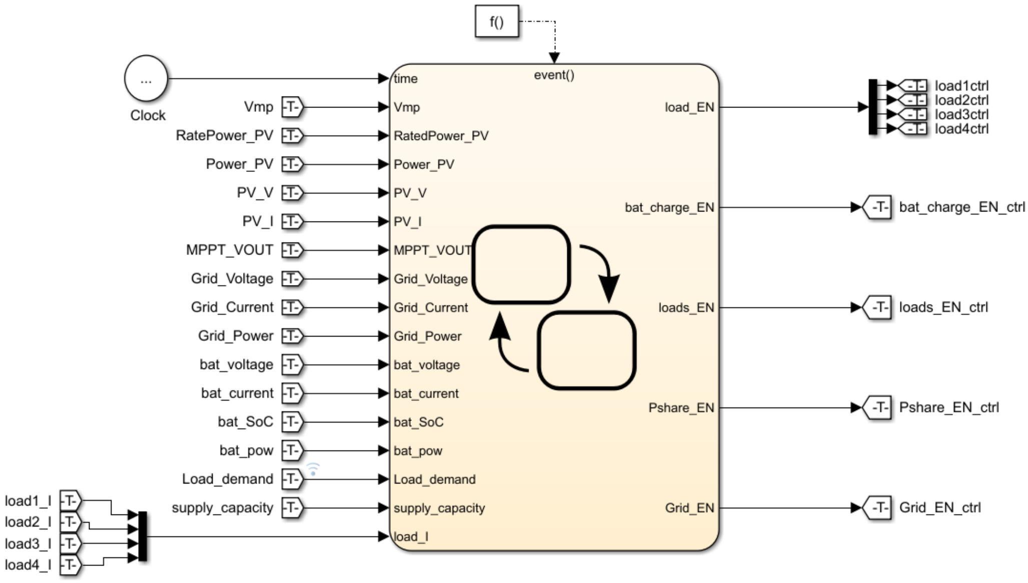

Figure 4.13: State chart block

The state chart block transitions the REMCS unit to four distinct states whereby each resource configures the system resource for optimal performance. These states represent different operational modes that the REMCS unit can adapt to as it interacts with the grid. Each state is designed to align with specific objectives and requirements, optimising resource allocation and utilisation. Three states are connected to Start, Running on Battery, PowerShare and charging.

4.5.1.1 Running on Battery State

The criteria for transitioning into the Running on Battery state depend on two key factors: the availability of solar power and whether the PV modules have achieved their maximum power point voltage (Vmp). The substates implement load shedding when the battery SoC goes below 30% by reducing supply capacity. The systems leave this state when bat_SoC goes above the last recorded SoC before going into Running on Battery mode.

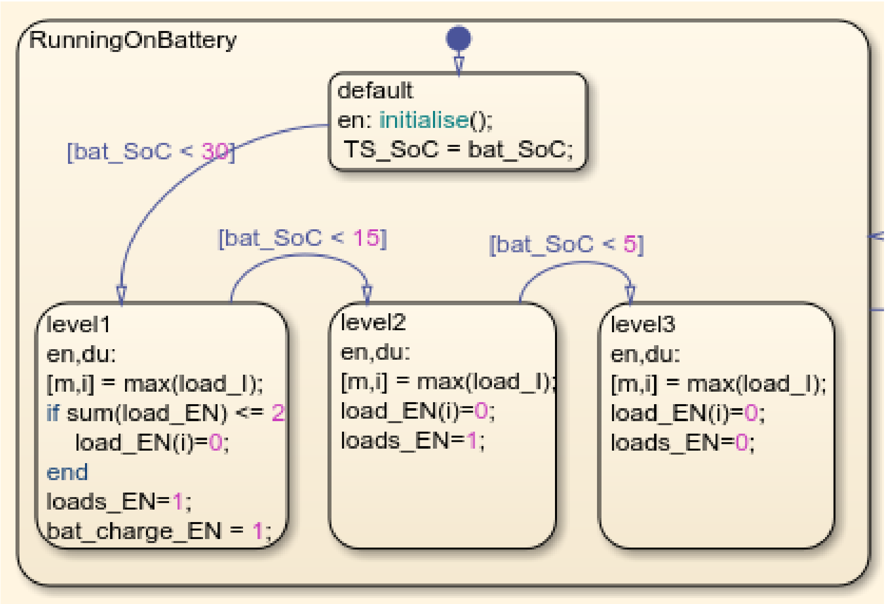

Figure 4.14: Running on battery

4.5.1.2 Charging State

The system transitions into a "Charging" state whenever the State of Charge (SoC) drops below 100%. Upon entering this state, default configurations are applied. Within the Charging state, there are two priority charge substates, PR_CHRG_LVL2 and PR_CHRG_LVL3, designed to prioritise battery charging then load servicing. During the PR_CHRG_LVL2 substate, load reduction measures are activated when the battery's SoC is below 50%. Charging continues until the SoC exceeds 75%, at which point load reduction is lifted.

4.5.1.3 Power Share State

Upon reaching a battery State of Charge of 100%, and when the photovoltaic (PV) module generates an excess of energy beyond the local load requirements, the system enters a "Power-Share" state. In this state, the system is perceived as an energy source by both the central controller and any other units connected to this system.

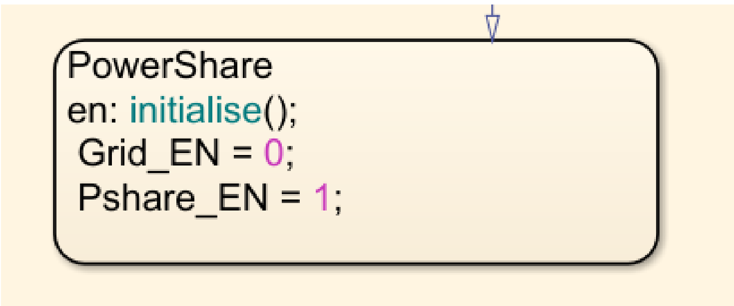

Figure 4.15: Power Sharing

4.6 Model parameters

The performance of the EMS is determined by the following:

Bat_SoC – The energy storage system plays a crucial role in enhancing grid reliability by supplying power during periods when energy sources may not be dependable. It is imperative to prioritize battery charging whenever Renewable Energy Sources (RES) are actively generating power.

SF_SoC (Solar farm state of charge)– The energy storage system within the solar farm provides power to all REMCS units and plays an important role in maintaining grid voltage stability. When systems operate autonomously, it is essential that they refrain from drawing power as the State of Charge (SoC) of the solar farm's energy storage system approaches depletion.

Loads – Predicting and planning for load demand presents a challenge, primarily because consumers do not adhere to a rigid schedule for switching on their loads. In microgrid systems, demand-side management strategies, as discussed in [31], have been adopted to enhance efficiency, reduce utility bills, and serve various other objectives.

In summary, the integration of an EMS into the grid is anticipated to enhance the charging rate of local Battery Energy Storage Systems (BESS), particularly during daylight hours when PV modules generate power. This integration also plays a vital role in maintaining grid stability by reducing the discharge rate of BESS. Additionally, the Energy Management System (EMS) is responsible for effectively directing surplus power generated by PV modules back into the grid. To achieve these objectives, the EMS can implement strategies to reduce overall load demand.

The benchmarks mentioned above will undergo testing within all four scenarios, with each load profile depicted in figures 4.3 through 4.7 being applied. This testing procedure will serve as the means to assess the performance of the EMS.

Table 4.3: Scenario 1: Model setup parameters

Irradiance profile	**Figure 4.1**
Battery size and capacity	Nominal voltage: 48 V DC Capacity: 22Ah Initial SOC: 50%
Load Size	Minimum: 60(W) Maximum: 570(W)
PV module	Maximum power: 240.53(W) Vmp: 30.72(V) Imp: 7.83(A)
Load profiles used	Case study 1: Load profile 1(Figure 4.3)
Load profiles used	Case study 4: Load profile 1(Figure 4.7)

4.6.1 Case study 1

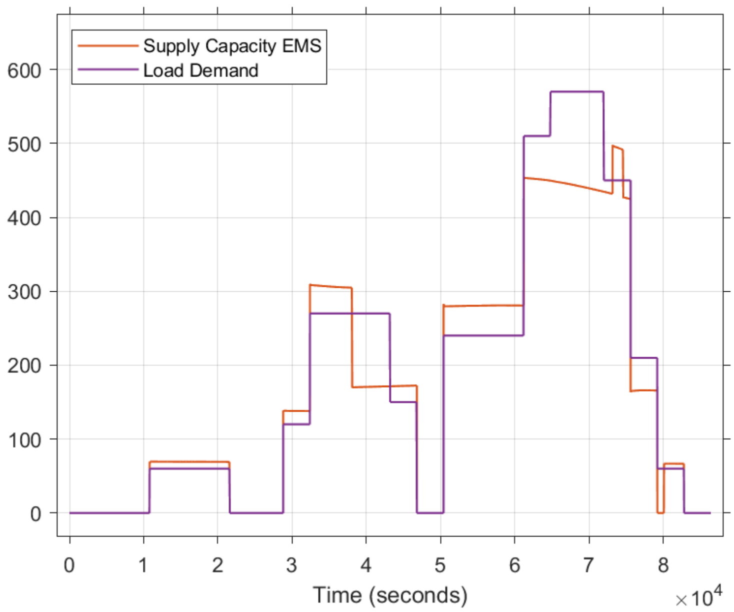

Figure 4.16: Supply capacity with EMS v load demand

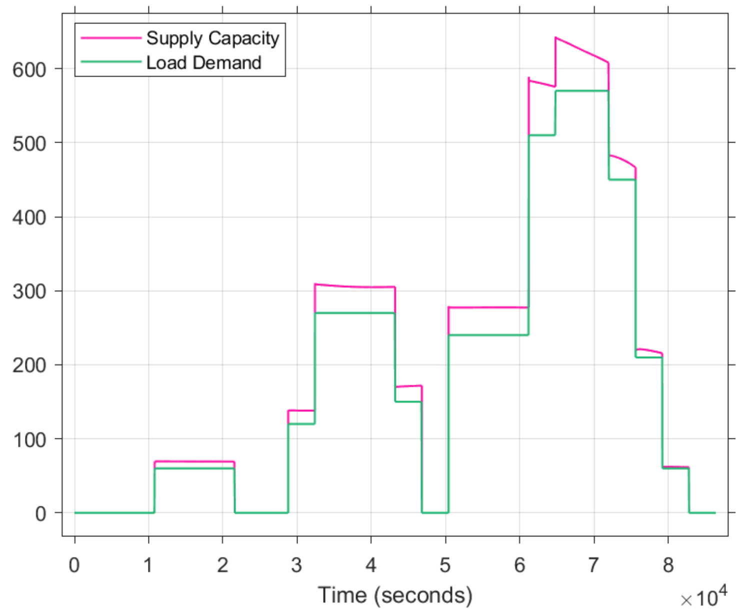

Figure 4.17: non-EMS Supply capacity with v load demand

To satisfy the load demand, the supply capacity must consistently equal or exceed the load demand. The results obtained in figure 4.17 demonstrate the capability of the energy source within the DC MG to fulfil the unit's energy load profile, particularly in the non-EMS integrated scenarios.

The inability of the EMS-Integrated DC MG to meet load demand can be traced to its energy prioritization feature, which allocates a portion of the available energy for battery charging.

Consequently, this feature results in a noticeable 10% improvement in the state of charge (SoC) of local storage when compared to the non-EMS system, as illustrated in Figure 4.18 at time $5 \times 10^4 s$.

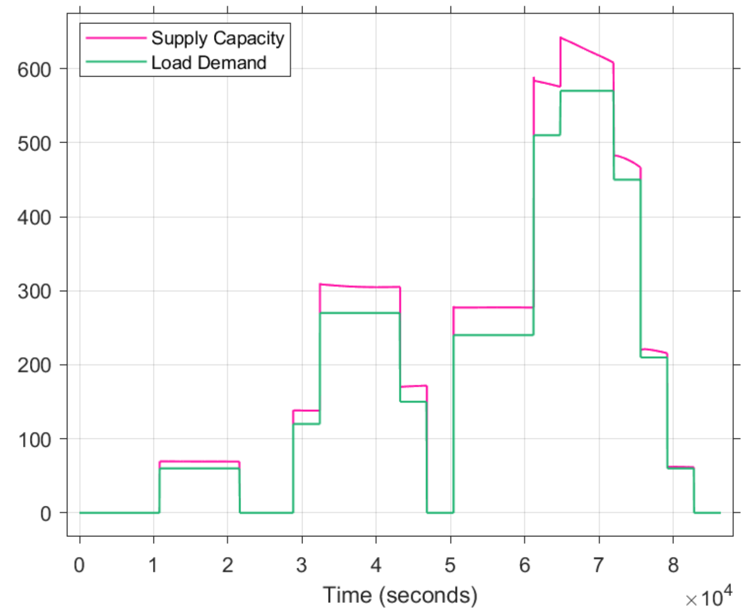

Figure 4.18: Local Storage SoC EMS v non-EMS system

The initial differences in SoC observed after 3.8×10^4 seconds between the non-EMS DC MG and the EMS-integrated DC MG can be attributed to the EMS's response time when detecting sufficient power from RESs. Peak load demand commences around 3.8×10^4 seconds, which closely coincides with the moment when PV panels cease power production due to the sunset. During peak demand, the slope remains consistent for both systems, primarily because of the identical load profile and the fact that RES is not generating power. The load demand persists until approximately 8.4×10^4 seconds, causing a significant decline in the State of Charge (SoC) of both the solar farm and local energy storage. The Solar Farm SoC comparison is shown in figure 4.18 To reduce dependence on external power sources, the EMS restricts the utilization of the solar farm's storage until the local storage drops below 15% or cannot meet the load demand. Solar farm SoC drops from 50% at time 0 seconds to 20% at time 86400. EMS-integrated systems have 16.5% more storage capacity than the non-EMS system as shown in fig. 4.19

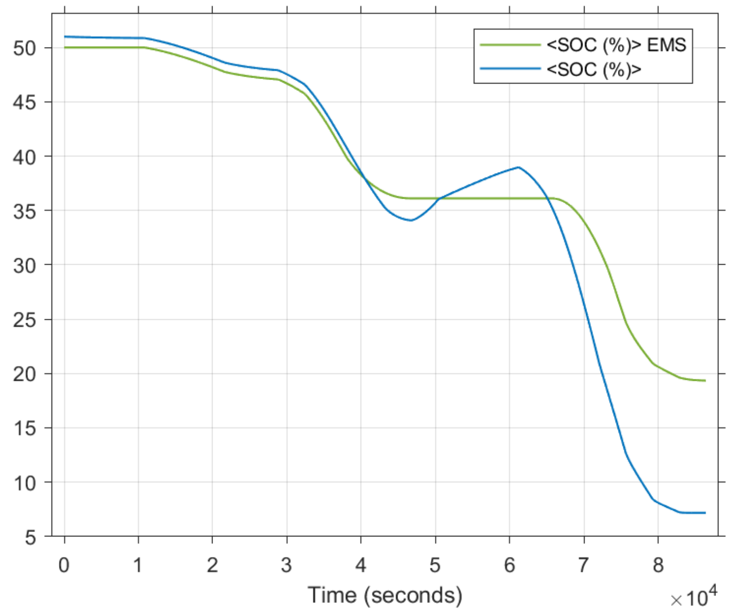

Figure 4.19: Solar Farm Storage SoC EMS v non-EMS system

The load demand data for case study 4 is illustrated in figures 4.20 and 4.21, with a specific focus on highlighting the EMS local storage prioritization feature.

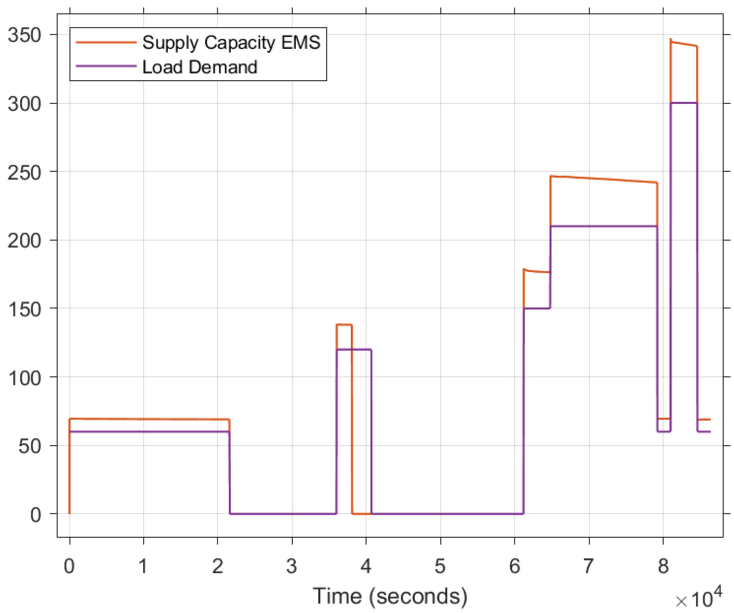

Figure 4.20: Supply capacity EMS v Load demand

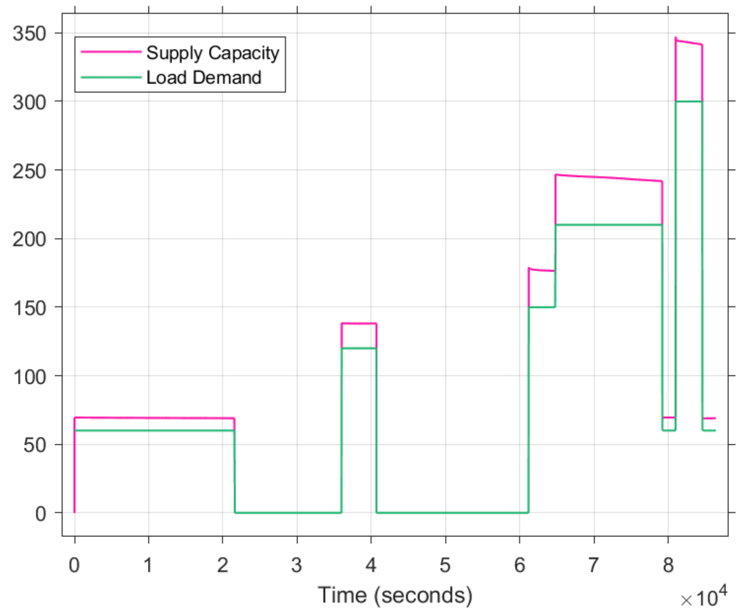

Figure 4.21: Non-EMS Supply capacity v Load demand

The comparison of local storage between the EMS and non-EMS systems in Figure 4.21 demonstrates the EMS's early response time and its charging rate. The higher charging rate of EMS systems results from using PV modules exclusively for local battery storage charging, as opposed to non-EMS systems which also have to charge solar farm SoC.

Figure 4.20 demonstrates the power sharing feature of the EMS. This feature activates when local storage is charged. Due to its higher charging rate, the EMS can bring the Solar farm SoC within 1% of the non-EMS system.

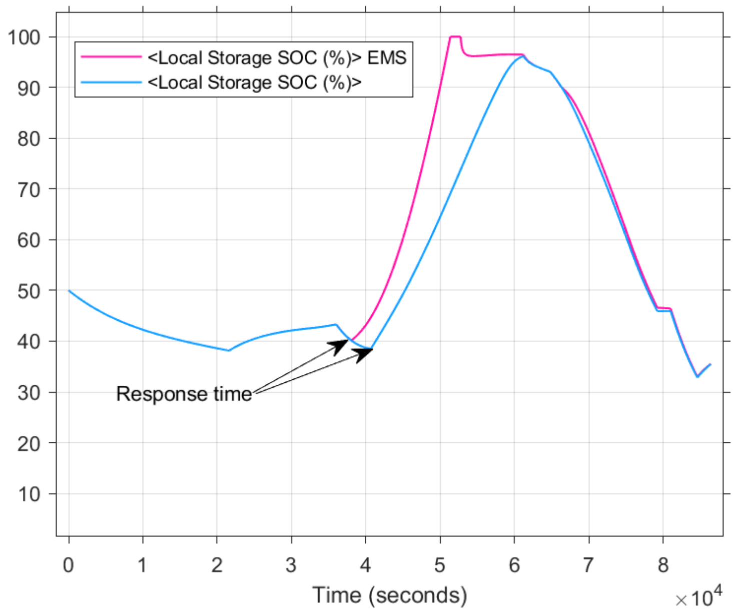

Figure 4.22: Local Storage SoC EMS v non-EMS

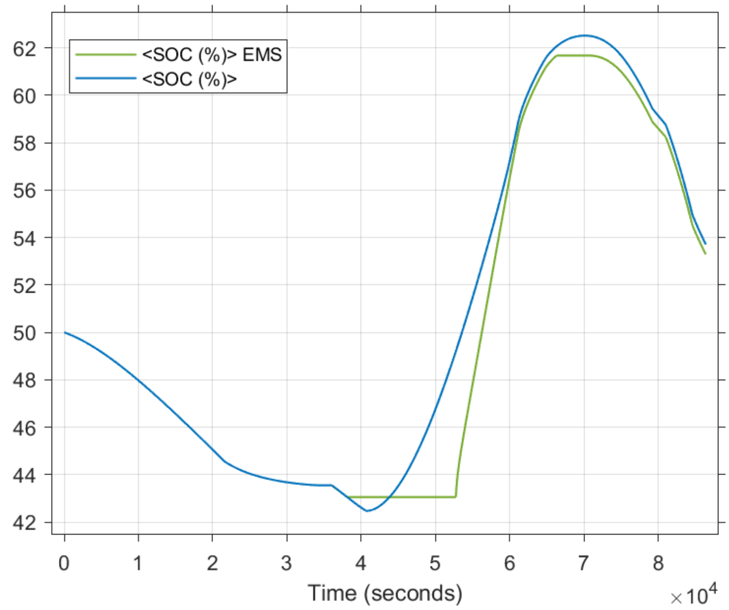

Figure 4.23: Solar Farm Storage SoC EMS v non-EMS

4.6.2 Case Study 2

Table 4.4 provides a profile for Unit 2 REMCS, which relies heavily on solar power. In the absence of local energy storage to store excess power generated from the PV modules, the EMS enables the power-sharing module when the load demand is reduced, allowing for efficient use of the surplus energy.

Table 4.4: Scenario 2: Model setup parameters

Irradiance profile	**Figure 4.1**
Battery size and capacity	Nominal voltage: 0 V DC Capacity: 0Ah Initial SOC: 0%
Load Size	Minimum: 60(W) Maximum: 570(W)
PV module	Maximum power: 240.53(W) Vmp: 30.72(V) Imp: 7.83(A)
Load profiles used	Case study 1: Load profile 1(Figure 4.3)
Load profiles used	Case study 4: Load profile 1(Figure 4.5)

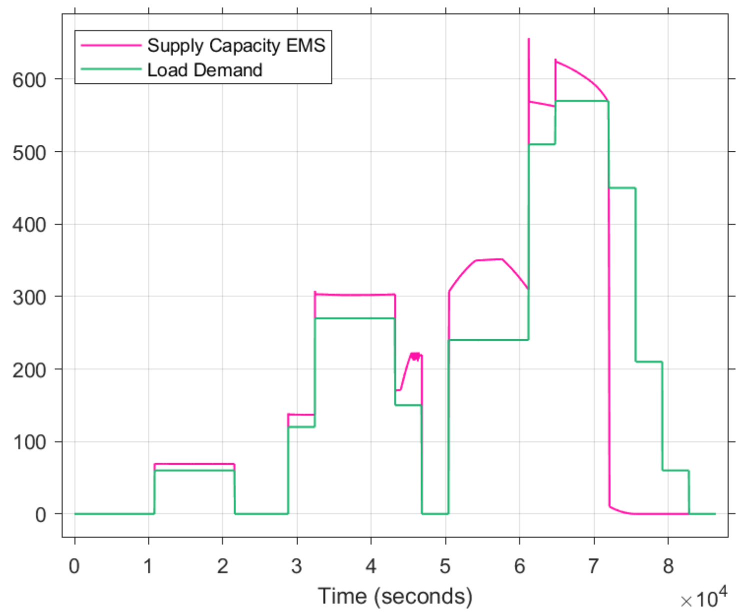

Figure 4.24: EMS Supply capacity v load demand

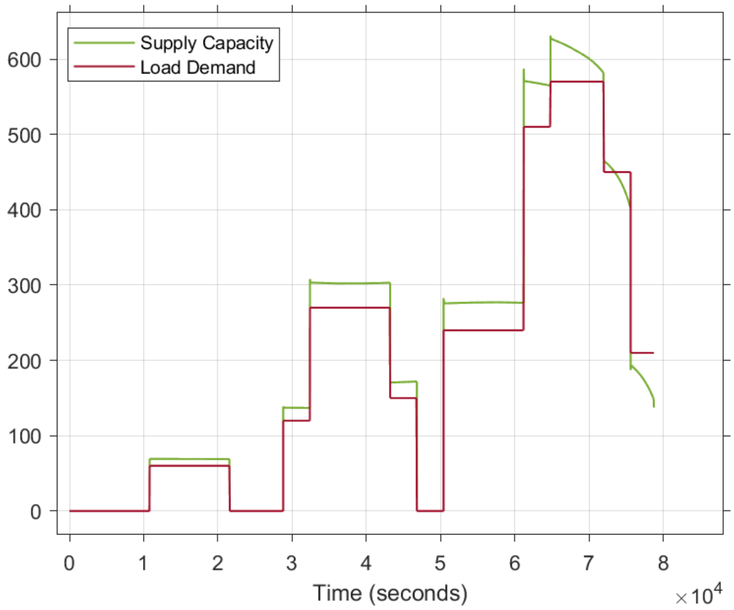

Figure 4.25: Non-EMS Supply capacity v load demand

The load demands versus supply capacity for the two systems are depicted in Figures 4.24 and 4.25. Both systems can meet load demand until $7.2 \times 10^4 s$ seconds for the EMS system and $7.6 \times 10^4 s$seconds for the non-EMS system.

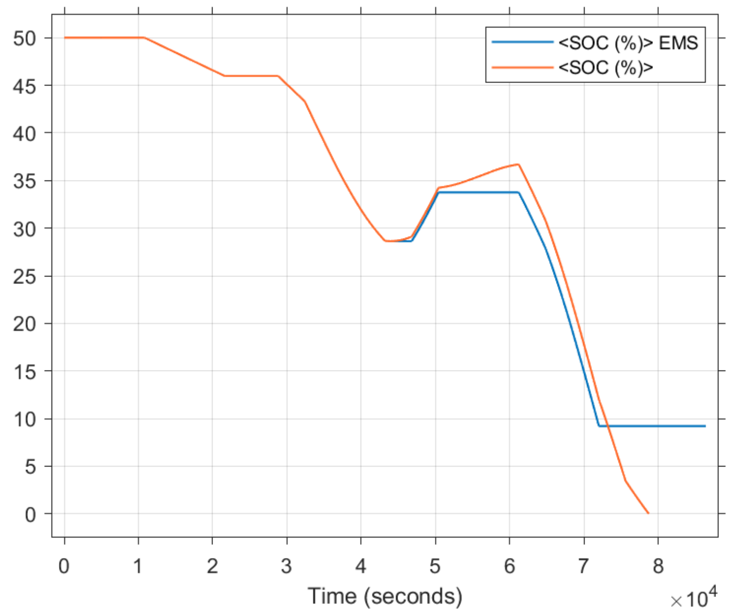

Figure 4.26: Solar Farm SoC EMS v non-EMS

Referring to Figure 4.26, the Solar farm gradually decreases its state of charge (SoC) from time 0 seconds to approximately $4.3 \times 10^4 s$seconds. Due to high load demand, the solar farm's SoC increases by 10% for the EMS system and 15% for the non-EMS system. The lower SoC in the EMS system compared to the non-EMS system can be attributed to the EMS's prioritisation of local energy storage, which attempts to charge local batteries that are non-existent for this particular unit, this defaults the EMS to Start. Start state is verified in Figure 4.27 from time $5 \times 10^4 s$seconds to time $6.02 \times 10^4 s$seconds.

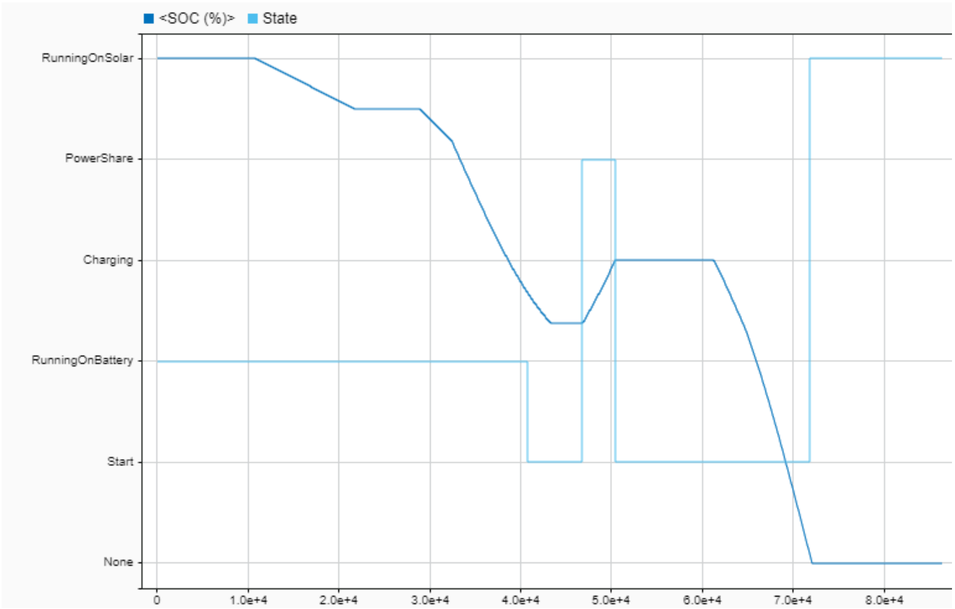

Figure 4.27: Local SoC and state transition

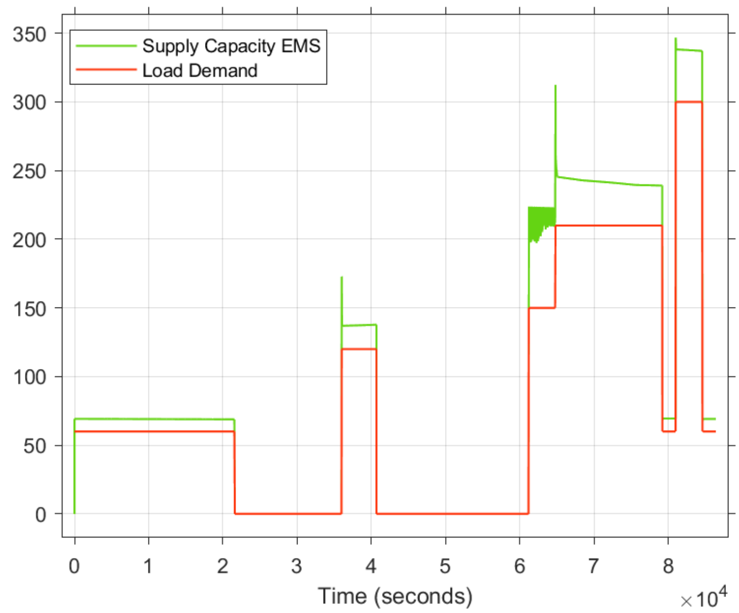

Figure 4.28: EMS Supply capacity v load demand

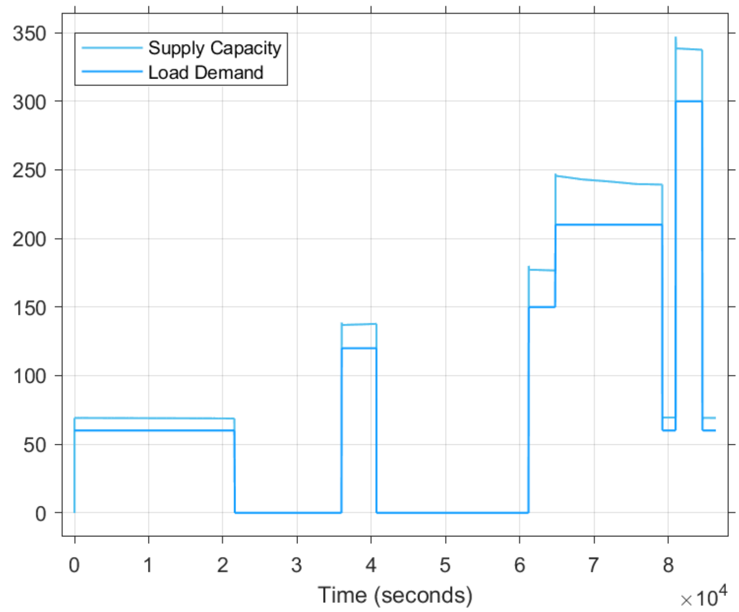

Figure 4.29: Non-EMS Supply capacity v load demand

Supply capacity results for Load Profile 3 are displayed in Figures 4.28 and 4.29. The demand for this profile peaks at 350W, which can be adequately powered by both PV modules and the solar farm source. Due to this moderate demand, the EMS and non-EMS systems increase the solar farm SoC to 69% and 71%, respectively.

In the absence of battery storage detection, the EMS switches to its default Start state, leading to a 2% lower SoC compared to the non-EMS system as shown in figure 4

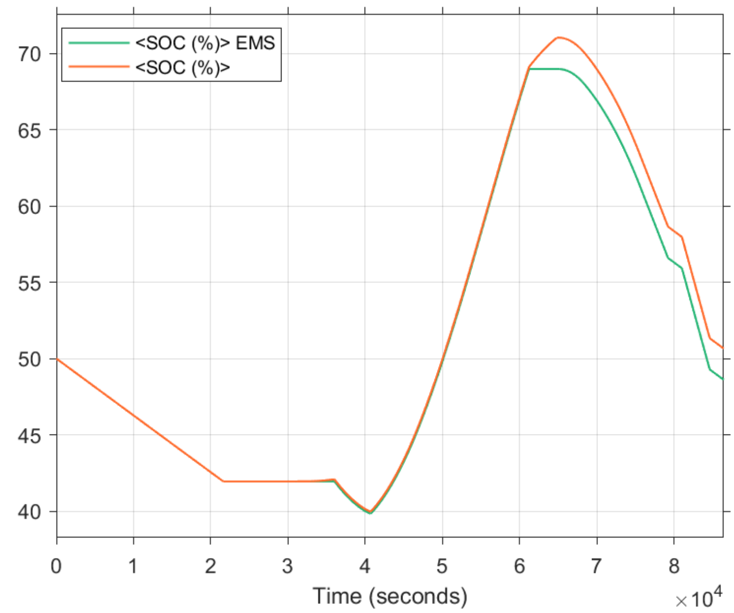

Figure 4.30: EMS supply capacity and state transition

4.6.3 Case Study 3

Table 4.5: Scenario 3: Model setup parameters

Irradiance profile	**Figure 4.1**
Battery size and capacity	Nominal voltage: 0 V DC Capacity: 0Ah Initial SOC: 0%
Load Size	Minimum: 60(W) Maximum: 570(W)
PV module	Maximum power: 240.53(W) Vmp: 30.72(V) Imp: 7.83(A)
Load profiles used	Case study 1: Load profile 1(Figure 4.3)
Load profiles used	Case study 4: Load profile 1(Figure 4.5)

Case study 3 presents an REMCS unit which lacks PV module, with no PV panels to charge local batteries, this unit is constantly running on battery.

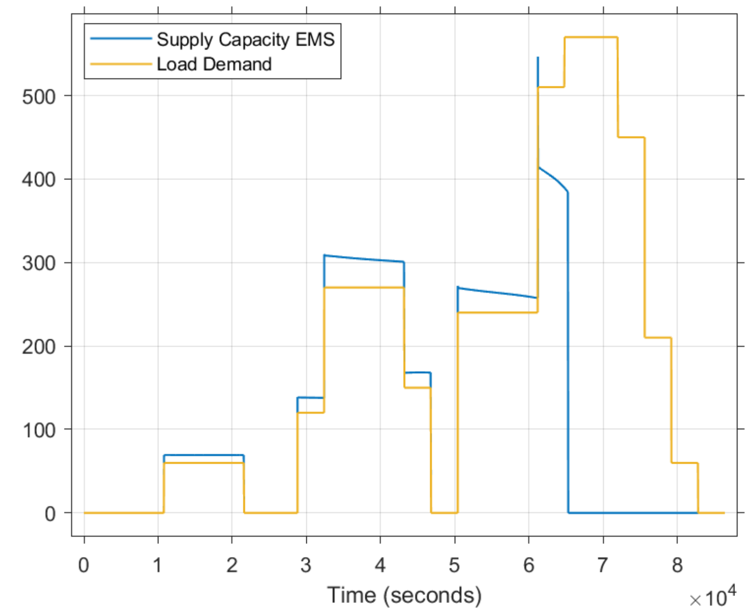

Figure 4.31: EMS Supply capacity v load demand

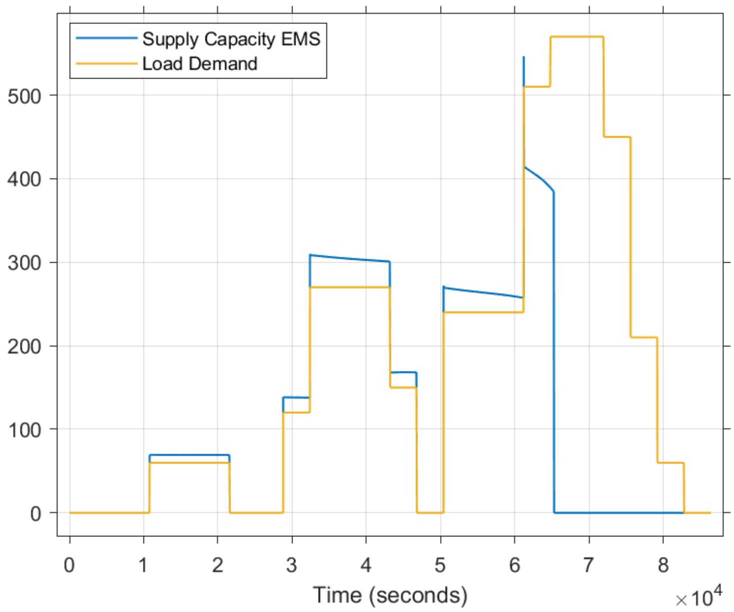

Figure 4.32: EMS Supply capacity v load demand

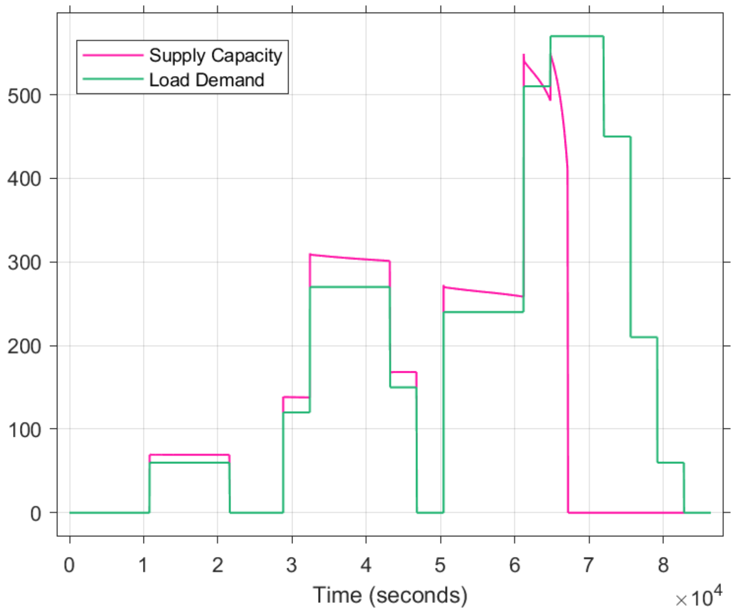

Figure 4.33: Non-EMS Supply capacity v load demand

When comparing load demand and supply capacity between figures 4.32 and 4.33, it is evident that EMS and non-EMS systems generally exhibit similar responses. However, there is a noticeable deviation occurring between $6.10 \times 10^4 s$seconds and $7 \times 10^4 s$seconds. During this time frame, the REMCS reduces supply capacity 1863 seconds earlier compared to the non-EMS system.

The early drop of supply capacity in the EMS system is directly attributable to EMS energy saving feature which cuts off all loads when SoC drops below 10%, as it can be show in Figure 4.34.

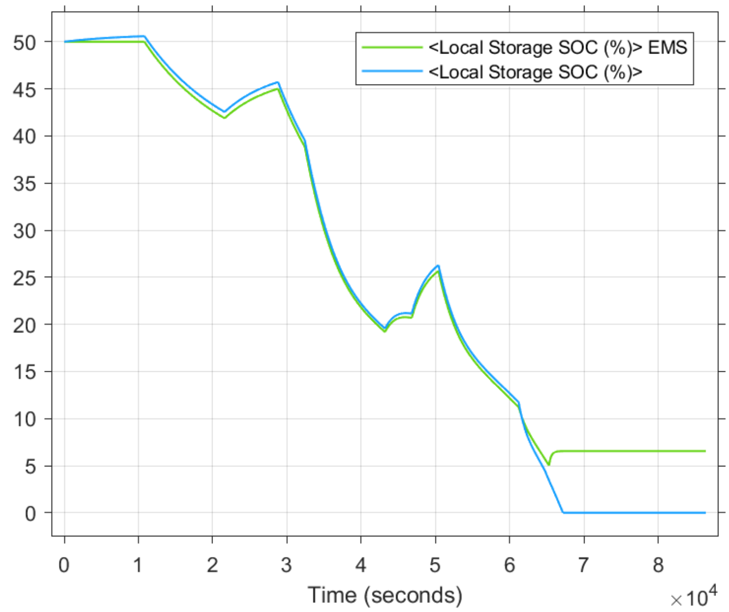

Figure 4.34: Local storage SoC EMS v non-EMS

Load profile 4 demonstrates the load shedding feature of the EMS which reduces supply capacity to extend battery usage.

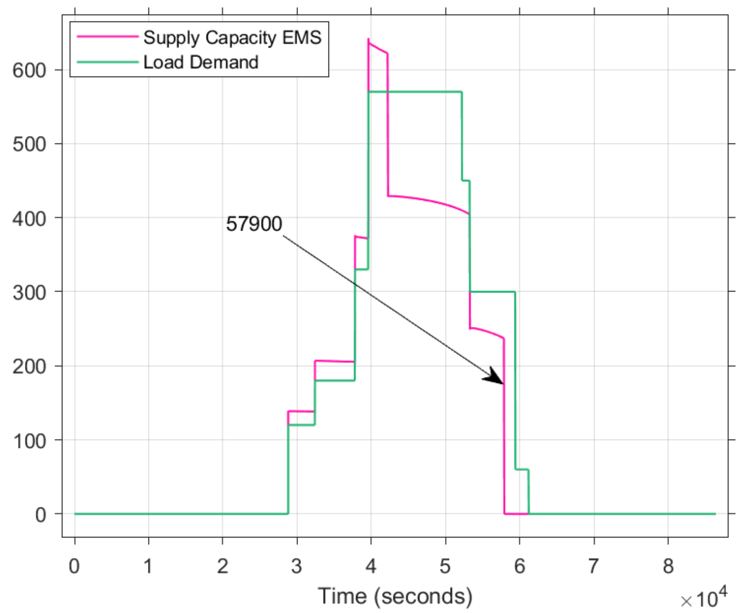

Figure 4.35: EMS Supply capacity v load demand

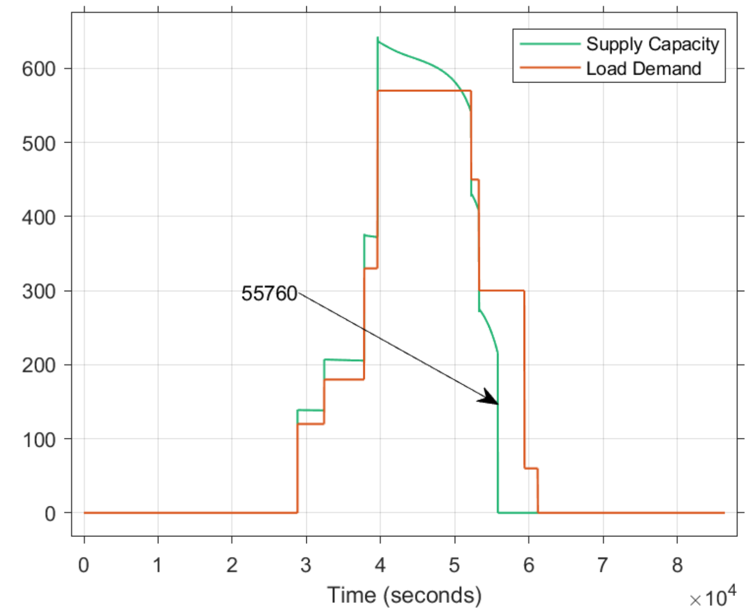

Figure 4.36: Non-EMS Supply capacity v load demand

The time differences between the systems are shown in figure 4.37 and 4.38. As a result of load shedding, EMS gains a 2140 seconds before dropping supply to zero.

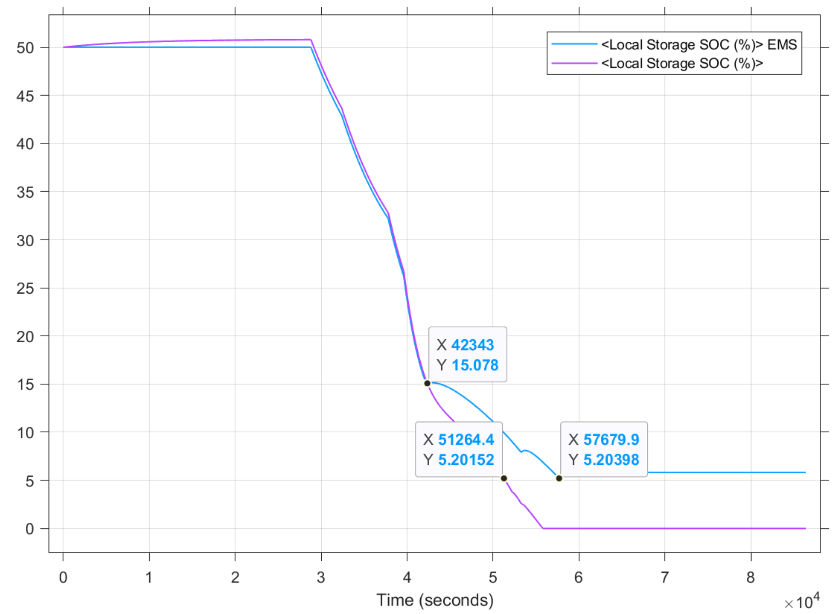

Figure 4.37: Local storage SoC EMS v non-EMS

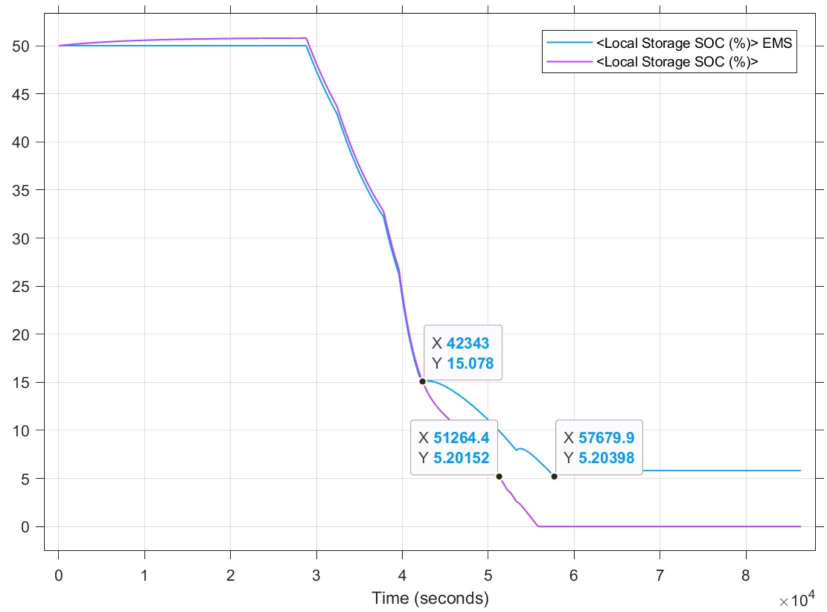

Figure 4.38: Local storage SoC EMS v non-EMS

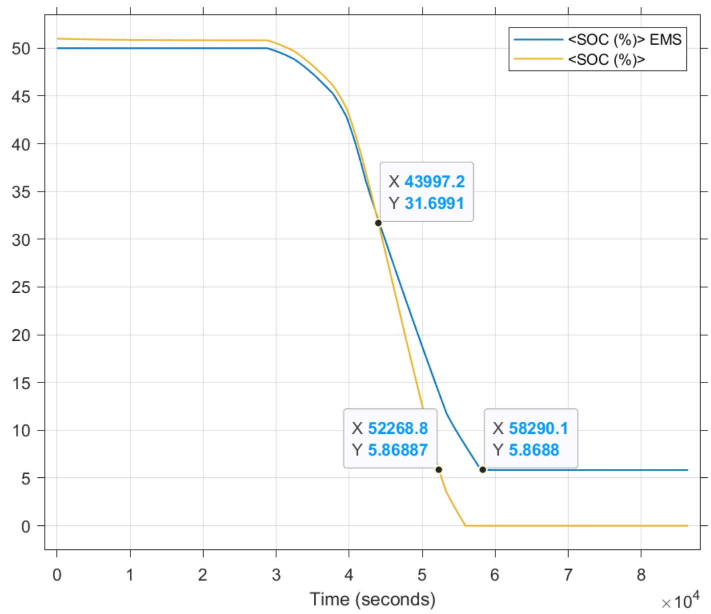

Figure 4.39: Solar Farm SoC EMS v non-EMS

The results of the improvement in the Energy Management System due to the implementation of load shedding are shown in Figures 4.38 and 4.39. The rate of discharge of SoC, or discharge rate, for the local energy storage has been reduced to -2.30% per hour, compared to -3.96% per hour in the non-EMS system. Similarly, for the solar farm, the discharge rate has been reduced to -6.5% per hour, compared to 11% per hour in the non-EMS system.

4.6.4 Case Study 4

Table 4.6: Scenario 3: Model setup parameters

Irradiance profile	**Figure 4.1**
Battery size and capacity	Nominal voltage: 0 V DC Capacity: 0Ah Initial SOC: 0%
Load Size	Minimum: 60(W) Maximum: 570(W)
PV module	Maximum power: 0(W) Vmp: 0(V) Imp: 0(A)
Load profiles used	Case study 1: Load profile 1(Figure 4.3) Case study 2: Load profile 1(Figure 4.4) Case study 3: Load profile 1(Figure 4.5) Case study 4: Load profile 1(Figure 4.6)

Case study 4 presents a unit which has no energy storage system or PV panel. It is an entirely grid-dependent unit which relies on solar farm and excess power from other units. The supply capacity response for this configuration is shown in figures 4.8.24 and 4.8.25. The EMS has control measures to prevent total grid collapse by completely disabling loads, figure 37 shows supply capacity being dropped to zero. The discontinuity on the non-EMS system in figure 38 is a result of Matlab simulation being unable to simulate a grid collapse condition due to hardware limitations.

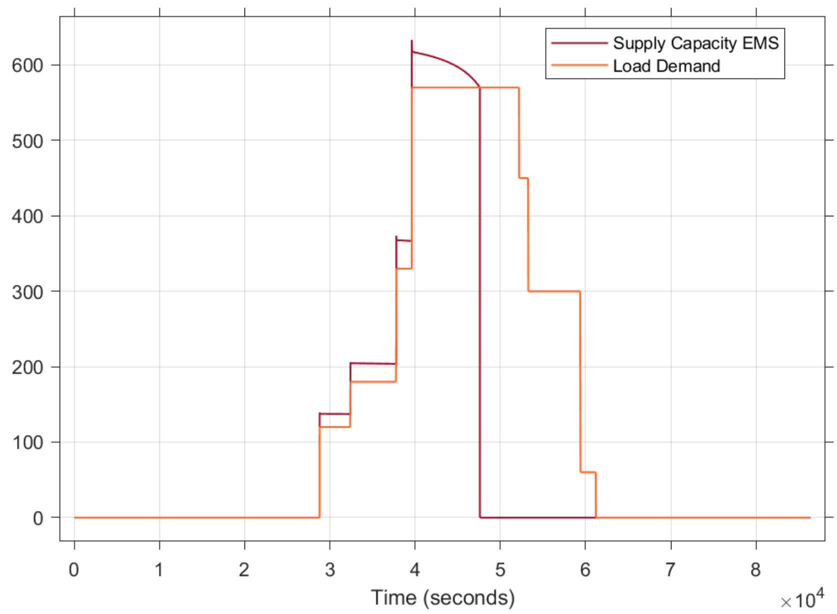

Figure 4.40: EMS Supply capacity v load demand

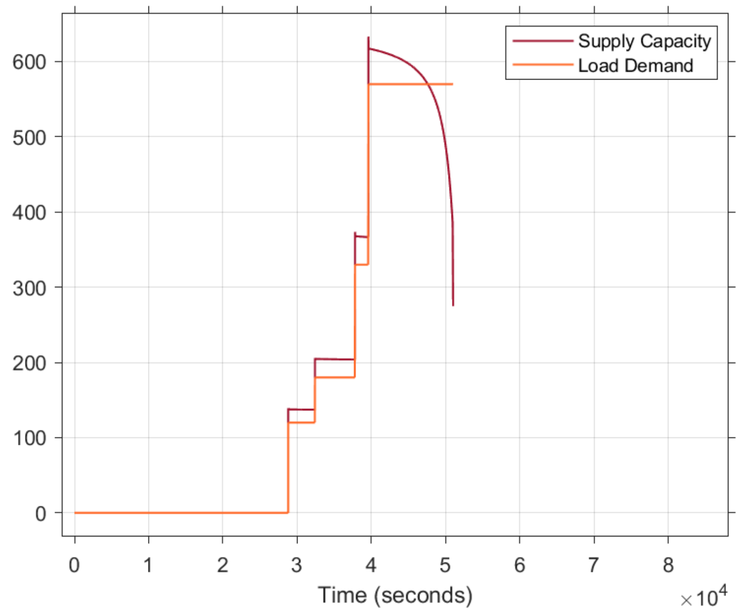

Figure 4.41: non-EMS Supply capacity v load demand

4.7 Lab-Developed Working System Setup

A functional system was developed in the lab, as depicted in Figure 4.9.1. Solar panels are mounted outside. The computers use Matlab Simulink to receive external data, process it, and display the system's real-time operation, The DC loads consist of car headlamps with power ratings between 60W and 120W. These lamps are connected in various combinations to simulate household loads, including cell phone charging stations. Additionally, one of the units uses a DC fridge as a load.

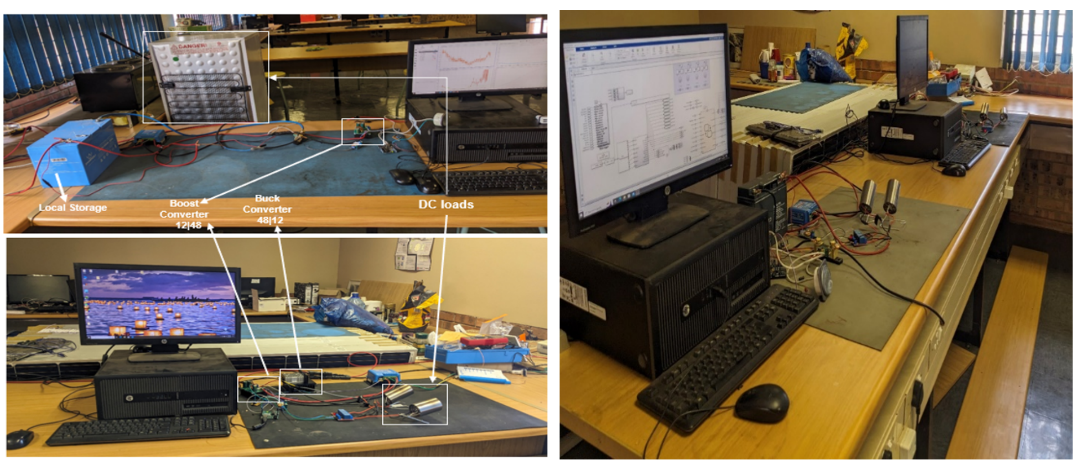

Figure 4.42: Lab setup of four units DC microgrid

The data obtained from the models was collected for a period of 5 days in which some loads were switched at random intervals to simulate everyday appliances usages. The purpose of this data collection was to analyse the behaviour of electrical loads in a typical household setting. By randomly switching loads, the object was to create a realistic representation of appliance usage patterns, including peak usage times and energy consumption fluctuations. This approach allows for a more accurate assessment of the models' performance in managing energy demand. The five-day supply capacity

Table 4.7: Scenario 3: Model setup parameters

Battery size and capacity	Nominal voltage: 12V DC Capacity: 100Ah
Load Size	Minimum: 60(W) Maximum: 570(W)
PV module	Maximum power: 330(W) Vmp: 36.92(V) Imp: 8.14(A)

v load demand shown in figure 4.9.2 indicates a well-managed load demand, power saving mode is enabled whenever demand exceeds supply.

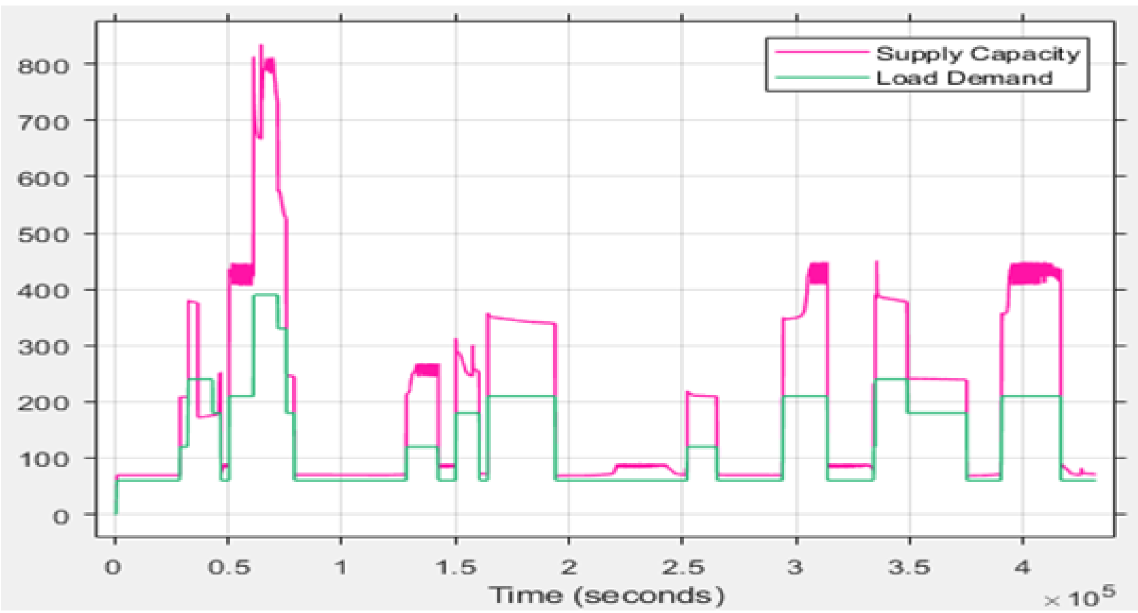

Figure 4.43: Unit 1 5-day Supply v Load Demand

This system ensures efficient energy use by dynamically adjusting to consumption patterns. When demand surpasses supply, power saving measures are activated to prevent overloading and maintain stability. This approach not only optimizes energy utilization but also extends the lifespan of the battery storage by preventing excessive discharge.

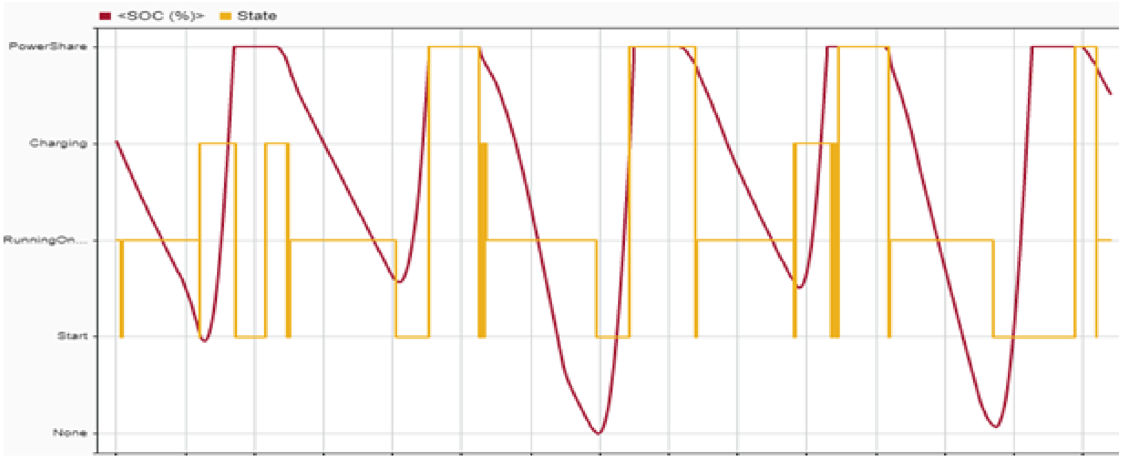

Figure 4.44: Five-day Solar farm SoC v Operation state.

4.7.1 Lab results - Unit 2

Table 4.8: Unit2 - Laboratory setup parameters

Battery size and capacity	Nominal voltage: 12V DC Capacity: 17Ah
Load Size	Minimum: 60(W) Maximum: 520(W)
PV module	None

Unit 2 relies on the grid to charge its battery storage, as illustrated in Figure 4.44. The control system maintains grid stability by disconnecting loads when necessary. Due to the limited battery size, the supply sometimes fails to meet demand, causing the unit to be unable to fully power appliances in certain situations. However, the control system prevents the batteries from completely discharging, thereby protecting their health.

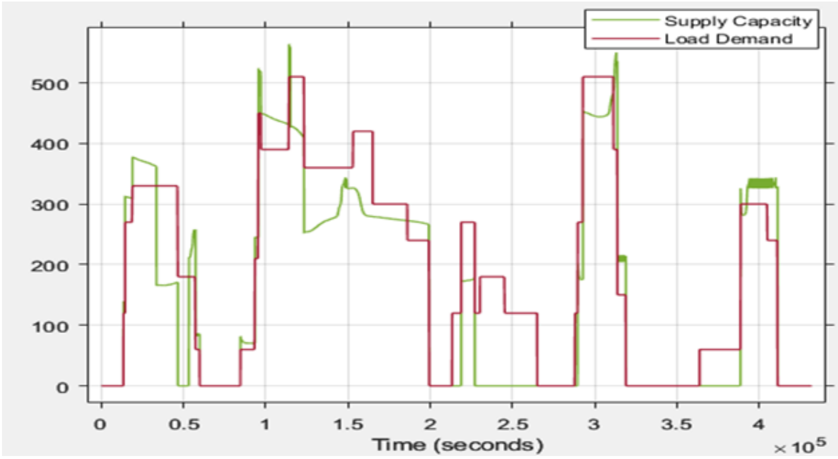

Figure 4.45: Unit 2 Supply Capacity v Load Demand.

Prioritizing grid usage over local storage allows local loads to operate for longer periods. However, due to the limited battery capacity, the local state of charge (SOC) drops quickly, necessitating the control system to switch to grid usage. The comparison between solar farm and local storage SOCs is shown below.

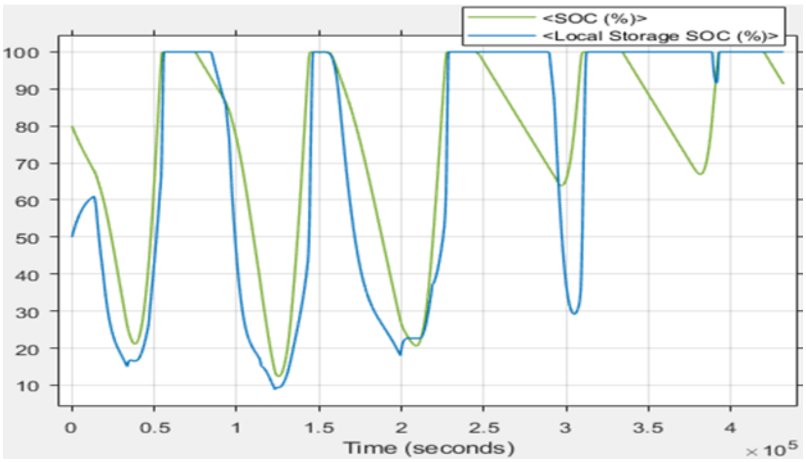

Figure 4.46: Unit 2 Solar Farm v local storage SoC

4.7.2 Lab results - Unit 3

Unit 3 is highly dependent on the grid from sunset to sunrise. During this period, loads are significantly limited to conserve power. This dependency highlights the importance of efficient energy management in off-peak hours. By restricting load usage, the system ensures that essential functions can continue without overloading the grid.

Table 4.9: Unit3 - Laboratory setup parameters

Battery size and capacity	None
Load Size	Minimum: 60(W) Maximum: 400(W)
PV module	Maximum power: 330(W). Vmp: 36.92(V). Imp: 8.14(A)

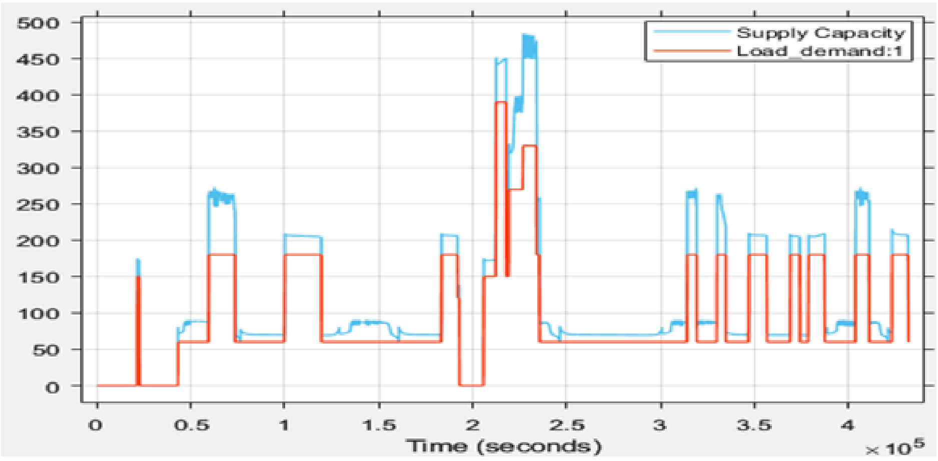

Figure 4.47: Unit 3 Supply Capacity v Load Demand

4.7.3 Lab results - Unit 4

Table 4.10: Unit3 - Laboratory setup parameters

Battery size and capacity	None
Load Size	Minimum: 60(W) Maximum: 400(W)
PV module	None

Unit 4 is entirely dependent on the grid, making it highly sensitive to any major changes in the grid system. This unit underscores the critical importance of maintaining grid stability. It also demonstrates the necessity of self-management; without an Energy Management System (EMS) to control local loads and the absence of local storage and generation capacity, this unit could potentially destabilize the grid.

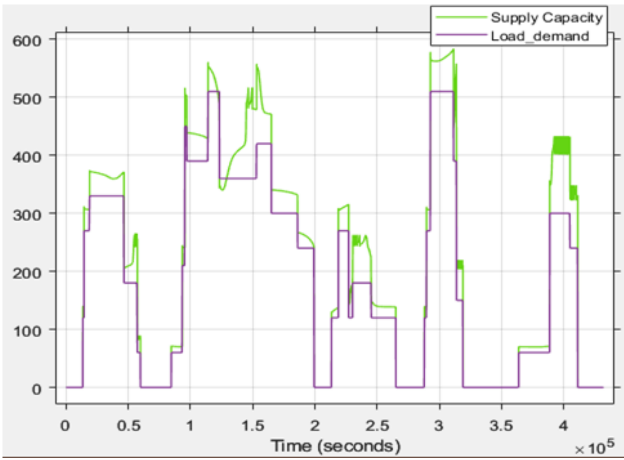

Figure 4.48: Unit 4 Supply Capacity v Load Demand

The system optimizes energy use by adjusting to consumption patterns, activating power-saving measures when demand exceeds supply, and extending battery lifespan by preventing over-discharge. Power sharing from solar panels occurs when local battery storage is full, benefiting the grid. In Unit 2, which relies on the grid for charging due to limited battery capacity and no PV module, the control system ensures stability by disconnecting loads as needed and preventing complete battery discharge. Grid usage is prioritized to extend operation times, though the local state of charge drops quickly, requiring a switch to grid power.

The laboratory system's responses are similar to the Matlab simulation since the unit's EMS remains consistent; any variations are due to differences in battery capacity and load.

Chapter 5

Conclusion

This dissertation has explored the impact of renewable energy integration on DC grid stability and efficiency. Through a comprehensive analysis of residential energy management and control systems (REMCS), this research has demonstrated that such systems can significantly enhance the utilization of renewable resources while maintaining grid stability.

5.1 Key findings

5.1.1 Efficiency in Energy Utilisation

The EMS improved system efficiency by adjusting to real-time consumption patterns. This prevents overloading and excessive discharge of battery storage, thus optimizing energy usage and extending battery life.

5.1.2 Power Sharing

The power share feature, detailed in Figure 4.44, allows for surplus energy from fully charged local battery storage to be redirected to the grid. This not only aids in rapid recharging but also in supplying connected loads, enhancing overall energy distribution efficiency.

5.1.3 Grid Dependence and Battery Capacity

The laboratory results for Unit 2, as outlined in Table 4.10, reveal that grid reliance for battery charging is crucial due to limited battery capacity and lack of PV modules. The control system's ability to disconnect loads to maintain grid stability highlights the importance of strategic energy management in scenarios with varying load demands.

5.1.4 Comparative analysis of Supply and Demand

Figure 4.45 illustrates the comparative performance of supply capacity versus load demand. Prioritizing grid usage over local storage allows for extended operation of local loads, although the rapid decrease in the state of charge (SoC) necessitates frequent switching to grid power.

This research contributes to the field by providing empirical evidence supporting the efficiency and reliability of REMCS in renewable energy systems. Future work could focus on integrating with energy utilities and integrating more advanced predictive algorithms to further enhance energy management. Overall, the findings underscore the potential of dynamic energy management systems to play a pivotal role in the transition towards more sustainable and resilient energy infrastructures.

5.2 references

References

[1] Mohamed A.A et al., eds. *Droop control design to minimize losses in DC microgrid for more electric aircraft*. 2001.

[2] Joseph. Ami and Mohammad. Shahidehpour. “Battery storage systems in electric power systems”. In: *2006 IEEE Power Engineering Society General Meeting* (2006), 8–pp.

[3] Mathew. Aneke and Meihong. Wang, eds. *Energy storage technologies and real life applications – A state of the art review*. 2016.

[4] Vosloo. Arno, ed. *Agent-Based Energy Management Systems for The Remote community microgrid*. 2015.

[5] Osama Ayadia et al. “Experimental comparison between Monocrystalline, Polycrystalline, and Thin-film solar systems under sunny climatic conditions”. In: *Energy Reports* 8 (2022), pp. 218–230.

[6] Nordman. B and Christensen. K. “DC Local Power Distribution: Technology,Deployment, and Pathways to Success”. In: *IEEE Electrification Magazine* 4 (2 2016), pp. 29–36.

[7] Renan F. Bastos et al. “Power-sharing for dc microgrid with composite storage devices and voltage restoration without communication”. In: *Electrical Power and Energy Systems* 138 (107928 2022).

[8] Mateo Beus et al., eds. *Three-level hierarchical microgrid control—model development and laboratory implementation*. 2020.

[9] Muhammad. BR et al. "Artificial intelligence-enabled probabilistic load demand scheduling with dynamic pricing involving renewable resource". In: *Energy Reports* 8 (2022), pp. 14034–14037.

[10] Zhenghong Chen et al., eds. *A Review on Control Strategies of AC/DC Micro Grid*. 2017.

[11] Burmester. Daniel et al. "A Review of Nanogrid Topologies and Technologies". In: *Renewable and Sustainable Energy Reviews* (67 2017), pp. 760–775.

[12] Zubieta. Luis E. *Power Management and Optimization Concept for DC Microgrids*. 2015.

[13] Ligang. Hou, Xianghua. Tang, and Xiongjie. Shi, eds. *Research on Control Method of Energy Storage Interface for DC Micro-grid*. 2019.

[14] Hammerstrom. D. J., ed. *AC Versus DC Distribution SystemsDid We Get it Right?* 2007.

[15] Andreadis. G. Bouzakis. K. D. Klazoglou. P. Niwtaki. K. "Review of Agent–Based Systems in the Manufacturing Section". In: *Universal Journal of Mechanical Engineering* 2 (2 2014), pp. 55–59.

[16] Muhammad. K, B. muhammad, and Muhammad. M. "DC Home Appliances for DC Distribution System". In: *Mehran University Research Journal of Engineering & Technology* 840 (36), p. 4.

[17] Techakittiroj. K. and Wongpaibool. V., eds. *Co-existance between AC-Distribution and DC-Distribution: In the View of Appliances*. 2009.

[18] Nandini. K.K., Jayalakshmi. N.S, and Vinay Kumar Jadoun. "An overview of DC Microgrid with DC distribution system for DC load". In: *Materials Today* 51 (1 2022), pp. 635–639.

[19] Cihan. Katar and Cengiz. Polat Uzunoğlu. "A comparative study on AC/DC analysis of an operational low voltage distribution system". In: *International Journal of Applied Power Engineering (IJAPE)* 10 (3 2021), pp. 193–206.

[20] Durga. Malleswara Rao Korada, Mahesh. Kumar Mishra, and Ram. Shankar Yallamilli, eds. *Dynamic Energy Management in DC Microgrid using Composite Energy Storage System.* 2020.

[21] Dinesh. Kumar and Firuz. Zare. "DC Microgrid Technology: System Architectures,AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects". In: *Special Section On Power Quality And Harmonics Issues Of Future And Smart Grids* (2017).

[22] Azadani. L.N. "Vertical axis wind turbines in cluster configurations". In: *Ocean Engineering* 272 (2023), pp. 113–855.

[23] Fulong. Li et al., eds. *Energy Management System for DC Microgrids Considering Battery Degradation.* 2020.

[24] Yuto. Lim et al., eds. *Study of Home Energy Management System for DC-based Nanogrid.* 2020.

[25] Manoj. Lonkar and Ponnaluri. Srinivas, eds. *A Review of DC Microgrid Operation and Control.* 2015.

[26] Melfi. M.J. and Umans. S.D. "DC Machines". In: *Encyclopedia of Electrical and Electronic Power Engineering* 1 (2023), pp. 264–279.

[27] Keerthana. M.S., G. Uma, and U.Sowmmiya. "A study of a solar PV and wind-based residential DC NanoGrid with dual". In: *International Journal of Electrical Power and Energy Systems energy storage system under islanded/ interconnected/grid-tied modes* (143 2022).

[28] Qianli. Ma, Haisheng. Fang, and Mengjie. Zhang. "Theoretical analysis and design optimization of thermoelectric generator". In: *Applied Thermal Engineering* 127 (2017), pp. 758–764.

[29] B. Marion et al., eds. *Performance Parameters for Grid-Connected PV Systems.* 2005.

[30] Starke. Michael, Tolbert. Leon M., and Ozpineci. Burak, eds. *AC vs. DC Distribution:A Loss Comparison.* 2008.

[31] Bruno Mota, Pedro Faria, and Zita Vale. “Residential load shifting in demand response events for bill reduction using a genetic algorithm”. In: *Energy* 260 (1 2022).

[32] S. Ould et al. “Overview of energy storage in renewable energy systems”. In: *International Journal of Hydrogen Energy* (2016), pp. 20914–20927.

[33] K. Padmavathi and S. Arul. Daniel. “Performance analysis of a 3 MWp grid connected solar photovoltaic power plant in India”. In: *Energy for Sustainable Development* 17 (2013), pp. 615–625.

[34] P. Pal et al. “Viability analysis of direct current (DC) standalone hybrid photovoltaic (PV)/ hydrogen fuel cell (HFC) energy system: A techno-economic approach”. In: *Materialstoday* 39 (67 2021), pp. 187–1812.

[35] Surya. Prakash, Sukumar. Mishra, and Narayana Prasad. Padhy, eds. *Modeling and Simulation of Microgrid*. 2016.

[36] Surya. Prakash, Sukumar.Mishra, and Narayana Prasad. Padhy, eds. *Coordinated Control of a Grid Connected DC MicroGrid with Multiple Renewable Sources*. 2016.

[37] Enrique. Rodriguez-Diaz et al., eds. *Real-Time Energy Management System for a Hybrid AC/DC Residential Microgrid*. 2017.

[38] Schmitz and Kenneth S. *Physical Chemistry*. 2018.

[39] *Solar irradiance data*. URL: `https://www.eskom.co.za/AboutElectricity/RenewableEnergy/Documents/SolarData_site3fullsetTellerie.xls`.

[40] Zahrasadat. Tabaie and Amir. Omidvar. “Human body heat-driven thermoelectric generators as a sustainable power supply for wearable electronic devices: Recent advances, challenges, and future perspective”. In: *Heliyon* 9 (2023), e14707.

[41] Jianfang. Xiao et al. *Smart Energy Hub - Modularized Hybrid AC/DC Microgrid: System Design and Deployment*. 2017.

[42] Chun. Chang Yoon et al. "Current sensor-less state-of-charge estimation algorithm for lithium-ion batteries utilizing filtered terminal voltage". In: *Journal of Power Sources* 273 (2015), pp. 255–263.

[43] Jin-Liang. Zeng et al. "Numerical investigation of a geothermal thermoelectric generator using gravity heat pipe structure". In: *International Conference on Power and Electrical Engineering (ICPEE)* 3 (2022), pp. 21–31.