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Master's Thesis

Study of Distributed Power Flow Control Scheme in Microgrid with Quality of Energy Services

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Abstract

The increasing demand for reliable, decentralized, and renewable-based energy systems has brought Direct Current (DC) microgrids (MGs) into the spotlight, particularly for remote, rural, and disaster-prone regions. DC MGs offer simplified integration of photovoltaic (PV) sources, energy storage systems (ESS), and DC loads by eliminating conversion losses typical in AC systems. However, real-world implementation of such systems remains limited, with most prior research focused solely on simulations and theoretical control strategies. It typically integrates various energy sources, including RESs, conventional energy sources, and energy storage systems (ESSs) in a distributed manner. However, designing safe and reliable MG involves complex challenges due to the diverse power criteria problems and interactions of RESs, ESSs, and energy loads, and the variable and intermittent nature of RESs and energy loads.

So, main objective of this research is to propose and implement a power flow control scheme in a MG with QoES for not only assigning and balancing the power flow among the RESs, ESSs, and energy loads, but also equalizing the state of charge (SoC) of ESSs. In particular, three sub goals of this research as follow: (i) to categorize the QoES of energy loads based on their types, characteristics, priority and user behaviors; (ii) not only to assign and balance energy supply and energy demand at each instantaneous time to prevent the fluctuations of RESs and energy loads, but also to equalize the SoC of ESSs to achieve safe and reliable MG during its operation; and (iii) to conduct a small-scale low-voltage experiment environment to demonstrate its feasibility and performance.

This thesis addresses that gap by designing, developing, and experimentally validating a small-scale DC microgrid platform that integrates photovoltaic generation, dual energy storage systems (ESS1 and ESS2), and both smart and traditional power loads. The SPA algorithm dynamically allocates power from multiple ESS units to priority loads based on real-time system conditions, such as battery SoC, load demand, and QoES (Quality of Energy Services) criteria. Unlike traditional systems where power is passively drawn by loads, this research introduces an active assignment mechanism that enhances energy efficiency, load prioritization, and SoC balancing across ESS units. Critical and non-critical loads including electric kettles, rice cookers, refrigerators (Glacier), and air conditioners (Airwave) are controlled using both internal smart interfaces and externally developed controllers built on Raspberry Pi, DPS5020 Buck converters, and MOSFET switching circuits.

This research further contributes by demonstrating the integration of smart devices (Glacier and Airwave) with traditional devices under a unified QoES-based logic, ensuring energy efficiency and load prioritization. It also implements a robust communication protocol using MQTT and HTTP APIs to synchronize control commands and sensor data. Comparative simulation and experimental results confirm the SPA algorithm's effectiveness in minimizing energy loss, maintaining DC bus voltage stability, and satisfying prioritized energy demand.

Collectively, this work offers a validated framework for implementing adaptive power management in small-scale DC microgrids. The proposed approach can serve as a foundational model for future studies involving mobile energy storage, autonomous scheduling, and scalable control systems for larger, more complex microgrid environments.

Keywords: DC Microgrid, Power Flow Control, Power Assignment Algorithm, Energy Management, Energy Storage System (ESS), Quality of Energy Services (QoES), Communication Protocol

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First and foremost, I would like to express my deepest gratitude to Allah for granting me the strength, patience, and courage to complete this journey. I am forever thankful for being surrounded by dedicated teachers, a loving family, and sincere friends throughout my life.

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To each of you, I dedicate this thesis with deepest respect, love, and gratitude. Your faith in me has been the light that guided my path.

Contents

List of Figures

List of Tables

List of Abbreviations

API	Application Programming Interface
AR	Airwave
DC	Direct Current
EK	Electric Kettle
ESS	Energy Storage System
GL	Glacier
MG	Microgrid
MQTT	Message Queuing Telemetry Transport
PZEM	Power-Zero Energy Meter
RC	Rice Cooker
PV	Photovoltaic
QoES	Quality of Energy Services
SoC	State of Charge
SPA	SoC-based Power Assignment
USB	Universal Serial Bus

List of Symbols

t	Time index
t^s	Starting time
t^o	Operating time
$\mathcal{J}$	Set of power generation units (PVs)
$\mathcal{K}$	Set of power loads
$\mathcal{H}$	Set of energy storage systems
$PG_j(t)$	Power generated by PG unit j at time t
$PL_k(t)$	Power demanded by load k at time t
$PS_h^c(t)$	Controllable power from ESS h at time t
EG_j	Energy generated by generator j
EL_k	Energy consumed by load k
ES_h	Energy stored in ESS h
E_{loss}	Energy loss in the microgrid
$SoC_h(t)$	State of charge of ESS h at time t
SoC_h^{ini}	Initial state of charge of ESS h
SoC_h^{min}	Minimum allowable SoC of ESS h
SoC_h^{max}	Maximum allowable SoC of ESS h
η_c	Charging efficiency of ESS
η_d	Discharging efficiency of ESS
Ess_h	Capacity of ESS h (in Wh)
$P_{ES_h}^{in}(t)$	Charging power of ESS h at time t
$P_{ES_h}^{out}(t)$	Discharging power of ESS h at time t
$P_{ES_h}^{in^{min}}$	Minimum charging power limit of ESS h
$P_{ES_h}^{in^{max}}$	Maximum charging power limit of ESS h
$P_{ES_h}^{out^{min}}$	Minimum discharging power limit of ESS h
$P_{ES_h}^{out^{max}}$	Maximum discharging power limit of ESS h
ΔSoC_h	Deviation of SoC of ESS h from average SoC
P_h^{bal}	Power balancing value of ESS h based on SoC
P_h^{def}	Total power deficit across all ESS units
P_h^{ex}	Equal power adjustment from P_h^{def}
PAR_h	Power assignment ratio of ESS h

Chapter 1

Introduction

In response to the pressing challenges of climate change and the need to reduce CO_2 emissions, the global energy sector is rapidly transitioning from traditional fossil fuels to cleaner, renewable energy sources (RESs) such as solar photovoltaics and wind turbines. These technologies are now central to efforts aimed at achieving sustainable and environmentally friendly energy systems. However, the increasing integration of RESs into existing power grids introduces new complexities due to their inherently intermittent and variable nature. Unlike conventional energy sources, the output of RESs fluctuates with weather and environmental conditions, creating challenges for maintaining the balance between supply and demand. To address these issues, there has been a significant move towards localized energy systems known as MicroGrids (MGs). A MG is a small-scale power network that can operate either connected to the main utility grid or independently in what is known as islanded mode. MGs are designed to integrate diverse energy sources, including RESs, conventional generators, and energy storage systems (ESSs), alongside various types of energy loads. By localizing generation and consumption, MGs offer increased flexibility and resilience, enabling more effective management of renewable generation and supporting the broader goals of energy sustainability and grid de-carbonization. This global shift towards renewable integration and decentralized energy architectures highlights the importance of developing advanced control strategies to ensure reliable, efficient, and sustainable operation of modern power systems.[1]

A MG is fundamentally characterized by its flexible architecture, capable of operating in two primary modes: connected to the main utility grid or independently as an islanded system. This dual capability makes MGs uniquely positioned to enhance the resilience and reliability of power supply, especially during grid disturbances or outages. Typically, a MG integrates a variety of energy sources and components in a distributed manner. These include RESs such as solar photovoltaic panels and wind turbines, conventional generation units (like diesel generators), ESSs such as batteries, and a range of energy-consuming loads. The combination of these diverse elements enables MGs to dynamically balance local generation and consumption. ESSs play a critical role within MGs by mitigating the inherent variability and intermittency of RESs. They store excess energy during periods of high renewable generation and discharge it when generation falls short of demand, thus maintaining system stability. Additionally, MGs often incorporate controllable loads that can be adjusted or scheduled to optimize energy usage in response to available supply. By intelligently coordinating these various resources, MGs contribute to more efficient energy management, reduced transmission losses, and improved local energy autonomy. This makes them a promising solution not only for integrating high shares of RES but also for supporting the evolving needs of modern power systems, such as demand-side flexibility and grid ancillary services.

DC MGs have emerged as a promising architecture for integrating distributed energy resources, particularly RESs like solar photovoltaics, which inherently produce DC power. A DC MG typically employs a DC bus as its central backbone, interconnecting RESs, ESSs, and various DC or AC loads via power electronic converters. This configuration offers significant advantages over traditional AC systems, including reduced conversion losses, simpler control, improved system efficiency, and easier integration with modern DC-based loads such as electric vehicles, data centers, and LED lighting.

The DC bus plays a pivotal role by enabling flexible power sharing among multiple sources and loads, maintaining voltage stability, and facilitating coordinated operation of the entire MG. Its straightforward structure eliminates the need for complex frequency and phase synchronization inherent in AC systems, making DC MGs particularly attractive for applications demanding high efficiency and reliability.

However, the deployment of DC MGs and effective utilization of the DC bus also introduce several technical challenges. Voltage stability must be carefully managed to avoid over-voltage or under-voltage conditions, particularly under varying load and generation scenarios. Coordinating multiple ESSs connected to the DC bus requires sophisticated control to balance state of charge (SoC) and prevent unequal cycling, which can degrade battery life. Furthermore, managing power quality and ensuring the seamless prioritization of critical versus non-critical loads demand advanced power flow control strategies that can respond dynamically to fluctuations in RES output and load demand.

Addressing these challenges is crucial for realizing the full potential of DC MGs as a core element of future resilient and sustainable energy systems. Despite their promising capabilities, DC MGs face significant challenges in design and operation due to the complex interactions among RESs, ESSs, and energy loads. The output of RESs fluctuates with weather and environmental conditions, while energy loads vary according to consumer behavior and demand patterns. This inherent variability can easily lead to imbalances between supply and demand, potentially compromising the stability and reliability of MG operations. A common approach to managing these distributed energy resources is through a DC bus, which serves as a unified electrical backbone connecting RESs, ESSs, and controllable loads. The DC bus allows for efficient power sharing, voltage regulation, and simplified integration of multiple energy devices, making it well-suited for modern MG architectures. ESSs are critical in buffering these fluctuations, but they come with their own limitations. Factors such as capacity constraints, charging/discharging rates, and gradual degradation over time must be carefully managed to avoid premature wear and ensure consistent performance. Moreover, unequal utilization of ESSs can lead to uneven SoC levels across different storage units, shortening their lifespan and reducing overall system efficiency. Adding to these complexities, DC MGs often serve a mix of critical and non-critical loads, each with distinct quality of energy service (QoES) requirements. Ensuring that high-priority loads are always met—even during periods of RES shortfall while optimally allocating power to lower-priority or adjustable loads demands advanced control strategies. Traditional approaches typically handle load prioritization, SoC balancing, and real-time power flow management as separate problems, resulting in fragmented and suboptimal solutions.

Thus, there is a clear need for integrated power flow control schemes that can simultaneously address these multiple objectives. Such solutions would enable DC MGs to reliably accommodate high shares of RESs, extend the lifespan of ESSs through balanced operation, and provide stable, high-quality energy services tailored to diverse load demands.

1.1 Historical Background of MG

The roots of direct current (DC) power distribution can be traced back to the birth of commercial electricity in the late 19th century. In 1882, Thomas Edison commissioned the world's first central DC power plant the Pearl Street Station in New York City marking the beginning of urban electrification. Edison's DC system was designed for local power delivery to lighting systems and motors but was limited to short distances due to voltage drop issues and the absence of effective voltage conversion technology. The subsequent "War

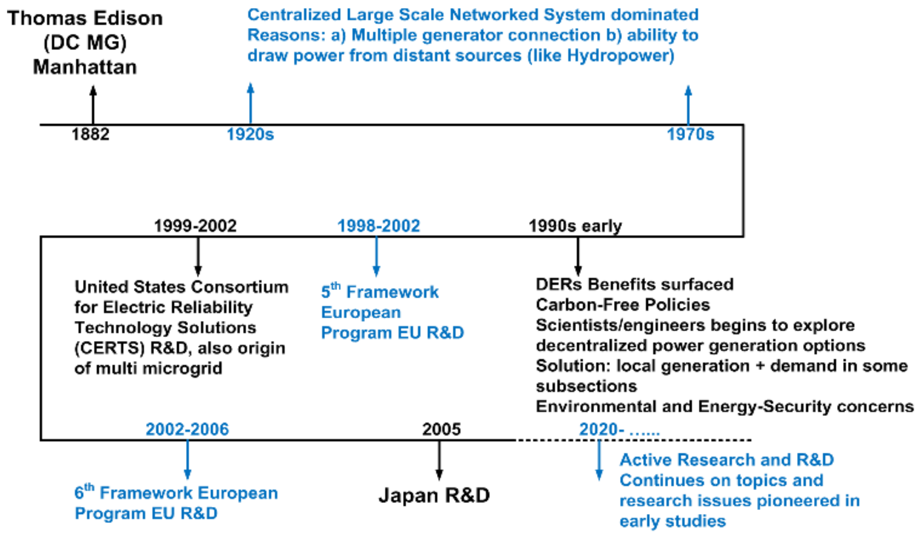

Figure 1.1: Micro-Grid (MG) evolution and history [3]

of Currents" in the late 1800s saw alternating current (AC), championed by Nikola Tesla and George Westinghouse, ultimately win dominance due to its ability to transmit power over long distances using transformers. In 2005 japan Research and Develop initiate the DC MG. As a result, AC became the global standard for centralized electricity distribution, while DC systems faded into the background. In 2005 japan Research and Develop initiate the DC MG. Despite the shift toward AC, DC technologies remained vital in certain industrial and niche applications. Throughout the 20th century, DC power was heavily used in electric railways, battery-powered systems, telecommunications, electrochemical processes, and data centers. These sectors relied on DC due to its inherent simplicity, compatibility with electronic devices, and ease of control. However, it wasn't until the early 2000s when the integration of renewable energy systems, battery storage, and power electronics became widespread—that a renewed interest in DC power distribution began to grow.

The modern resurgence of DC MG has been driven by multiple converging factors. First, the explosive growth of photovoltaic (PV) systems, which inherently generate DC power, made direct integration with DC loads more attractive by eliminating the need for repeated DC-AC-DC conversions. Second, the advancement of lithium-ion battery technologies and ESSs further supported localized, bidirectional DC energy flow. Third, the proliferation of DC native devices such as LED lighting, laptops, servers, and electric vehicles (EVs) created an ecosystem where maintaining DC distribution not only reduced losses but also simplified infrastructure.

In recent decades, academic and industrial research has shifted from centralized DC distribution systems to the design of modular, decentralized DC MG. These MG are characterized by their ability to operate independently (in islanded mode) or in conjunction with larger grids (in grid-connected mode). Researchers have proposed control strategies for maintaining DC bus voltage, managing power flows, balancing SoC across multiple ESSs, and implementing fault-tolerant architectures. Significant attention has also been given to communication protocols, intelligent load management, and system resilience in the face of disturbances or limited generation.

DC MG are now seen as key enablers for rural electrification, off-grid applications, smart homes, disaster response systems, and remote industrial sites. The simplicity, modularity, and compatibility of DC systems make them especially well-suited for regions where AC grid infrastructure is unreliable or nonexistent. Furthermore, as power electronic converters continue to improve in efficiency and cost-effectiveness, the transition toward hybrid and fully DC systems becomes increasingly viable.

This thesis builds upon this historical foundation by contributing an experimentally validated DC MG with integrated energy storage, smart loads, and communication driven control moving beyond simulation-based research into practical implementation.

1.2 Motivation of the Study

In recent decades, the global energy landscape has undergone a fundamental transformation, spurred by urgent climate goals, rapid urbanization, and the decentralization of power generation. The escalating demand for clean, resilient, and sustainable energy has driven governments, researchers, and industries to explore alternatives to centralized fossil-fuel-based grids. Among these, decentralized renewable energy systems have gained considerable momentum, especially in the form of solar photovoltaic (PV) installations and battery-based ESSs. This momentum reflects not only the economic feasibility of RES but also a collective recognition of the environmental and societal benefits of de-carbonization. As a result, the global push for decarbonized and decentralized energy systems has become more than a technical aspiration; it is now a strategic imperative.

While conventional AC-based grids have long served as the backbone of national energy infrastructure, they pose several limitations when deployed in rural, remote, or disaster-prone regions. Long transmission distances, synchronization challenges, and infrastructure costs make AC grids difficult to scale down for localized applications. In contrast, DC MG offer a flexible and efficient alternative. Their compatibility with solar PV, batteries, and increasingly DC-native loads such as LED lighting, electronics, and electric mobility devices makes them particularly attractive for small-scale and off-grid scenarios. Furthermore, DC systems eliminate the need for multiple energy conversions, reducing losses and simplifying control strategies.

In disaster-affected or infrastructure-limited regions, where quick deployment and energy reliability are essential, DC MG provide a viable solution. They enable isolated communities to gain access to electricity without depending on centralized utilities, enhancing energy equity and resilience. However, the operation of these MG introduces a set of new challenges. Unlike conventional centralized control systems, DC MG require decentralized decision-making, often based on real-time data and communication between distributed components.

Among the core challenges is the real-time coordination of power flows among PV sources, ESS units, and various loads. Renewable generation is inherently intermittent, and user demand is variable and unpredictable. Without intelligent coordination, this mismatch can lead to either power scarcity or storage overflow. Furthermore, when multiple ESS units are present, imbalance in their SoC can degrade battery health and reduce overall system efficiency. At the same time, the presence of both critical and non-critical loads demands a nuanced power allocation strategy that can differentiate between high-priority services (e.g., refrigeration, medical devices) and flexible loads (e.g., kettles, cooking appliances).

Maintaining stable voltage across the DC bus adds another layer of complexity. Any deviation from the nominal voltage may cause malfunction or damage to connected devices. Hence, the control system must continuously regulate the DC bus voltage while balancing SoC and prioritizing loads based on their Quality of Energy Services (QoES). These interdependent objectives must be addressed simultaneously to ensure optimal system performance.

A review of current literature reveals that while various power management algorithms have been proposed, most of them are validated only in simulation environments. Simulation-based models, although useful, often fail to capture real-world phenomena such as communication delays, sensor inaccuracies, component tolerances, and hardware failures. This gap between simulation and practical implementation limits the applicability of proposed solutions in real MG deployments.

This research is motivated by the need to bridge this gap by developing an experimental DC MG platform that integrates PV sources, ESSs, and controllable loads using real-time hardware-based control. The platform enables implementation and validation of a unified power flow control algorithm that incorporates SoC balancing, QoES-driven load prioritization, and DC bus voltage regulation. The system utilizes lightweight communication protocols (e.g., MQTT and HTTP) to enable distributed coordination between controllers, ensuring scalability and responsiveness.

On a broader level, this study contributes to the practical realization of intelligent MG that can operate autonomously in diverse environments. It aims to support both academic research and real-world applications such as rural electrification, smart homes, and emergency response systems. On a personal level, the research aligns with a long-standing interest in embedded systems, power electronics, and the use of renewable technologies to address social and environmental challenges. The motivation stems from a desire to contribute to a cleaner, more inclusive energy future through practical engineering innovation.

1.3 Research Problem

With the global transition toward sustainable energy systems, DC MG have emerged as a promising solution for integrating RESs such as PV panels with distributed ESSs. However, the practical deployment and real-time control of DC MG face several technical and coordination challenges. Chief among these is the need to maintain stable and balanced power flow in the presence of intermittent generation, dynamic loads, and unequal battery SoC. While various control strategies have been proposed in the literature, many remain limited to simulation environments and do not account for real-world factors such as communication delays, asynchronous device behavior, or hardware constraints.

Furthermore, most existing methods address individual aspects of MG operation such as voltage regulation, SoC balancing, or load prioritization in isolation. This fragmented approach often leads to suboptimal system performance and reduced reliability. There is a significant need for a holistic control strategy capable of integrating all three functions simultaneously: equalizing SoC across multiple ESS units, regulating voltage along the shared DC bus, and dynamically allocating power based on the QoES required by different loads.

Therefore, the core problem addressed in this research is the design and experimental implementation of a unified power flow control strategy for a DC MG that can manage distributed energy resources, prioritize critical loads, and maintain system stability under real-time constraints. This involves the development of a coordinated control algorithm, a robust communication protocol, and a working testbed capable of validating the approach in a real-world environment.

1.4 Research Objective

The primary objective of this research is to design, implement, and evaluate a reliable power management framework for a DC microgrid incorporating both smart and traditional energy storage systems (ESSs) and diverse types of loads. This objective is realized through the development of a State of Charge (SoC)-based Power Assignment (SPA) algorithm that dynamically allocates power from distributed ESS units to prioritized loads under real-time constraints. The system aims to maintain operational continuity, optimize energy utilization, and ensure service quality through intelligent scheduling and control. The main objective of this research is to propose and implement a power flow control scheme in a MG with QoES for not only assigning and balancing the power flow among the RESs, ESSs, and energy loads, but also equalizing the state of charge (SoC) of ESSs. Specific research objectives include:

- To establish a functional and adaptive DC microgrid testbed that integrates smart ESS units, photovoltaic generation, and both critical and non-critical programmable loads.
- To develop and validate the SPA algorithm capable of maintaining SoC balance across multiple ESSs while assign and balance energy supply and energy demand at each instantaneous time to prevent the fluctuations of RESs and energy loads.
- To implement a Quality of Energy Services (QoES) framework that ensures fair and efficient load prioritization under power-constrained conditions. to categorize the QoES of energy loads based on their types, characteristics, priority and user behaviors
- To design a robust communication protocol and control scheme that enables synchronized operation among all smart and traditional components within the microgrid.

The ultimate goal is to contribute a practical and scalable approach to intelligent energy management in DC microgrids, particularly for rural, off-grid, or disaster-prone areas where flexibility, resilience, and real-time coordination are critical.

1.5 Organization of the Thesis

This thesis is structured into five chapters, each addressing a critical aspect of the research, from conceptual development to experimental validation:

- **Chapter 1: Introduction**
  This chapter introduces the motivation, historical background, research problem, objectives, contributions, and the overall structure of the thesis.

- **Chapter 2: Background and Related Work**
  It provides a comprehensive review of DC microgrid architecture, power flow control strategies, DC bus management challenges, and existing communication and control protocols. The research gap and motivation are identified through critical analysis of the literature.

- **Chapter 3: Architecture and System Model of DC-Based Microgrid**
  This chapter outlines the proposed system architecture, describes the components involved (e.g., PV, ESS, loads), communication framework, the Quality of Energy Services (QoES) framework, and the SoC-based Power Assignment (SPA) algorithm.

- **Chapter 4: Experimental Setup and Implementation**
  Details the experimental environment, hardware integration, implementation of the proposed control logic, and simulation settings. It also includes real-time observations and technical challenges encountered during system deployment.

- **Chapter 5: Evaluation and Results**
  Presents both simulation and experimental results to evaluate the effectiveness of the SPA algorithm, load prioritization behavior, SoC balancing, and system responsiveness under varying demand and supply conditions.

This structured progression allows the reader to follow the theoretical foundation, system design, implementation, and evaluation stages of the proposed DC microgrid control strategy.

Chapter 2

Background

In recent years, DC MG have emerged as an efficient and versatile solution for integrating DERs, particularly RESs such as photovoltaic (PV) systems and fuel cells. Unlike traditional alternating current AC MG, DC MG inherently align with the native output of many RESs and modern loads, reducing the need for multiple stages of AC/DC conversion. This leads to lower energy losses, simpler system configurations, and improved overall efficiency. A DC MG is a localized power system that distributes and manages electricity using DC rather than the conventional alternating current (AC). It typically integrates various DERs such as solar PV panels, batteries, fuel cells, and DC loads like LED lighting or electric vehicles. Because many modern electronic devices and renewable sources inherently operate on DC, using a DC MG can reduce conversion losses and improve overall efficiency. Moreover, DC MG are well-suited for energy storage systems and can provide faster and more stable control during load fluctuations. They are increasingly deployed in remote areas, smart buildings, data centers, and off-grid applications where energy efficiency, resilience, and compatibility with RES are critical.[1]

2.1 Overview of DC MG

A DC MG typically consists of a DC bus that interconnects various DERs, ESSs, and DC or AC loads through appropriate power electronic converters. This architecture not only simplifies the interconnection of diverse energy sources and storage devices but also makes it easier to integrate emerging DC loads like electric vehicles, LED lighting, and data centers. Consequently, DC MG have become increasingly attractive for applications requiring high energy efficiency, such as commercial buildings, residential communities, and remote off-grid installations. Moreover, DC MG eliminate the need for fre-

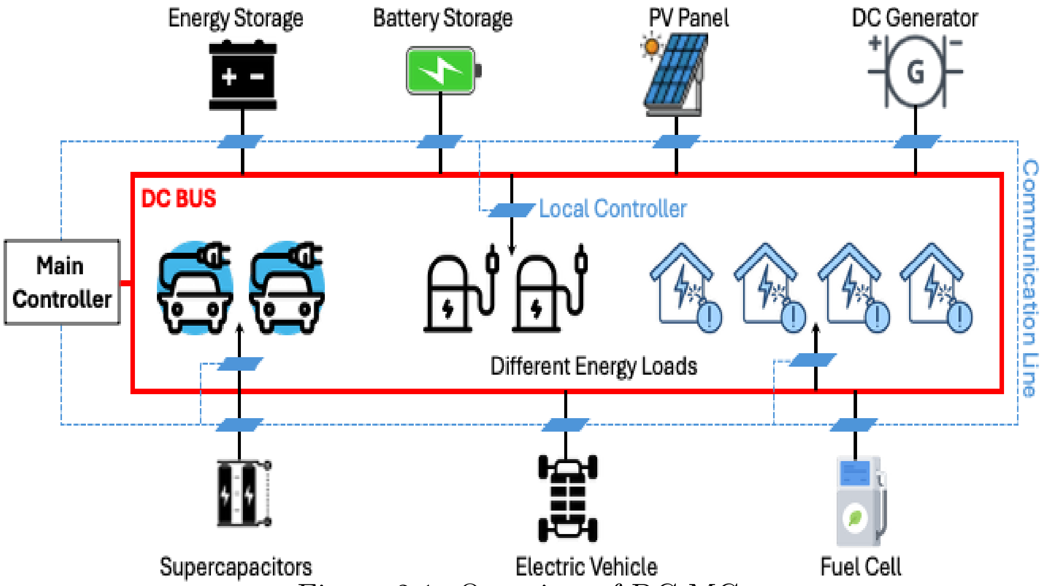

Figure 2.1: Overview of DC MG

quency and phase synchronization required in AC systems, allowing for more straightforward control strategies. They also offer the potential for enhanced reliability by enabling localized energy generation and consumption, which reduces dependency on the main utility grid and can improve resilience during disturbances or outages.

However, despite these advantages, DC MG are not without challenges. Voltage stability on the DC bus must be carefully managed to prevent overvoltage or undervoltage conditions, especially under the fluctuating inputs from RESs and dynamic load variations. Coordinating multiple ESSs and ensuring balanced power sharing remain essential to achieving reliable and long-lasting system performance. As research progresses, DC MG are expected to play a critical role in advancing sustainable and resilient power systems.In recent years, direct current (DC) MG have emerged as an efficient and versatile solution for integrating DERs, particularly RESs such as photovoltaic (PV) systems and fuel cells. Unlike traditional alternating current (AC) MGs, DC MG inherently align with the native output of many RESs and modern loads, reducing the need for multiple stages of AC/DC conversion. This leads to lower energy losses, simpler system configurations, and improved overall efficiency.

2.2 Related Work

A DC MG incorporating DC bus signaling (DBS) offers a promising and cost-effective solution for improving electricity access in rural and remote areas, especially in developing countries. By enabling decentralized power management, such systems can provide more reliable energy to communities that traditionally lack stable grid connections. As discussed in [5], a three-layer modular model for MG has been proposed, emphasizing the Basic DC MG Model (Layer 1). This foundational layer ensures effective power management at all times within the MG. Through this framework, it becomes possible to implement various energy management strategies by adjusting the voltage regulation priorities of different devices, thereby achieving goals like reducing battery capacity needs or lowering dependence on the AC grid.

Other studies have focused on key technical aspects that support the stable operation of DC MG. For example, [6] examine two main areas. First, they summarize and analyze different DC/DC converter structures and control strategies that help maintain a stable input voltage on the DC bus. Second, they explore methods for direct control of the DC bus voltage, categorizing them into approaches based on energy storage devices, controller-driven voltage regulation, and other specialized techniques. Further contributions to MG design include the work in [8], which proposes a dual DC bus nanogrid system operating with both 380 V and 48 V buses. This arrangement allows distributed energy resources to be integrated across two voltage levels, with an interlink converter facilitating coordinated power sharing between the buses. Additionally, [9] present a current-fed dual-active bridge (CF-DAB) converter specifically developed to evaluate dual-bus nanogrids experimentally. They also propose a control structure and an average model to demonstrate closed-loop performance, offering practical insights into advanced multi-bus DC MG implementations.

Several recent studies explore the role of DC MG, particularly nanogrids, in advancing residential renewable energy systems. In [10], the concept of employing multiple DC nanogrids to form a renewable energy community is investigated. Each nanogrid utilizes a DC Bus Signaling (DBS) distributed control strategy to manage its local power flows in response to requests from an aggregator. Notably, this strategy is adaptive, meaning it operates both when the nanogrid actively provides services to the aggregator and when it functions independently. Building on the idea of DBS, [11] introduces a control approach known as Price-Based Power Management (PBPM). Here, the DBS mechanism is coupled with an internal pricing concept, allowing each nanogrid to make energy management decisions based on market-like principles. This simplifies the design of the system's state machines by clearly defining operational modes such as buying or selling energy depending on the internal price, thereby facilitating efficient handling of energy surpluses or shortages. Control strategies at the primary level have also been a subject of investigation. In [12], two methods are studied to maintain a stable DC bus voltage under varying conditions, such as when constant power loads (CPLs) are connected or when there are sudden power flow changes on the source or load side. The first approach employs cascaded PI regulators, while the second utilizes a nonlinear control scheme, each offering distinct advantages in dynamic performance.

Further innovations are presented in [13], where a novel power management framework for a DC MG is proposed using a DBS method. The system consists of two subgrids interconnected via a bi-directional DC/DC interlink converter (IBD). Within each subgrid, both power-based droop control and SoC-based droop control of batteries are implemented to regulate the DC bus voltage. A dedicated controller manages power flow through the IBD based on these bus voltages. Additionally, [14] proposes a control strategy that continuously monitors the DC bus voltage and adjusts the output of photovoltaic (PV) systems by switching between maximum power point tracking (MPPT) mode and voltage regulating mode. If the DC bus voltage is below a certain threshold, the PVs operate in MPPT mode to maximize energy harvesting. Otherwise, they transition to voltage regulating mode to maintain the bus voltage within an acceptable range, thereby enhancing overall system stability. Recent advancements in DC MG technology continue to highlight innovative converter topologies, control strategies, and power management techniques. In [15], a high-gain multiport DC-DC converter is proposed specifically for low-voltage hybrid energy storage systems that combine batteries and supercapacitors. This design features a current-fed dual active bridge (CF-DAB) structure, which ensures galvanic isolation between the battery and the DC bus. The use of voltage multiplier cells on the DC bus side further enables a high voltage conversion ratio between the supercapacitor and the DC bus. Additionally, the topology supports wide zero-voltage switching (ZVS) operation across all switches and allows for bidirectional power flow among any two ports.

Several studies also explore enhanced control schemes to improve the operational resilience and quality of DC MG. For example, [16] proposes a control approach applicable in both ringed and separated MG configurations. This method offers multiple benefits, including balancing unbalanced loads, mitigating harmonics from nonlinear loads, enhancing voltage stability, handling sags and swells, enabling partial operation during outages, and generally boosting system resilience. A broader perspective on DC MG systems is provided in [17], which delivers a comprehensive discussion on MG architecture, power flow analysis, comparative control strategies, challenges along with practical recommendations, and both classical and intelligent energy management strategies (EMS). This work serves as a valuable reference for understanding the multidimensional aspects of DC MG design and operation. Specific power management methods continue to be an active area of research. In [18], a control algorithm is introduced to maintain power balance in standalone DC MG where renewable energy sources (RES) and battery energy storage systems (BES) are connected via dual active bridge (DAB) converters. This scheme dynamically selects appropriate operating modes for the RES and BES based on load demands, generation conditions, and the state of charge of the batteries.

Furthermore, [19] presents an optimal distributed control strategy aimed at keeping the average DC bus voltage close to its nominal value while ensuring accurate power sharing among multiple bulk energy storage units (ESUs). By constructing correlated and voltage-independent intermediate variables that are exchanged among the ESUs, the method effectively handles communication delays that typically impair voltage observers. Simulation studies conducted in Simulink/MATLAB confirm the robustness and correctness of this approach, reinforcing its potential application in practical DC MG systems. Optimizing power and energy management in DC MG continues to be a central focus of current research. In [20], an optimal energy management strategy (EMS) is proposed that leverages the salp swarm algorithm (SSA). This nature-inspired optimization technique is chosen for its strong convergence characteristics and relatively low computational complexity. The paper thoroughly details the step-by-step design of the EMS and validates its effectiveness through hardware-in-the-loop (HIL) testing, demonstrating its practical applicability in DC MG environments.

Addressing more complex optimization scenarios, [21] formulates the energy management challenge as a non-convex mixed-integer nonlinear (MINL) problem, which is notably difficult to solve with standard techniques. To tackle this, the authors employ the branch and reduce optimization navigator (BARON) algorithm, a robust global optimization method. The study explores single-objective scenarios focused on minimizing either cost or emissions, and then extends to a multi-objective case that simultaneously considers reasonable operational trade-offs between the two. Insights from the single-objective results are used to define feasible constraints for optimizing the multi-objective scenario through a constraints-based approach. Further advancements are seen in [22], which presents a novel optimization-driven power management strategy (PMS) for a battery/supercapacitor hybrid energy storage system (HESS) configured in a semi-active structure within a DC MG. Given that regulating the DC bus voltage is the primary role of the HESS, the paper emphasizes the importance of supercapacitor control due to its direct connection to the DC bus. This approach underscores how careful design of HESS control can enhance voltage stability and overall system performance in DC MG applications.

2.3 Power Flow Control Strategies

In DC MG, basic power flow control strategies are essential for regulating voltage and ensuring balanced power sharing among sources and loads. The most fundamental method is droop control, which enables decentralized operation by adjusting output voltage in proportion to current or power changes. This allows multiple converters or sources to share loads without relying on communication links. While simple and robust, droop control may suffer from poor voltage regulation. To improve system performance, centralized control has also been used, where a central unit collects system data and optimally allocates power. However, this introduces dependence on communication infrastructure and can reduce system flexibility. Hierarchical control structures combine the benefits of both by organizing control into layers: primary (local), secondary (voltage correction), and tertiary (optimization). These basic strategies provide the foundation for more advanced techniques, enabling reliable and efficient operation of low-voltage DC systems in applications such as smart homes, renewable integration, and disaster recovery. In low-voltage DC (LVDC) MG, power flow control plays a critical role in ensuring stable, efficient, and coordinated energy distribution among distributed energy resources (DERs), storage units, and loads. Unlike AC systems, LVDC MG avoid issues like reactive power and synchronization, but they introduce new challenges such as voltage stability, current balancing, and bus voltage regulation under variable loading and generation. Power flow control plays a vital role in ensuring reliable and efficient operation of DC MG, particularly as they integrate diverse renewable sources, energy storage systems (ESS), and varying load types. Effective strategies must simultane-

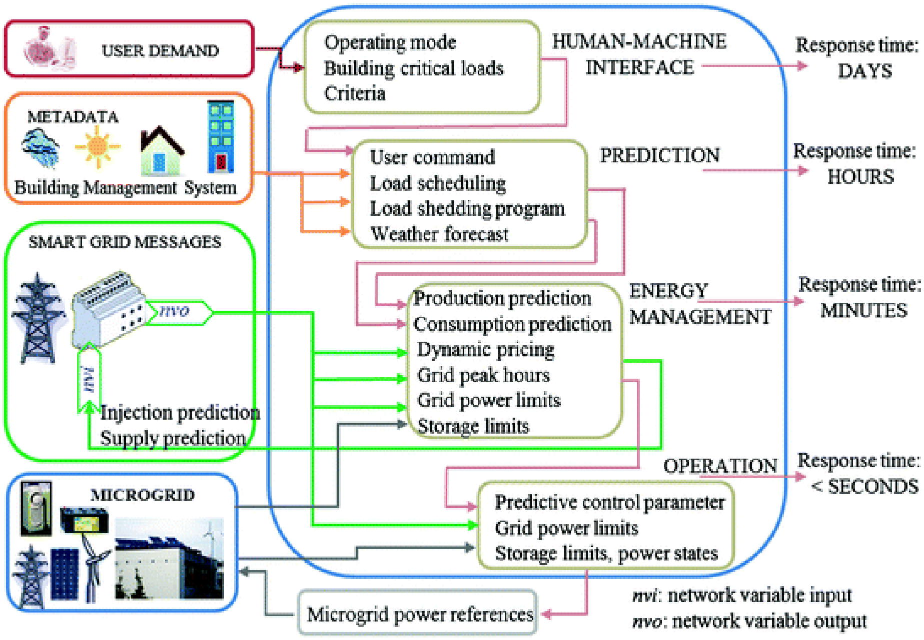

Figure 2.2: Control strategies of DC MG [7]

ously maintain DC bus voltage stability, balance state of charge (SoC) across ESS units, and optimize energy distribution according to both system and user-level priorities.

Several foundational approaches to power flow management rely on DC bus signaling (DBS) techniques, which enable decentralized coordination by using variations in the DC bus voltage as a communication medium. In [3], a layered modular MG model is introduced where the "Basic DC MG Model" (Layer 1) provides the core framework for implementing various energy management scenarios through voltage regulation priorities. This model supports objectives such as minimizing battery usage and reducing dependence on external AC grids. Extending this, [8] demonstrates how DBS strategies can adaptively manage individual nanogrids within a community, coordinating their operation both when directly serving an aggregator and when operating independently.

Building on DBS, several studies incorporate market-inspired mechanisms. In [9], a price-based power management (PBPM) approach ties internal electricity prices to DBS control, simplifying system operation by directly associating voltage thresholds with buying or selling decisions. This approach effectively manages energy surpluses or shortages within nanogrids by mirroring economic market behaviors.

Converter-based control techniques also form a major category. For instance, [13] proposes a high-gain multiport DC-DC converter leveraging a current-fed dual active bridge (CF-DAB) topology. This configuration ensures galvanic isolation and supports bi-directional power flow among batteries, supercapacitors, and the DC bus, facilitating fine-grained power control. Similarly, [16] develops a power management algorithm for standalone DC MG interfacing renewable energy sources (RES) and battery ESS through DAB converters. The algorithm selects optimal operating modes by considering real-time load demands, generation levels, and battery SoC conditions.

Advanced droop and hybrid droop control strategies have also been extensively studied. In [11], a novel control integrates both power-based and SoC-based droop mechanisms within two interconnected DC subgrids. This arrangement, managed via an interlinking bi-directional DC/DC converter (IBD), dynamically balances local energy flows and regulates DC bus voltage. Complementarily, [17] proposes a distributed optimal control method that optimizes average DC bus voltage without relying on conventional voltage observers, thereby improving robustness against communication delays.

Moreover, more comprehensive optimization-driven power management frameworks are emerging. In [18], a salp swarm algorithm (SSA) is employed to devise an optimal energy management strategy (EMS) for a DC MG, with validation through hardware-in-the-loop experiments. In more complex scenarios, [19] formulates the power flow control as a non-convex mixed-integer nonlinear problem, solved via the BARON global optimization engine. This allows simultaneous minimization of cost and emissions. Finally, [20] presents a strategy for managing battery/super capacitor hybrid energy storage systems (HESS), with a special focus on controlling the super capacitor directly linked to the DC bus, thereby enhancing bus voltage stability.

Taken together, these diverse contributions underscore how power flow control strategies in modern DC MG increasingly integrate multi-layered objectives: regulating DC bus voltage, balancing SoC across storage systems, managing power quality for critical and non-critical loads, and even incorporating economic signals. However, despite notable advances, many existing solutions still treat these objectives in isolation. This highlights the need for holistic power flow control frameworks capable of simultaneously addressing these intertwined challenges in real-time operational environments.

2.4 Role and Challenges of the DC Bus

The DC bus serves as the central electrical backbone of a DC MG, enabling seamless integration and coordination among distributed energy resources (DERs), energy storage systems (ESS), and various loads. Its primary role is to maintain a stable voltage level, thereby facilitating reliable power sharing and supporting real-time power flow control across the MG.

A stable and well-regulated DC bus allows diverse energy devices—including photovoltaic panels, batteries, supercapacitors, and even AC-interfaced loads through inverters—to operate cohesively. In [3], the concept of a layered DC MG architecture demonstrates how the foundational "Basic DC MG Model" (Layer 1) ensures effective power management by coordinating power flows via voltage regulation on the DC bus. Similarly, in nanogrid-based community energy systems, the DC bus becomes a medium for distributed coordination, enabling each nanogrid to respond adaptively to aggregator requests or local needs through DC Bus Signaling (DBS) strategies [8], [9].

The DC bus also plays a critical role in advanced multiport systems and hybrid energy storage configurations. For instance, [13] employs a high-gain multiport DC-DC converter that directly links the supercapacitor to the DC bus, using voltage multiplier cells to achieve significant conversion ratios. This setup underscores how the DC bus acts as a direct conduit for balancing fast-changing energy flows between supercapacitors and the broader MG. Likewise, hybrid control schemes in [11] and [20] leverage direct connections of supercapacitors to the DC bus to stabilize voltage while coordinating with batteries through droop or optimization-based management.

However, maintaining a stable and efficient DC bus is not without challenges. Voltage deviations can occur due to sudden changes in generation or load profiles, leading to overvoltage or undervoltage conditions that may threaten system reliability [16]. When constant power loads (CPLs) are connected or significant power flow changes arise, specialized controllers—such as cascaded PI regulators or nonlinear schemes—are required to keep the DC bus voltage within acceptable limits [10]. Additionally, communication delays in distributed control architectures can impair accurate observation of average DC bus voltage, necessitating innovative solutions like the voltage-independent optimal control proposed in [17].

Harmonics introduced by nonlinear loads, unbalanced power demands, and the need to operate partially under fault or outage conditions further complicate DC bus management. As explored in [14], maintaining voltage stability in such scenarios often requires multi-layered strategies that integrate load balancing, harmonic compensation, and voltage sag/swell mitigation. Moreover, when economic market-based controls such as price-based power management (PBPM) are applied via DBS [9], the DC bus must dynamically respond to internal "price signals," adding another layer of complexity to voltage and power flow regulation.

Taken together, these studies highlight that while the DC bus is essential for coordinating energy flows and enabling diverse operational objectives in DC MG, it also represents a critical point of vulnerability. Ensuring its stability requires careful integration of converter design, advanced control algorithms, load and storage coordination, and robust communication mechanisms all tailored to the specific characteristics and demands of the MG.

2.5 Communication and Control Protocols

Modern DC MG rely on robust communication frameworks to coordinate distributed generation, energy storage systems (ESS), and diverse load types. Effective communication is essential for real-time monitoring, control decision-making, and executing power flow management strategies. This becomes even more critical when employing advanced schemes such as SoC balancing, price-based power management, or adaptive DC bus signaling (DBS).

Several studies have highlighted the importance of communication protocols tailored to MG environments. For instance, [10, 11] apply DC Bus Signaling (DBS) itself as a low-level indirect communication mechanism, where voltage deviations on the DC bus act as control signals. While simple and cost-effective, such indirect methods can be complemented by higher-layer communication protocols to achieve richer system observability and coordinated responses. Other works incorporate explicit data exchanges over communication networks. In [13], distributed droop control strategies adjust power outputs based on locally exchanged SoC and voltage data. Meanwhile, optimization-driven approaches in [19, 20, 21] rely on iterative information sharing among ESS units to compute optimal power flows. Communication delays in such systems can significantly impact control performance, motivating the design of algorithms resilient to latency or packet loss. In this study, a mathematical model of a DC islanded MG (ImG) incorporating time-delay effects is developed, along with three complementary control strategies—stabilizing, robust, and robust-predictor methods—to mitigate the impact of these delays [23]. The influence of different communication approaches on system performance, particularly regarding communication delays, is further analyzed and assessed through detailed MATLAB/Simulink simulations [24]. To address the challenges posed by variable and bounded communication delays, [25] introduces a novel control framework that ensures both precise proportional power sharing and average voltage regulation among distributed generators (DGs). This is achieved using a surplus consensus-based observer, enhancing coordination despite communication uncertainties. Additionally, to improve the control performance of DC MG, [26] proposes a droop control technique inspired by the frequency droop concept traditionally employed in AC MG. By simulating a virtual frequency mechanism, this method extends familiar AC stability principles into the DC domain, thereby strengthening the dynamic response and load-sharing capabilities of the DC MG.

Protocols such as ECHONET Lite, Modbus, or MQTT (when implemented on lightweight IoT devices) are increasingly explored for such applications, enabling structured messaging between controllers, sensors, and actuators. A robust communication setup must consider data rates, synchronization needs, latency constraints, and cybersecurity to protect sensitive operational data and maintain MG reliability. In this research, a practical communication protocol (e.g., HTTP and MQTT) has been developed to interface with power electronic devices, gather real-time voltage, current, and SoC measurements, and execute distributed power flow control decisions. This will form a key component of the proposed integrated power management framework, ensuring that control objectives such as SoC equalization, voltage stability, and load prioritization are met under dynamic operating conditions.

2.6 Research Gap and Motivation

Extensive research has been conducted on power flow control, voltage stability, and energy management in DC MG, reflecting the growing interest in these systems as a foundation for integrating renewable energy sources (RESs) and enhancing local energy resilience. Numerous studies have explored DC Bus Signaling (DBS) as a decentralized method for power coordination, implementing adaptive and price-based control schemes to facilitate effective load and generation balancing [5, 10, 11]. Similarly, sophisticated converter topologies such as multiport DC-DC converters and current-fed dual active bridges (CF-DAB) have been introduced to support bi-directional energy flow, galvanic isolation, and high conversion ratios between ESS components and the DC bus [15, 18].

Control strategies have also advanced significantly, with research presenting cascaded PI regulators, nonlinear controllers, and hybrid droop methods to regulate DC bus voltage under fluctuating loads and varying generation conditions [12, 13, 26]. Optimization-driven approaches have emerged to minimize operational costs, emissions, or improve power-sharing among hybrid energy storage systems (HESS), using techniques such as the salp swarm algorithm or the BARON global optimization solver [20, 21, 22].

Despite these developments, several critical gaps persist. Most existing approaches tend to address individual challenges—such as SoC balancing, voltage stability, or load prioritization—in isolation. Integrated frameworks that simultaneously achieve proportional power sharing, SoC equalization across diverse ESSs, voltage regulation on the DC bus, and dynamic prioritization of loads based on QoES requirements remain scarce. Furthermore, while indirect communication via DBS and distributed droop control have been widely studied, fewer works rigorously incorporate the impacts of explicit communication protocols and associated delays on real-time power flow decisions [23, 24, 25]. This highlights the necessity for a holistic power flow control scheme that unifies these objectives within a single operational strategy. Such a scheme should not only stabilize the DC bus voltage and maintain balanced SoC across ESSs but also dynamically allocate power to loads according to their criticality and service quality needs, all while remaining robust against communication delays and uncertainties. This research is motivated by the opportunity to develop and experimentally validate such an integrated approach, thereby advancing the practical deployment of reliable, efficient, and sustainable DC MGs.

Chapter 3

Architecture and System Model of DC based MG

3.1 Introduction

The increasing global demand for sustainable and resilient energy systems has accelerated the development of decentralized power architectures, particularly DC MG. These systems offer a highly efficient and flexible platform for integrating RESs such as PV arrays, as well as ESSs and a wide variety of modern DC loads. Due to the direct compatibility with DC-powered components and the reduction in power conversion losses, DC MGs have emerged as a practical and future-ready alternative to traditional AC-based distribution systems, especially in small-scale, localized applications such as residential areas, rural electrification, and remote communities.

While extensive research has explored the modeling, simulation, and control of DC MG, many of these studies remain limited to software-based validation without demonstrating real-world feasibility. Control schemes are often tested in idealized environments, which do not account for practical factors such as sensor delays, voltage fluctuations, asynchronous device behavior, and communication losses. These limitations can obscure the actual performance of power flow control strategies when implemented in physical systems.

To bridge this gap, this study proposes and implements an experimental DC MG platform that integrates PV generation, distributed ESSs, and priority-based loads, all interconnected through a 12V DC bus. The aim is to investigate a practical power flow control algorithm that ensures effective load management, balances the SoC among ESS units, and maintains system stability under real-time conditions. By incorporating real sensors, hardware controllers, and a communication protocol, this research enables direct observation of control performance and behavior under realistic operational scenarios.

The significance of this work lies in its departure from purely simulation-based evaluations. By physically constructing and analyzing the proposed architecture, this study not only validates theoretical models but also reveals challenges and limitations that are often hidden in digital simulations. The outcome is a more grounded understanding of how intelligent control and coordination strategies can be applied to enhance the reliability, efficiency, and adaptability of future DC MG systems.

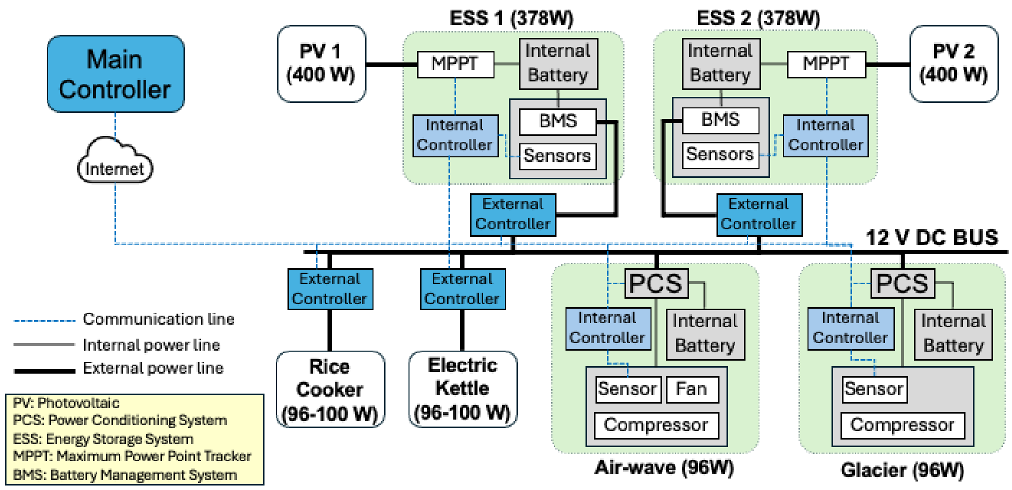

Figure 3.1: Proposed System Model for DC MG

3.2 Proposed System Architecture of DC based MG

The proposed architecture represents a real-world implementation of a low-voltage direct current (LVDC) MG designed for small-scale energy sharing and smart power management. In Fig. 3.14 the system comprises two distributed ESSs, two PV generation units, and multiple energy loads interconnected via a 12V DC bus. Each ESS is equipped with internal and external controllers, a battery management system (BMS), and sensors for monitoring voltage, current, and SoC. The PV systems are interfaced through maximum power point tracking (MPPT) modules to ensure optimal energy harvesting under varying environmental conditions. A central controller, operating over a communication network, coordinates power assignments across all devices.

A key objective of the system is to ensure continuous and reliable power delivery while dynamically responding to load priorities and energy source availability. The DC bus serves as both a physical power backbone and a communication reference for decentralized coordination. Loads are categorized by their criticality and power demand. High-priority loads, such as refrigeration and air systems, are guaranteed service during limited supply, while non-critical appliances like kettles and cookers are managed based on availability and storage health.

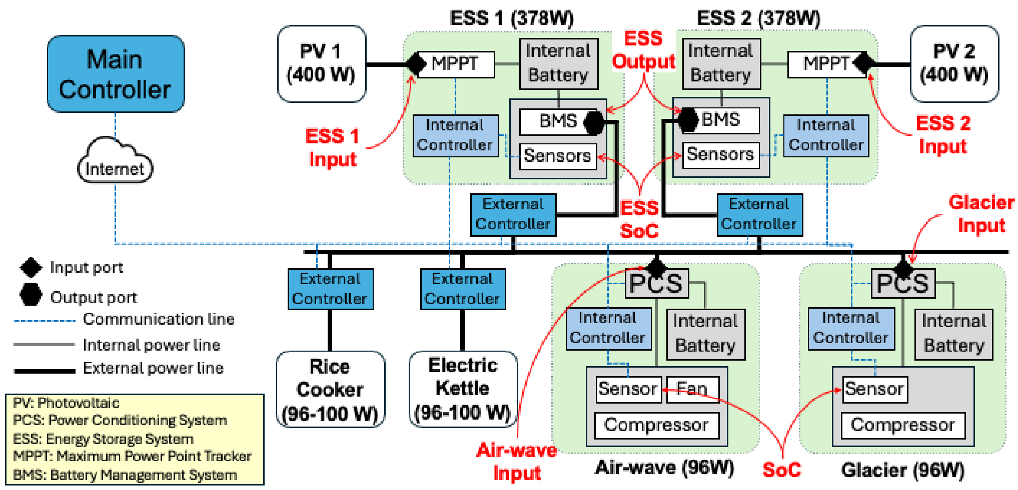

Figure 3.2: Measuring Point of the DC MG

This architecture enables the implementation and testing of a power flow control algorithm that simultaneously addresses three main operational goals: (i) real-time power allocation based on available generation and consumption demand, (ii) equalization of SoC between multiple ESS units to prolong battery life and optimize storage usage, and (iii) prioritization of energy services according to QoES requirements.

Unlike many existing studies that are confined to simulation platforms, this system is developed as a fully functional physical testbed. It allows for real-time experimentation using actual energy flows, embedded control logic, and communication between devices. This shift from simulation to experimentation is a key contribution of the research, as it reveals the practical challenges of system latency, sensor noise, communication delay, and asynchronous component behavior all of which are critical to the deployment of real DC MG applications. The architecture provides a flexible platform not only for validating control strategies but also for exploring fault recovery, resilience, and intelligent load response under varying supply conditions.

3.2.1 Measuring Point of the DC MG

In Fig. 3.14, the key measurement and control points for power, voltage, current, and state of charge (SoC) within the DC microgrid system are illustrated. The power input of the ESS is monitored at the Maximum Power Point Tracking (MPPT) interface, where sensors capture the real-time charging power, input voltage, and SoC parameters. These measurements are crucial for ensuring the optimal harvesting of solar energy and tracking the ESS charging dynamics. The power output point of the ESS is connected to the battery management system (BMS), which subsequently interfaces with the external controller. This controller governs the regulated power flow from the ESS units to the common DC bus, where sensors capture the real-time discharging power, voltage and current.

For smart loads such as the Glacier and Airwave, power is drawn directly from the DC bus and first routed through their respective Power Conditioning Systems (PCS). The PCS dynamically allocates the incoming power between internal battery charging and direct load operation, depending on the internal SoC and active mode of operation. From the Input point can get the input power, current and voltage, also snesor can provide the SoC level od internal batteries.

In contrast, traditional appliances such as the electric kettle (EK) and rice cooker (RC) do not possess internal smart control or energy storage. To integrate these devices within the microgrid, dedicated external controllers were developed and connected to the DC bus. These controllers are responsible for both enabling/disabling power flow and monitoring key electrical parameters such as current and voltage, thereby ensuring safe and scheduled energy delivery aligned with system priorities.

3.2.2 Components

The experimental DC MG testbed is composed of several essential components that work collaboratively to maintain reliable energy delivery and intelligent power control. These include photovoltaic generation units, energy storage systems, a central DC bus, categorized loads, and microcontroller-based control systems. The system is designed for real-time operation, enabling dynamic decision-making based on power availability and demand.

1. Photovoltaic (PV) Generation Units

The MG includes two photovoltaic panels, each rated at 400W, serving as the primary renewable energy input. In Fig representing the details of the PV panels.

Figure 3.3: ECOFLOW 400W Portable Solar Panel used in this research

Table 3.1: Specifications of ECOFLOW Portable Solar Panel

Parameter	**Specification**
Panel Type	Monocrystalline Silicon
Maximum Output Power	400 W
Voltage Range	11–60 V
Max Input Current	13 A
Connector Type	XT60
Use Case	Charging ESS Units (ESS1, ESS2) via MPPT
Weight	Approx. 16 kg
Foldable	Yes (portable design)
Waterproof Rating	IP68

2. Energy Storage Systems (ESS)

Two independent energy storage systems (ESS1 and ESS2) are integrated into the architecture. Each ESS contains a lithium-ion battery, a built-in BMS, and an external micro-controller for regulation. These storage units are essential for buffering fluctuations in solar power, maintaining load continuity during low generation periods, and enabling SoC-based load and energy balancing. The external controller measures voltage, current, and SoC, and supports controlled charge/discharge operation in coordination with the central controller.

Figure 3.4: ECOFLOW Delta Pro Power Station

Table 3.2: Specifications of ECOFLOW Delta Pro Portable Power Station

Specification	**Value**
Battery Type	LFP ($LiFePO_4$)
Capacity	3600 Wh (expandable up to 25 kWh)
AC Output Power	3600 W (7200 W surge)
DC Output Ports	2× DC5521 (12.6V, 3A), 1× Car Port (12.6V, 10A)
AC Charging Input	1800 W (120V, 15A or 240V, 30A)
Solar Charging Input	11–150 V, 15 A, Max 1600 W
Battery Cycle Life	3500 cycles to 80%+ capacity
Wi-Fi	Supported (via EcoFlow app)
Weight	45 kg
Dimensions	63.5 × 28.4 × 42 cm

3. DC Bus Infrastructure

The 12V DC bus acts as the primary electrical backbone of the MG. It interconnects all major components, including the PV systems, ESS units, and DC loads. The bus supports centralized and decentralized energy distribution and also functions as a platform for indirect communication via voltage signaling. Its low-voltage nature and simplified wiring make it suitable for residential and small-scale testbed applications.

4. DC Load Devices

In the context of developing and testing a DC Microgrid (DC MG), this research incorporates several practical DC load devices to simulate real-world applications and evaluate load management strategies. The selected DC loads are commercially available appliances that can operate on 12V or 24V DC inputs, making them suitable for low-voltage DC distribution systems.

4.1 EcoFlow AirWave The EcoFlow AirWave is a portable air conditioning unit designed for energy-efficient operation. In this research, it is utilized as a DC load to represent cooling demand within the DC MG framework. It supports DC input voltages ranging from 11–60V, with a maximum input current of 13A and a power rating of up to 400W for solar input. The unit also provides heating and cooling modes with rated DC input power of approximately 495W (cooling) and 540W (heating).

Figure 3.5: EcoFlow AirWave Portable Air Conditioner

4.2 EcoFlow Glacier The EcoFlow Glacier is a dual-zone portable refrigerator and freezer that is included in the DC MG testbed to simulate refrigeration loads. It is powered via 12V/24V DC inputs and is designed for mobile or off-grid applications. Its integration into the microgrid allows analysis of continuous low-power DC load behavior, which is critical for food preservation and daily energy planning in off-grid scenarios.

4.3 Electric Kettle A modified electric kettle is employed to represent high-power intermittent DC loads. The kettle operates on either 12V or 24V DC with a maximum input current of 8A, translating to a power consumption of up to approximately 192W. This load is valuable for testing rapid energy draw and thermal management strategies in the microgrid.

4.4 Rice Cooker Similar to the electric kettle, a DC-powered rice cooker is included to emulate real-life kitchen appliances in off-grid or microgrid

Table 3.3: Specifications of EcoFlow AirWave Portable Air Conditioner

Specification	**Value**
Cooling Capacity	5100 BTU
Heating Capacity	6100 BTU
Rated Cooling Power (DC)	495 W
Rated Heating Power (DC)	540 W
Car Charging Input	96 W / 192 W (12/24V, 8A Max)
Solar Charging Input	11–60V, 13A, 400W Max
Noise Level	44–56 dB
Battery (Optional Add-On)	1159 Wh
Weight (without battery)	13 kg

Figure 3.6: EcoFlow Glacier Portable Refrigerator

Table 3.4: Specifications of EcoFlow Glacier Portable Refrigerator

Specification	**Value**
Cooling Range	10°C to -25°C
Compressor Power	120 W (typical)
Rated Input (DC)	11–60V, up to 8A
Battery (Built-in/Optional)	298 Wh
Charging Options	Solar, AC, Car Port
USB-C Output Port	100W (optional for external devices)
Refrigeration Time (with battery)	Up to 40 hours (depends on use)
Weight (with battery)	16.6 kg

environments. The rice cooker also operates at 12V/24V DC and draws up to 8A, making it a moderate to high-power load. Its thermal inertia and

Figure 3.7: DC Electric-Kettle

Table 3.5: Specifications of 12/24V DC Electric Kettle

Specification	Value
Input Voltage	12V / 24V DC
Rated Current	8A Max
Power Consumption	96W (12V) / 192W (24V)
Heating Element Type	Resistive coil
Typical Use	Boiling water (0.5–1.0 L)
Control Method	PWM via Raspberry Pi

batch processing nature make it suitable for demand-shaping analysis.

Table 3.6: Specifications of 12/24V DC Rice Cooker

Specification	Value
Input Voltage	12V / 24V DC
Rated Current	8A Max
Power Consumption	96W (12V) / 192W (24V)
Heating Method	Electric coil heating plate
Typical Use	Cooking 1–2 servings of rice
Control Method	PWM via Raspberry Pi

5. External Controller for ESSs Each ESS is paired with an external controller responsible for local data acquisition and device control. External controller consistes the Buck covertor DPS 5020 and Raspberry Pi. It can control the power output of ESS, it can provide constant volatge and current.

Figure 3.8: DC Rice Cooker

These controllers collect real-time measurements of voltage, current, and battery SoC, and transmit the data to a main controller. while external controllers handle local operations such as switching and SoC equalization. **5.1 Buck Converter DPS5020** The DPS5020 is a programmable buck converter module capable of delivering a wide range of output voltages and currents. It is commonly used in DC microgrids and laboratory settings for regulated DC power supply.

Figure 3.9: Buck Converter DPS5020 Module

6. External Controller for EK and RC

For the External controller of Electrickettle and Rice cooker, this reaserch

Table 3.7: Specifications of DPS5020 Buck Converter

Specification	**Value**
Input Voltage Range	6V – 60V DC
Output Voltage Range	0V – 50V DC
Output Current Range	0A – 20A
Output Power	Up to 1000W
Display	1.44-inch TFT LCD
Control Interface	Rotary encoder with push button
Communication	UART / TTL / PC software control
Cooling Method	Active fan cooling
Protection	Over-voltage, over-current, over-temp

develop with the MOSFET D4148 , PZM 017 and raspberry Pi. **6.1 MOSFET D4148** The D4184 MOSFET module is a compact and efficient switching component commonly used for controlling high-current DC loads in embedded systems. It utilizes low-resistance N-channel MOSFETs (typically AOD4184) capable of handling up to 50A at 40V, making it ideal for switching devices like motors, lights, and power supplies. Designed for low-side switching, the module is easily integrated with microcontrollers such as the Raspberry Pi using simple GPIO control.

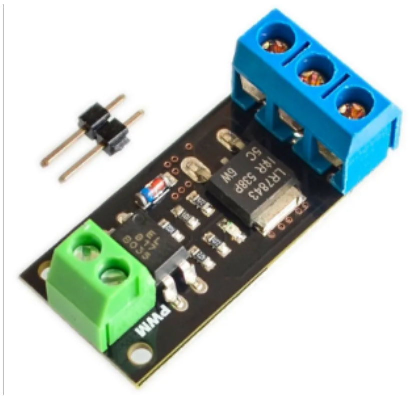

Figure 3.10: MOSFET D4184 Module for DC Switching

6.2 PZEM 017 On the other hand, the PZEM-017 is a digital energy monitoring module designed to measure DC voltage, current, power, and energy consumption in real time. It communicates via the MODBUS-RTU protocol over RS485, allowing precise energy data collection, especially in solar, battery, and DC microgrid applications. Together, these modules offer a practical solution for smart energy control and monitoring systems.

Table 3.8: Specifications of D4184 MOSFET Module

Specification	**Value**
MOSFET Model	IRF D4184
Channel Type	N-Channel
Maximum Drain Current (I_D)	40A
Drain-Source Voltage (V_{DS})	30V
Gate Threshold Voltage	2V – 4V
$R_{DS(on)}$	¡10 m
Control Signal Voltage	3.3V / 5V compatible
Application	DC load control, motor drivers, relay replacement

Figure 3.11: PZEM-017 DC Energy Monitoring Module

7. Raspberry Pi 3 Model B

The Raspberry Pi 3 Model B is a compact and affordable single-board computer commonly used for embedded systems and IoT applications. In this research, the Raspberry Pi serves as the central controller for data acquisition, real-time monitoring, and load management in the DC microgrid system. It communicates with devices such as the DPS5020 Buck Converter, PZEM-017 energy meters, and EcoFlow power stations through GPIO, USB-serial, and MQTT-based protocols.

With a built-in Wi-Fi and Bluetooth module, the Raspberry Pi 3B also facilitates cloud communication and remote system control, making it ideal for intelligent microgrid management.

Table 3.9: Specifications of PZEM-017 Energy Meter

Specification	**Value**
Voltage Range	0 – 300 VDC
Current Range	0 – 20 A (via external shunt)
Power Range	0 – 6000 W
Energy Range	0 – 9999 kWh
Communication Protocol	MODBUS RTU (RS485)
Supply Voltage	5V DC
Baud Rate	9600 bps
Measurement Accuracy	±0.5%
Application	DC Microgrids, Solar Monitoring, Energy Auditing

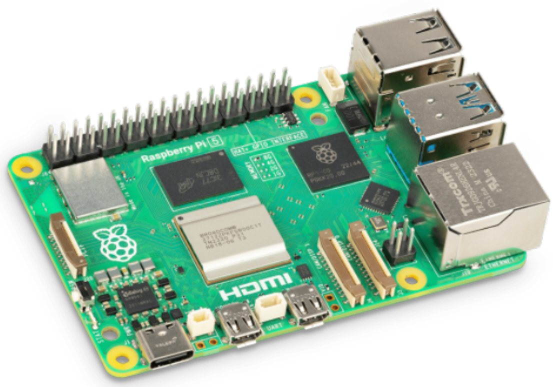

Figure 3.12: Raspberry Pi 3 Model B used as the microgrid controller

Table 3.10: Specifications of Raspberry Pi 3 Model B

Specification	**Value**
Processor	1.2GHz Quad-Core ARM Cortex-A53
RAM	1GB LPDDR2
Wireless Connectivity	802.11n Wi-Fi, Bluetooth 4.1
USB Ports	4 × USB 2.0
GPIO Pins	40-pin header
Storage	MicroSD slot (boot + storage)
Operating System	Raspberry Pi OS / Linux-based systems
Power Input	5V micro-USB (2.5A recommended)

5.5 Router

In this research, a wireless router is used to enable reliable network connectivity between the Raspberry Pi, EcoFlow devices, and the cloud platform.

The router establishes a local Wi-Fi network through which MQTT communication and REST API data exchanges are performed. It ensures continuous data transmission, low-latency command execution, and supports internet-based monitoring of the microgrid system.

The router plays a vital role in remote access, real-time control, and integration with smart energy management systems. It supports DHCP for IP allocation and provides network stability for the Raspberry Pi and other Wi-Fi-enabled devices in the setup.

Table 3.11: Specifications of the Wireless Router

Specification	**Value**
Wireless Standard	IEEE 802.11 b/g/n
Frequency Band	2.4 GHz
Number of LAN Ports	$4 \times 10/100$ Mbps Ethernet
WAN Port	$1 \times 10/100$ Mbps Ethernet
Security Protocols	WPA2-PSK, Firewall, MAC Filtering
Power Supply	9V/0.6A (varies by model)
Management	Web UI, DHCP, Port Forwarding

3.3 Communication Protocol

A robust and responsive communication protocol is essential for enabling intelligent coordination among distributed components in a DC MG. In this proposed architecture, communication facilitates real-time data exchange between the main controller, external/internal controllers, and various energy and load devices. The adopted system combines the use of MQTT (Message Queuing Telemetry Transport), HTTP protocols, and local Wi-Fi networks to ensure timely and reliable data transmission.

3.3.1 System Architecture and Communication Layers The system employs a hybrid communication model structured into cloud-based and local layers. The main controller communicates with external MQTT brokers and the ECOFLOW cloud server using HTTP requests. These cloud services act as intermediaries between the main control logic and the distributed devices, enabling both centralized oversight and local autonomy. MQTT is used as the primary protocol for device-level communication due to its lightweight, publish-subscribe mechanism, which is ideal for bandwidth-constrained or latency-sensitive applications.

3.3.2 Device-Level Communication via MQTT All physical devices—including energy storage systems (ESS1 and ESS2), smart appliances

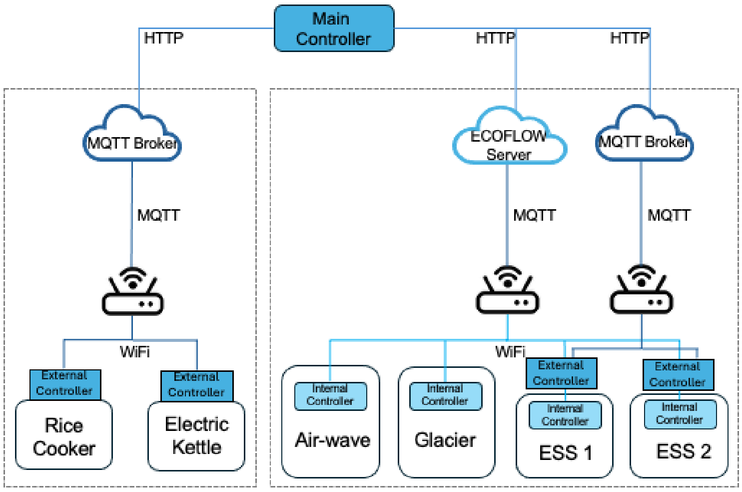

Figure 3.13: Communication Protocol in DC based MG

(Air-wave and Glacier), and normal loads (rice cooker, electric kettle) are equipped with either internal or external controllers capable of Wi-Fi communication. These controllers subscribe to specific MQTT topics to receive power control commands or publish sensor data (e.g., voltage, current, SoC, device status) back to the MQTT broker. For example, ESS controllers transmit real-time SoC data, while load controllers listen for on/off control signals based on available power and priority settings.

3.3.3 Integration with Cloud Services The ECOFLOW Glacier and Air-wave units are linked to the ECOFLOW server via MQTT, using an internal controller and built-in networking modules. This allows for remote status monitoring and command dispatching. Similarly, ESS controllers are connected to the MQTT broker through Wi-Fi routers, enabling secure and fast transmission of control signals between the local system and the cloud-based logic.

3.3.4 Communication Flow and Control Logic The communication process begins with the main controller acquiring system-wide data through HTTP from the cloud and MQTT messages from the local broker. Based on this data, it executes the power flow control algorithm and dispatches operational commands to each device over MQTT. Commands include charging/discharging instructions for ESSs, load switching decisions based on QoES, and updates to MPPT or PCS control states. This ensures a tightly coordinated control environment that can respond adaptively to changes in generation, demand, and storage conditions.

3.3.5 Advantages of the Proposed Protocol This communication framework offers several advantages: (i) The MQTT protocol reduces overhead and enables low-latency responses suitable for real-time control. (ii) The use of HTTP for cloud interfaces maintains compatibility with external APIs and servers. (iii) Distributed controllers improve system scalability and fault tolerance by maintaining local control even when centralized communication is delayed.

Overall, the proposed communication protocol underpins the control architecture by enabling reliable and efficient coordination among all components of the DC MG. It also provides a foundation for extending the system with additional devices, intelligent forecasting, or remote monitoring in future implementations.

3.4 SoC-based Power Assignment Algorithm

3.4.1 MG Physical Constraints

This Section represents the system model of MG. The system model mainly consists of PV Power generation (PGs) system, energy storage (PSs) system and energy loads (PLs). In the MG environment for this system is formalize the PGs, PLs, and PSs. In this $\mathcal{J}$, $\mathcal{K}$, and $\mathcal{H}$ are set of PGs, PLs, ans PSs. We donate the $PG_j^f(t)$ is a set of fluctuating PGs at time t, where $j \in J = \{1, 2, \ldots, J\}$ and the J is total number of PGs. $PL_k^f(t)$ is a set of fluctuating PLs at time t, where $k \in K = \{1, 2, \ldots, K\}$ and K is the total number of PLs. $PS_h^c(t)$ is a set of controllable PSs at time t, where $h \in H = \{1, 2, \ldots, H\}$ and H is the total number of PSs. t is denoted of time step, t^s is demoted for starting time and t^o is representing the operating time.

Mainly these three component are connected with the DC bus for power flow between them. EG_j is denoted as energy generated from the PGs, it will flow from PGs toward the PSs and PLs. Stored energy is denoted as ES_h, it could flow from the PGs to the PSs or PSs to the PLs. As well as load energy denoted as EL_k, it will flow from PGs and PSs toward the PLs. Energy balance relationship of DC MG can be expressed as

$$EG_j = EG_k + ES_h + E_{loss} \tag{3.1}$$

where EG_k and EL_k could be computed as

$$EG_j(t) = \int_0^t \left(\sum_{j \in J} PG_j(t) \right) dt \tag{3.2}$$

$$EL_k(t) = \int_0^t \left(\sum_{k \in K} PL_k(t) \right) dt \tag{3.3}$$

where ES_h is representing the stored energy of ESs. Its could be computed as

$$ES_h(t) = {ES_h}^{ini}(t) + {ES_h}^{in}(t) - {ES_h}^{out}(t) \tag{3.4}$$

where ${ES_h}^{ini}$ is initial energy of ESs. It could be computed as

$${ES_h}^{ini}(t) = (SoC_h^{ini} - SoC_h^{min}) \times Ess_h \tag{3.5}$$

where SoC_h^{ini} is representing the initial state of charge of ESs and SoC_h^{min} is representing the minimum state of charge of ESs.

${ES_h}^{in}$ is charging energy that will be computed with the charging power ${ES_h}^{in}$ and charging efficiency η_c of ESs and ${ES_h}^{out}$ is discharging energy that will be computed with the discharge power ${ES_h}^{out}$ and discharging efficiency η_d of ESs. These are calculated from time 0 to time t as

$${ES_h}^{in}(t) = \eta_c \cdot \int_0^t {PS_h}^{in}(t)dt \tag{3.6}$$

$${ES_h}^{out}(t) = \eta_d \cdot \int_0^t {PS_h}^{out}(t)dt \tag{3.7}$$

The state of charging SoC of ESs can be computed as

$$SoC_h(t) = SoC_h^{ini} + \frac{{ES_h}^{in}(t)}{Ess(h)} - \frac{E_{ES_h}^{out}(t)}{Ess(h)} \tag{3.8}$$

The SoC of the ESSs must remain within the specified operating ranges to prevent overcharging and over discharging. We denote the minimum state of charge as $\mathrm{SoC}^{\mathrm{min}}$ and the maximum state of charge as $\mathrm{SoC}^{\mathrm{max}}$,

$$SoC_h^{min} \leq SoC_h(t) \leq SoC_h^{max} \tag{3.9}$$

The charging power $P_{ES_h}^{in}$ to the ESs and discharging power $\mathcal{P}_{ES_h}^{out}$ from ESs should be under the bound of the maximum and minimum limitation as,

$$\mathcal{P}_{ES_h}^{in\ min} \leq \mathcal{P}_{ES_h}^{in}(t) \leq \mathcal{P}_{ES_h}^{in\ max} \tag{3.10}$$

$$\mathcal{P}_{ES_h}^{out\ min} \leq \mathcal{P}_{ES_h}^{out}(t) \leq \mathcal{P}_{ES_h}^{out\ max} \tag{3.11}$$

For SOC balancing In MG environment consisting of number of ESs. compute the deviation of each ESS unit's SoC from the average SoC

$$\Delta SoC_h = SoC_h - \frac{\sum_{h=1}^{H} SoC_h}{H} \tag{3.12}$$

Power balance $\mathcal{P}^{bal}_{ES_h}$ for each ESS unit based on its SoC deviation can be computed,

$$P^{bal}_h = \frac{\Delta SoC_h \times Ess(h)}{t} \tag{3.13}$$

Total power deficit $\mathcal{P}^{def}_{ES_h}$ across all ESS units can be computed,

$$P^{def}_h = P^{out}_h - \sum_{h=1}^{H} P^{bal}_h \tag{3.14}$$

Distribute the deficit or excess power equally across all ESS units,

$$P^{ex}_h = \frac{P^{def}_h}{H} \tag{3.15}$$

Power Assignment ratio PAR_h for each ESS unit can be computed,

$$PAR_h = \frac{P^{bal}_h + P^{ex}_h}{P^{out}_h} \tag{3.16}$$

3.4.2 Software Architecture for DC MG

In a MG environment, a controller engages in message exchange with all PGs and HADs. The controller may calculate the overall energy supply from power generators and the total energy requests from PLs after receiving these communications. Figure 3.4 shows the state change of the control scheme.

In a DC microgrid (MG) environment, the software architecture plays a pivotal role in enabling intelligent control, efficient communication, and real-time decision-making across distributed components. The controller serves as the central decision-making entity and interacts with all major units, including power generators (PGs), power storage systems (PSs), and home appliance devices (HADs) such as DC loads. The architecture is designed around a message-driven communication protocol, where each unit periodically reports its operational state including energy availability, demand, and system status to the controller.

Once the controller receives the updated data from all PGs and HADs, it computes the aggregate supply capability and total demand requirements across the microgrid. Based on this computation, the controller executes a power allocation algorithm such as the proposed SoC-based Power Assignment Algorithm to optimize energy usage while considering storage SoC levels, device priorities, and physical constraints. This software layer ensures that energy is allocated dynamically and efficiently, adapting to fluctuations in solar PV generation, battery capacity, and user load behavior.

Figure 3.4 illustrates the state-change process within the control architecture. It shows the feedback loop between sensing modules, decision-making logic, and actuation components. The sensing modules collect power and SoC data from PV inverters, batteries, and smart appliances. This data is processed and analyzed in real-time by the controller software, which determines which devices to turn on or off, how much energy to allocate, and whether energy should be stored or consumed. The control decisions are then transmitted to the respective HADs or storage units through digital signals, often via GPIO, MODBUS, or MQTT-based protocols. The modular software ar-

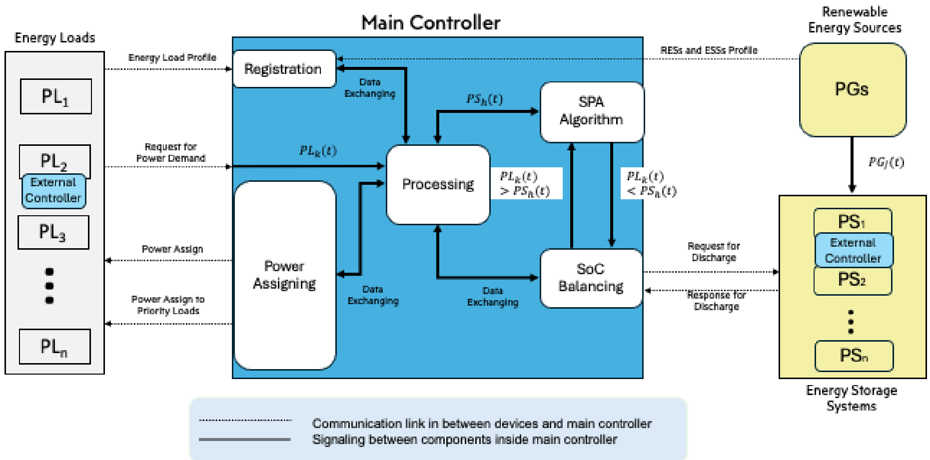

Figure 3.14: Software architecture for the controller of DC based MG

chitecture also supports expandability. New devices or sensors can be added to the MG without disrupting the core control logic, provided they adhere to the communication protocol. This flexibility is critical in real-world deployments where the energy infrastructure may scale over time. Furthermore, the control system ensures fault tolerance by regularly validating the status of each component and responding accordingly if a unit fails or disconnects.

In summary, the software architecture for the DC MG is designed to maintain a balance between supply and demand while ensuring reliability, scalability, and energy efficiency. It acts as the digital backbone of the microgrid, bridging hardware-level sensing and actuation with high-level energy management intelligence.

3.4.3 Logical Connection

The diagram illustrates the logical structure of power flow within the proposed DC MG, highlighting the bidirectional and adaptive energy exchange between the distributed generation units, energy storage systems, and loads. The key entities involved include PV, ESS, and both smart and traditional loads such as the Airwave (AR), Glacier (GL), Electric Kettle (EK), and Rice Cooker (RC). At the core of the architecture lies a central DC bus

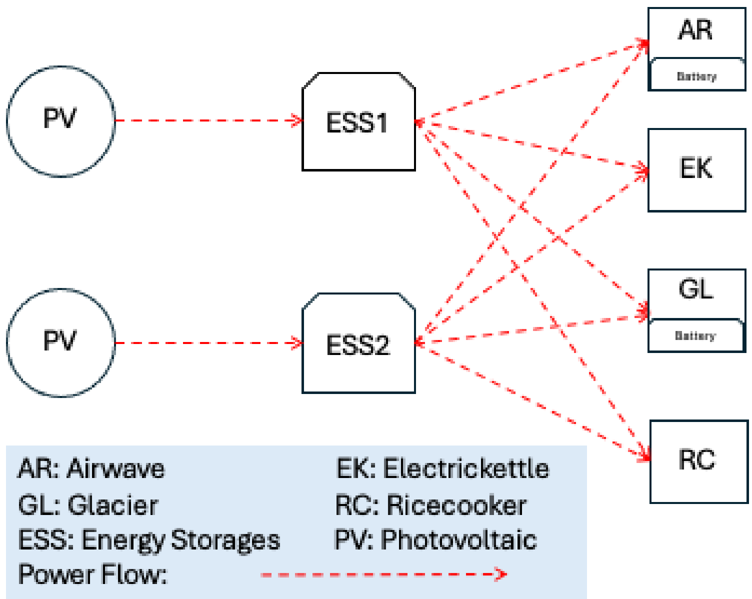

Figure 3.15: Logical power connection of DC based MG

node, which serves as the main conduit for energy distribution. The PV sources inject renewable energy directly into both ESS separately sunlight hours, while ESS units connected to the bus can flow power towards loads, depending on the real-time energy demand and supply balance.

The power flow direction indicate dynamic power flow paths governed by a real-time control algorithm. These paths reflect the system's intelligent dispatching strategy, which prioritizes energy routing based on QoES principles. For example, EK and RC are treated as critical loads, demanding immediate and uninterrupted power when in use, whereas AR and GL are non-critical loads that contain internal batteries and can defer operation under energy deficit conditions.

Furthermore, the interconnection between ESS and all load types emphasizes a multi-source support framework, where energy for any given load can originate from one or more ESS units. This redundancy enhances system flexibility and reliability, particularly in off-grid or variable-generation scenarios.

Overall, the diagram presents a modular and scalable power flow structure, where real-time decisions are made based on system states such as SoC, load priority, and generation availability. This logical topology underpins the system's ability to ensure load continuity, optimize resource utilization, and maintain DC bus stability under diverse operating conditions.

3.4.4 Proposed SoC based Power Assignment Algorithm

In DC-based MGs with multiple energy storage systems, maintaining power reliability and balancing supply-demand dynamics in real time is a complex task. This complexity arises particularly in isolated or renewable-driven environments where energy availability is uncertain and loads have varying priorities. To address this challenge, a SoC-based Power Assignment (SPA) algorithm is developed in this study to intelligently assign available power to connected loads based on both the priority level of each load and the available energy reserves in the ESS units. The proposed SPA algorithm dynamically manages energy allocation by interfacing multiple power loads (PLs), power sources (PSs), and PV units through a centralized decision-making framework. At each time step t, the system collects the following real-time data:

- State of charge (SoC) of each energy storage system (ESS_h).
- Output power availability from each ESS.
- Operational status and current power consumption $PL_k(t)$ of each load .

Using this data, the algorithm computes two critical energy metrics:

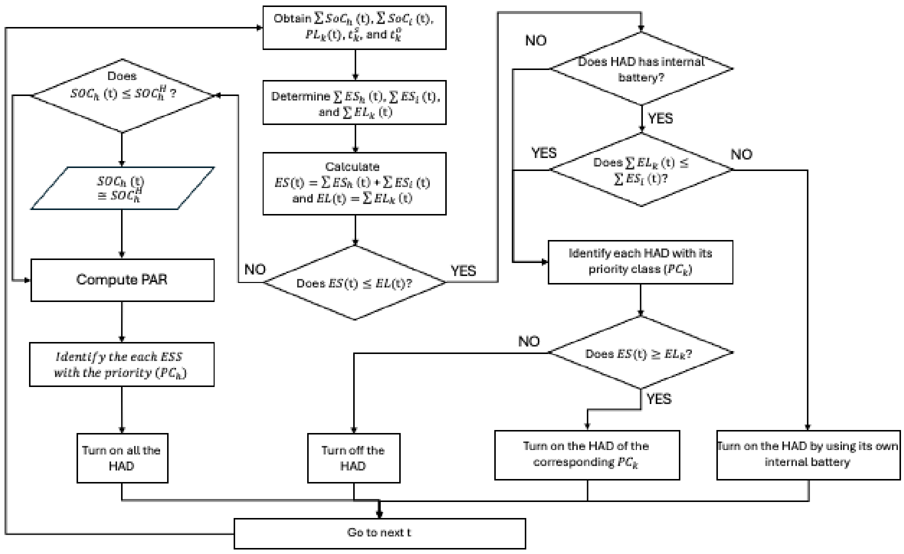

Figure 3.16: Flowchart of the SoC based Power Assignment Algorithm

- Available energy from each ESS, denoted as $E_{S_h}(t)$.
- Energy demand from each load, denoted as $E_{L_k}(t)$.

The algorithm first evaluates the total system demand against the aggregated supply from all PSs:

$$\sum_{k=1}^{N} E_{L_k}(t) \quad vs. \quad \sum_{h=1}^{M} E_{S_h}(t) \tag{3.17}$$

If the total energy demand is less than or equal to the available energy supply, the system enables all home appliances devices (HADs), including both critical and non-critical loads.

However, if the supply is insufficient to meet the demand, the system invokes the load prioritization policy defined in the QoES framework. This ensures that critical, non-buffered loads receive energy allocation first, while non-critical or battery-buffered loads are deferred.

Energy assignment to each load is governed by a weighted prioritization scheme based on the SoC of each ESS. ESSs with higher SoC values are prioritized for discharging, thus enabling load sharing in a manner that promotes long-term SoC balancing across all storage units. Mathematically, for two ESS units h_1 and h_2, the condition for preferential discharge is:

$$If SoC_{h_1} > SoC_{h_2} \Rightarrow assignpowerfromESS_{h_1} \tag{3.18}$$

In addition to optimizing energy usage, the SPA algorithm enforces safety constraints to prevent over-discharge or overcharge of any ESS. These include threshold cutoffs and operational SoC bands (e.g., $SoC_{\min} = 20\%$, $SoC_{\max} = 95\%$), ensuring the longevity and protection of storage systems.

Through this dynamic balancing strategy, the SPA algorithm achieves three primary goals:

1. Real-time, load-aware power allocation.
2. SoC equalization across multiple ESSs.
3. Preservation of critical services during supply shortages.

The SPA algorithm operates as a centralized control mechanism hosted on the main controller, which continuously receives SoC data from ESS1 and ESS2 and monitors the operational state of all connected loads. The primary objective of the algorithm is to optimize power allocation in such bases of QoES that:

- High-priority, non-buffered loads such as the electric kettle (EK) and rice cooker (RC) are always served first, provided that at least one ESS has SoC greater than 22%.
- Lower-priority buffered devices like the glacier (GL) and airwave (AR), which include internal batteries, are only powered when SoC levels are stable and higher-priority loads are inactive.

The control flow begins with the evaluation of SoC thresholds. If GL or AR drops below 50% and the condition $SoC_{ESS1} > 22\%$ or $SoC_{ESS2} > 22\%$ is met, the system initiates a charging request. Once the respective device reaches its upper SoC threshold (99% for GL and 95% for AR), the system terminates the charging process to prevent overcharging and conserve energy.

The algorithm also implements runtime scheduling to support cyclical operation of certain loads. For instance, GL is activated in cooling mode every hour provided its SoC is above 60%. Similarly, AR operates under a dual-mode configuration (cooling and fan modes), where mode switching is handled based on real-time power consumption and elapsed time.

In case of critical SoC drops (e.g., GL ¡ 40% or AR ¡ 20.1%), an emergency logic is triggered to shut off all non-critical and even some critical loads like EK and RC, thereby prioritizing backup charging to maintain QoES.

To summarize, the SPA algorithm integrates priority queues, threshold-based switching, runtime logic, and conditional overrides to ensure:

1. Efficient load prioritization.
2. Balanced discharge of ESS units.
3. Protection of device life cycles.
4. Preservation of critical operations under energy constraints.

The control decisions are implemented using Python scripts deployed on a Raspberry Pi controller, which interfaces with other devices via MQTT and HTTP protocols. Through this implementation, the algorithm supports a modular and scalable control structure that can adapt to varying MG configurations and load conditions.

Table 3.12: Notation Description

Symbol	**Description**
t	Every time step
t_k^s	Starting time
t_k^o	Operating time
$PL_k(t)$	Total power demand at time t
$\sum SoC_h(t)$	State of charge of all ESS at time t
$\sum SoC_i(t)$	Initial state of charge of all ESS at time t
$ES(t)$	Total ESS energy at time t
$\sum ES_h(t)$	Energy of the h-th ESS at time t
PC_k	Priority class of load k
PC_h	Priority class of ESS h
PAR	Power Assignment Ratio
HAD	Home Appliance Devices

3.5 Quality of Energy Services

3.5.1 QoES for Power flow control

The Quality of Energy Services (QoES) framework in this study is designed to prioritize energy allocation to different loads based on their criticality, operational characteristics, and internal battery capabilities. In a resource-constrained DC MG where energy availability fluctuates due to solar dependence, QoES serves as the guiding principle to maintain essential services while optimizing system reliability and energy efficiency.

The proposed control strategy classifies loads into critical and non-critical groups, taking into account their battery status and usage priority. The classification is as follows:

- **EK**: Electric Kettle – Critical load, high power demand, without internal battery.
- **RC**: Rice Cooker – Critical load, high power demand, without internal battery.
- **AR**: Airwave – Non-critical load, includes internal battery.
- **GL**: Glacier – Non-critical load, includes internal battery.

- **Load Prioritization Strategy:** The control logic ensures that in conditions of limited power availability, the system gives highest priority to EK and RC. Non-critical loads such as AR and GL are prevented from drawing power from the ESSs if critical loads are active and battery reserves are limited. EK is given slightly higher priority than RC when both are scheduled simultaneously.
- **Conditional Charging Activation:** To preserve energy, GL and AR are charged only when their SoC levels fall below 50% and either ESS1 or ESS2 has sufficient charge (greater than 22%). The control logic first checks whether the devices are not already charging, and then issues the command to begin charging if conditions are met.
- **Automatic Disconnection Based on SoC Thresholds:** Once GL and AR reach their desired SoC levels (99% and 95% respectively), they are disconnected automatically from the charging circuit. This prevents overcharging and ensures that energy is conserved for other essential operations.
- **Scheduled Operation Based on Timing Logic:** Time-based control is implemented for activating cooling cycles of GL and AR. For example, GL is scheduled to enter cooling mode every hour if SoC exceeds 60%, and similarly, AR can initiate cooling or fan mode based on power meter readings and elapsed time conditions.
- **Emergency Power Cutoff:** When SoC of GL or AR drops below 20.1%, or if GL's SoC falls below 40%, all loads (including EK and RC) are turned off to allow full priority to the low SoC device. This safeguard ensures uninterrupted operation of refrigeration or air conditioning in critical scenarios.
- **Control Logic Implementation:** All decisions are enforced through real-time Python scripts executed on a Raspberry Pi, interfaced with other components via MQTT and HTTP APIs. The logic responds to live sensor

feedback and elapsed time parameters to adaptively manage the MG's load behavior.

This hierarchical and adaptive QoES logic enables the system to maintain operational stability even under energy deficits, while upholding the service quality of critical appliances and maximizing system responsiveness.

3.5.2 QoES for Communication Protocol

The QoES model is not only applied to energy flow but is also integrated into the system's communication architecture to ensure that data packets and control messages are transmitted and executed based on their operational criticality. In such time-sensitive and energy-optimized systems, communication reliability and order-of-execution play an indispensable role in system performance. The QoES model extends beyond power flow control and is rigorously applied to the communication layer of the DC MG. Let us define a communication system with message set $\mathcal{M} = m_1, m_2, ..., m_n$ where each message m_i is assigned a weight $w_i \in Z^+$ representing its operational priority. The complete set of messages $\mathcal{M}$ includes control signals, telemetry updates, and system status packets. A priority queue $\mathcal{Q}$ orders messages such that those with higher weights (e.g., emergency shutdowns or mode switching) are serviced before routine updates (e.g., power logging or periodic sensor reads).

This prioritization ensures real-time responsiveness to critical events and is foundational to maintaining quality of service across the cyber-physical system. Each message m_i is further time-stamped t_i and acknowledged a_i to enable robust message tracking and loss prevention mechanisms.

- **Priority Queue Implementation:** A priority queue $\mathcal{Q}$ is defined for message dispatching, where each message m_i is associated with a weight $w_i \in Z^+$ based on its type. High-priority messages such as ON/OFF commands and mode switches are assigned larger weights (lower queue rank), ensuring they are dequeued and transmitted before lower-priority messages like sensor data logging. Mathematically, the dispatch rule follows:

$$Order(m_i, m_j) = \{ m_{\,i}, if w_i > w_j \ m_j, otherwise \tag{3.19}$$

- **Device Status Update Strategy:** Periodic telemetry such as SoC, current, voltage, and temperature is transmitted using a strategy that guarantees at-least-once delivery semantics. The use of MQTT in QoS-1 mode ensures messages are received at least once, even if duplicates occasionally occur a tolerable event in systems with periodic sampling intervals.
- **Critical Command Assurance:** For one-time critical operations (e.g., switching a load), an exactly-once execution mechanism is implemented

using idempotent command signatures and acknowledgement tokens. This prevents re-execution and ensures command atomicity even in the presence of retry logic.

- **Exponential Backoff Retries:** To manage packet loss and reduce network congestion, failed HTTP requests are retried using exponential backoff. Let Δt_k be the retry interval after k failures, then:

$$\Delta t_k = \Delta t_0 \times 2^k \tag{3.20}$$

This ensures lower network stress under repeated failure conditions while maintaining delivery integrity.

This layered and quantitative communication protocol supports timely, efficient, and prioritized information flow in the MG, thereby reinforcing the integrity of the QoES framework and guaranteeing system responsiveness to both planned schedules and unexpected dynamic changes.

3.6 Simulation Environment

To validate the functionality and effectiveness of the proposed SoC-Based Power Assignment (SPA) algorithm prior to physical implementation, a comprehensive simulation environment was developed using Python. This simulated testbed enabled iterative experimentation under controlled and repeatable conditions, offering valuable insights into power flow control strategies, load prioritization behavior, and SoC balancing mechanisms in a DC microgrid.

The simulation integrates realistic energy consumption profiles and generation data collected from high-availability devices (HADs), including critical and non-critical loads such as electric kettles (EK), rice cookers (RC), Airwave (AR), and Glacier (GL). Additionally, solar generation patterns from PV modules were modeled based on real-world irradiance profiles to simulate intermittent energy supply conditions. The state of charge (SoC) for both energy storage systems (ESS1 and ESS2) was dynamically updated at each timestep based on charging/discharging currents, load demands, and PV input availability.

The core objective of the simulation is to evaluate how the SPA algorithm manages power dispatch and SoC regulation across multiple ESS units while satisfying varying load priorities defined in the QoES framework. Each load is assigned a priority index, and switching logic is applied based on available energy, SoC safety margins, and runtime conditions. The SPA algorithm's decision engine uses live SoC readings and estimated energy demand from

Table 3.13: Simulation Parameters

Parameter (Description)	**Value**
Time (Simulation interval)	0–23 hours
ESS Capacity (per unit)	3600 Wh
η_d (Discharging efficiency)	92%
SoC_{min} (Minimum SoC threshold)	20%
$SoC_{ESS1}(0)$ (Initial SoC of ESS1)	85%
$SoC_{ESS2}(0)$ (Initial SoC of ESS2)	95%
Glacier Rating (Charging power)	120 W
Glacier Battery Capacity	298 Wh
$SoC_{GL}(0)$ (Initial SoC of Glacier)	95%
Airwave Rating (Operating power)	295 W
Airwave Battery Capacity	1195 Wh
$SoC_{AR}(0)$ (Initial SoC of Airwave)	75%
Electric Kettle Rating	96 W
Rice Cooker Rating	96 W

each load $PL_k(t)$ to determine the optimal power source assignment from PS_h.

As shown in Slide 20, the simulation results illustrate the sequential and adaptive power allocation to different loads. The figure demonstrates how Glacier and Airwave are activated only when SoC levels permit, while EK and RC are prioritized during power-constrained intervals. The load switching pattern clearly reflects the influence of SoC thresholds and time-based logic implemented in the algorithm.

Moreover, the simulation identifies potential pitfalls in parallel ESS discharging, confirming earlier experimental observations. It reveals the need for a hierarchical discharge mechanism to prevent asynchronous switching due to internal BMS conflicts. These findings informed hardware-level decisions and safety logic later used in experimental testing.

Simulation parameters, including initial SoC, PV power input, load profiles, and switching intervals, are tabulated in Table 3.13 for reproducibility. The simulation thus serves as a foundational layer for system validation, enabling risk mitigation and performance assurance prior to real-world deployment.

3.6.1 Results and Discussion

This subsection presents a comparative analysis of the energy profile simulation results for the proposed DC microgrid architecture, specifically contrasting the performance with and without the implementation of the SPA algorithm. The aim is to evaluate the impact of the SPA algorithm on energy distribution efficiency and demand satisfaction across all connected loads.

Fig. 3.17 illustrates the energy supplied from ESS1, ESS2, the internal batteries of Glacier and Airwave, as well as the photovoltaic (PV) system, without applying the SPA algorithm. The energy contribution appears irregular and unbalanced, often leading to suboptimal utilization of available sources and over-reliance on a single ESS unit in certain periods.

In contrast, Fig. 3.18 shows the energy supply profile when the SPA algorithm is activated. The power assignment becomes more balanced between ESS1 and ESS2, and the internal batteries of Glacier and Airwave are utilized more intelligently. The algorithm improves overall energy sharing and reduces energy stress on individual storage units.

Further, Fig. 3.19 and 3.20 compare the energy demand satisfaction levels for individual priority loads namely Glacier, Airwave, Electric Kettle (EK), and Rice Cooker (RC). In the absence of the SPA algorithm, as shown in Figure 3.19, critical loads frequently remain underserved due to inefficient energy allocation.

On the other hand, Fig. 3.20 demonstrates that with the SPA algorithm, the energy demand of both critical EK and RC and non-critical Glacier and Airwave loads is satisfied more consistently. This is due to the algorithm's priority-aware scheduling and SoC-based power distribution logic, which ensures that available energy is allocated in accordance with load criticality and battery constraints.

Table 3.14: Comparison of Energy Parameters With and Without SPA

Parameters	**With SPA**	**Without SPA**
PV Energy	5490 Wh	5490 Wh
ESS Input	5050.8 Wh	5050.8 Wh
ESS Output	5946.89 Wh	5664 Wh
Total Loss	915.026 Wh	931.7217 Wh

This section evaluates the effectiveness of the proposed SPA algorithm in terms of energy loss minimization and SoC balancing between energy storage units.

Figure 3.21 illustrates the energy loss profile of the DC microgrid system when operated without the SPA algorithm. The graph highlights significant

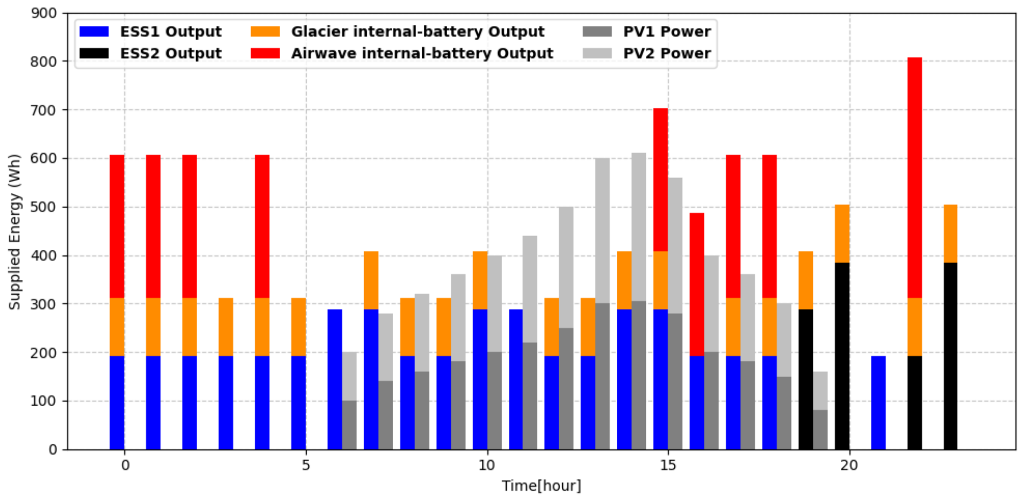

Figure 3.17: Supplied Energy Profile without SPA algorithm

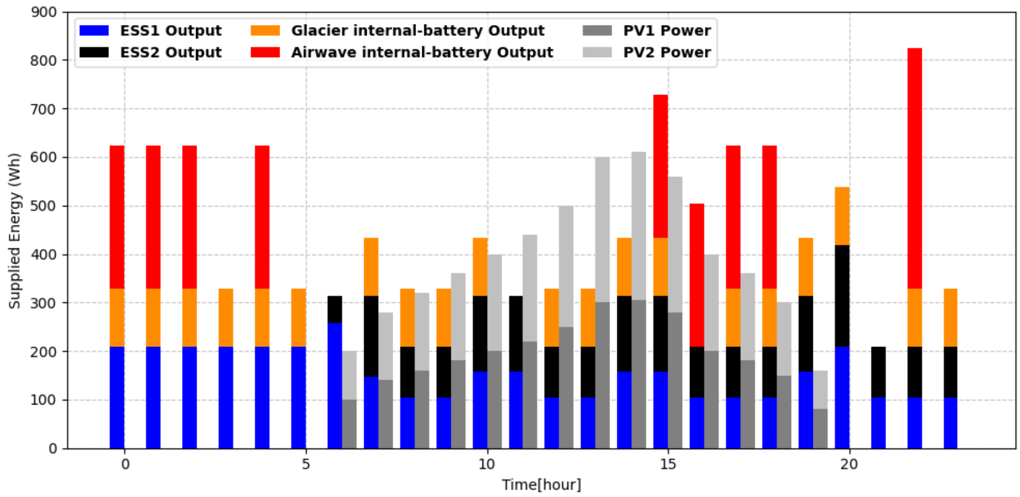

Figure 3.18: Supplied Energy Profile with SPA algorithm

energy wastage due to poor coordination between storage units and inconsistent load allocation. In contrast, Figure 3.22 presents the energy loss profile when the SPA algorithm is employed. It is evident that total system losses are substantially reduced, as energy is more efficiently distributed among the loads and internal storage devices.

Table 3.6.1 summarizes the total energy losses in both scenarios. The results show that the energy loss in the system without the SPA algorithm is markedly higher compared to the loss observed when the algorithm is imple-

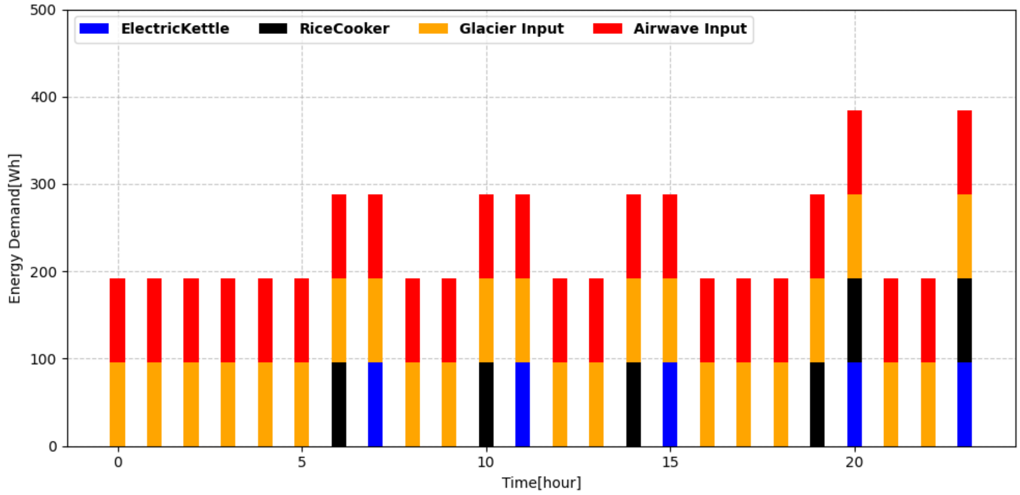

Figure 3.19: Demand Energy Profile without SPA algorithm

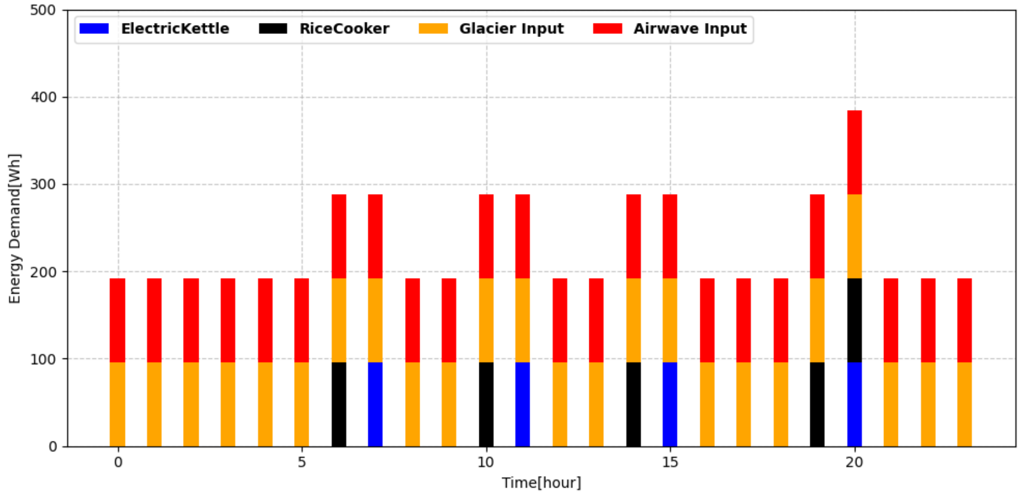

Figure 3.20: Demand Energy Profile with SPA algorithm

mented. This validates the effectiveness of the SPA approach in optimizing energy utilization and minimizing wastage.

In addition, Figure 3.23 compares the SoC trajectories of ESS1 and ESS2 in the absence of the SPA algorithm. It is observed that ESS1 undergoes rapid discharge, violating the lower SoC boundaries, while ESS2 remains underutilized and violating the upper bounds. This imbalance occurs due to the lack of a coordinated mechanism for joint discharging, leading to inefficient use of storage resources.

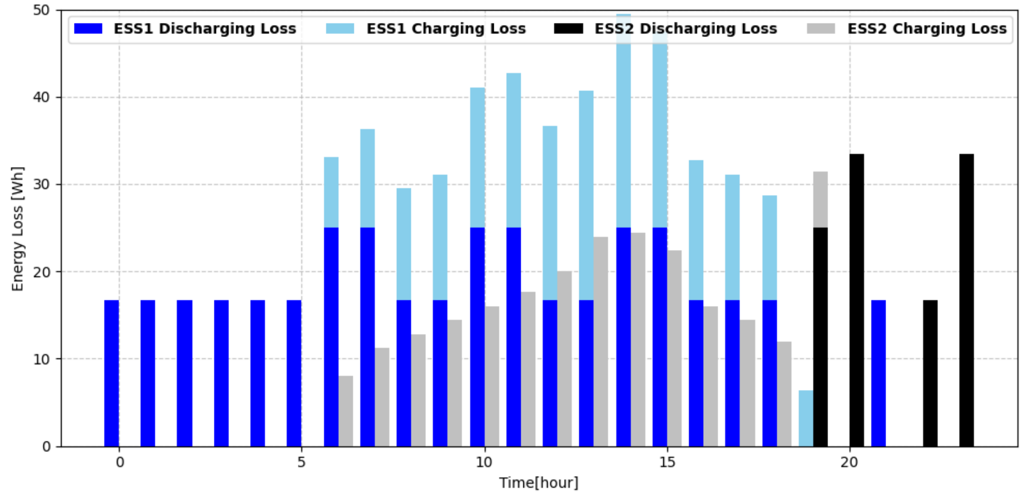

Figure 3.21: Energy Loss Profile without SPA algorithm

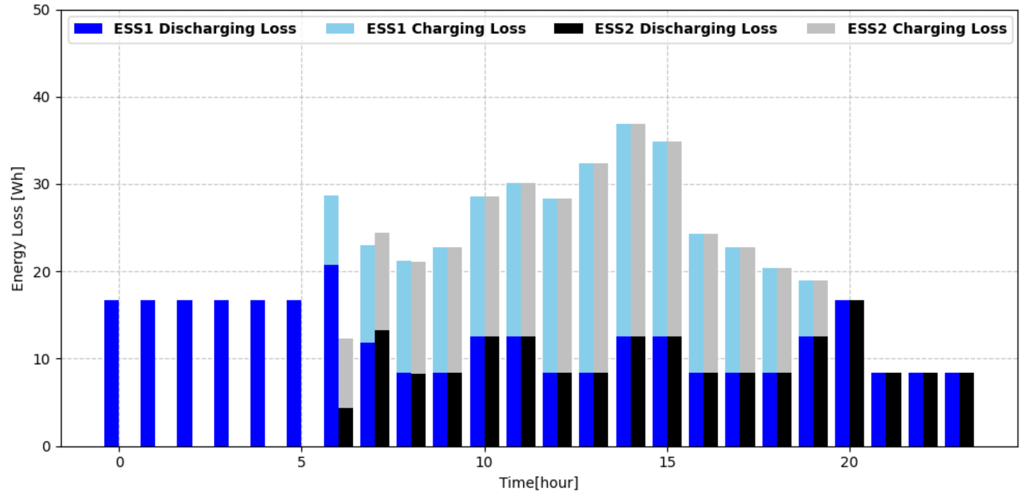

Figure 3.22: Energy Loss Profile with SPA algorithm

In contrast, Figure 3.24 displays the SoC profile when the SPA algorithm is applied. Here, both ESS units contribute to the load based on their respective SoC levels and the adaptive power assignment ratio. This coordinated SPA control achieves SoC balancing at hour 6 and preserves the health and reliability of both ESS units throughout the operational period.

Figure 3.25 illustrates the complete PV power profile used in the simulation and experimental setup. The graph presents real-time data including PV power output in watts, voltage, and current (amperes), capturing the

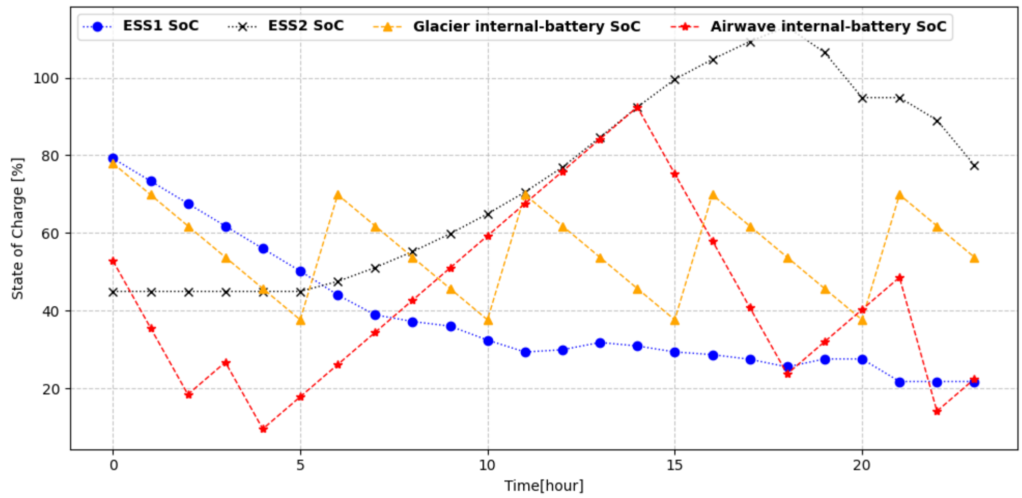

Figure 3.23: SoC Profile without SPA algorithm

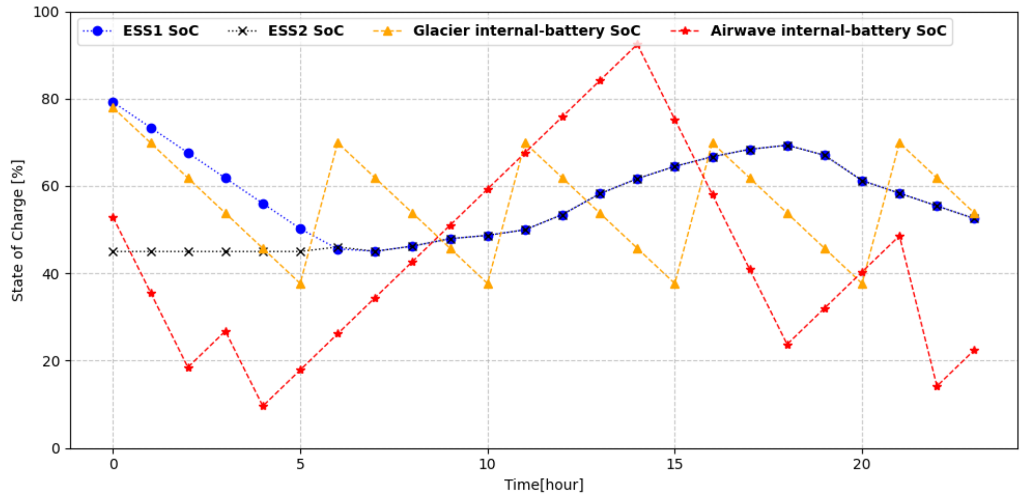

Figure 3.24: SoC Profile with SPA algorithm

dynamic behavior of solar generation throughout the day. This data forms the basis for evaluating the impact of solar intermittency on energy flow and load scheduling within the DC microgrid.

These findings confirm that the SPA algorithm not only enhances load satisfaction and reduces energy loss but also ensures fair utilization and extended life of the energy storage infrastructure.

Overall, these comparative results validate the effectiveness of the SPA algorithm in enhancing energy flow coordination, improving demand satisfaction, and achieving a more balanced operation of the DC microgrid.

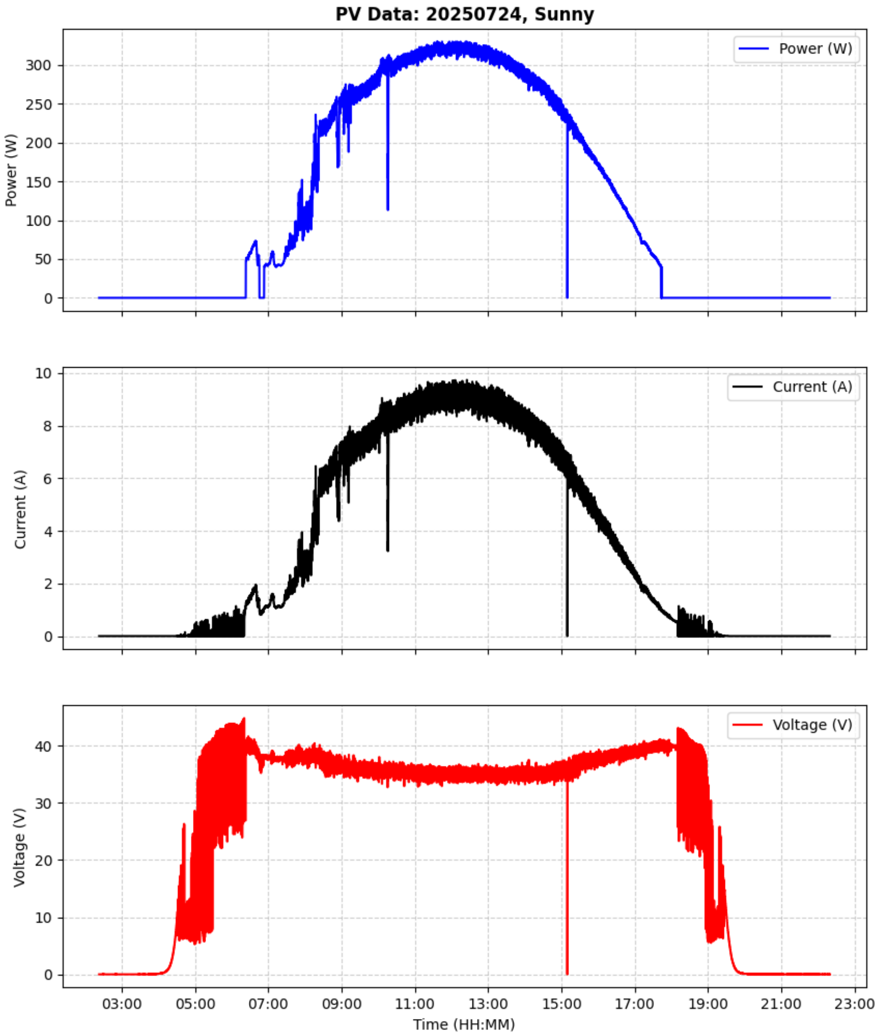

Figure 3.25: PV Profile for whole day

Chapter 4

Experimental Setup and Implementation

4.1 Overview of Experimental Environment

The experimental validation of the proposed DC MG architecture was carried out in a dedicated laboratory setup that closely emulates real-world energy management scenarios in isolated and semi-urban environments. The primary objective of this setup was to evaluate the performance of the proposed control algorithm under actual hardware constraints, variable generation profiles, and dynamic load conditions. The system was designed as a modular, low-voltage 12V DC MG incorporating RESs, smart controllable, uncontrollable loads, and ESSs.

The experimental platform Fig.4.1integrates two solar photovoltaic (PV) panels rated at 400 W each, configured to simulate distributed renewable generation within the MG. PV power can flow towards the both ESS unite. Both unit can charge form Both PV panels.

Two independent ESS units are connected to the DC bus via buck converters, controlled using DPS5020 modules. These ESS systems are monitored in real time for voltage, current, and SoC levels. Current and voltage sensing for each ESS and load component is handled by high-precision PZEM-017 sensors, which provide feedback to the central controller. The sensors communicate via Modbus RTU over RS-485, interfaced through USB-to-serial converters to the Raspberry Pi controllers.

The main controller is implemented using a Raspberry Pi 4B, running a custom Python-based control program. This central unit performs SoC-based power flow decisions, sends control commands to distributed devices, and receives continuous feedback via MQTT and HTTP protocols. Each controllable device (e.g., electric kettle, rice cooker, smart refrigerator) is equipped with either an internal or external microcontroller capable of receiving on/off commands via MQTT. The system prioritizes loads based on a predefined Quality of Energy Services (QoES) scheme. MOSFET-based

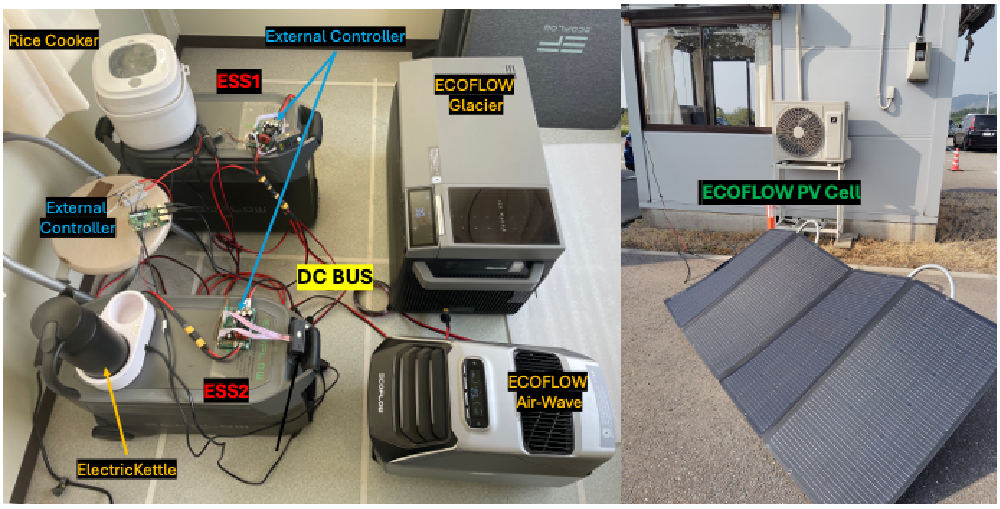

Figure 4.1: Experimental Setup

switching circuits, using D4148 diodes for protection and gate drivers for control, are employed to interface high-current DC loads with the MG. These switches are triggered by GPIO signals from the Raspberry Pi or external controllers, allowing for safe and automated load control. All switching circuits are mounted on custom-designed boards with overcurrent protection and fuse safety. These switching circuit is used with EK and RC.

Wi-Fi routers and local network infrastructure ensure stable communication among all MG nodes. The system also integrates cloud communication via HTTP to interface with the EcoFlow server for real-time status monitoring of GL and AR units. MQTT brokers run locally on the Raspberry Pi to coordinate low-latency, publish-subscribe interactions among devices.

The entire setup is housed within a modular and reconfigurable testbed that enables the addition or removal of components for future experimentation. Simulated solar profiles and variable load patterns are used to test the system under different operating conditions, enabling a comprehensive assessment of the control logic, hardware responsiveness, and communication reliability. This hands-on experimental environment bridges the gap between simulation-based validation and real-world deployment, offering a robust platform for reliable DC MG research.

4.2 Hardware Configuration

The experimental validation of the proposed DC MG architecture was carried out in a dedicated laboratory setup Fig.4.1 that closely emulates real-world energy management scenarios in isolated and semi-urban environments. The primary objective of this setup was to evaluate the performance of the proposed control algorithm under actual hardware constraints, variable generation profiles, and dynamic load conditions. The system was designed as a modular, Low voltage (LV) 12V DC MG incorporating distributed RES, smart loads, smart ESS and traditional loads.

4.2.1 Photovoltaic System Integration

The PV system comprises two 400W solar panels. In this system model, the PVs act as power generators (PGs) and supply energy to the DC microgrid. Each PV panel is connected separately to an ESS unit, enabling both ESSs to be charged independently. The charging process operates under predefined safety conditions to ensure stable and secure power flow.

4.2.2 Energy Storage Units (ESS1 and ESS2)

The DC MG includes two independent ESS units, each equipped with lithium-ion battery packs. These are smart devices integrated with Power Conversion Systems (PCS), Battery Management Systems (BMS), and Maximum Power Point Tracking (MPPT) circuits to manage charging and discharging operations. Each ESS contains internal sensors and meters for monitoring current, voltage, state of charge (SoC), input/output power, and temperature. The ESS units are connected to the DC bus and integrated with the EcoFlow server for communication and control. This setup enables independent operation of the ESS units, supporting controlled SoC balancing and facilitating the implementation and testing of power-sharing algorithms. Safety features, such as thermal cutoffs and current limiters, are also incorporated into each unit to ensure reliable operation.

4.2.3 Power Load Configuration

The load subsystem comprises multiple DC appliances, including an electric kettle, rice cooker, AirWave, and Glacier. All loads are connected to the

DC bus. Some of these smart loads, such as the AirWave and Glacier, have their own built-in batteries and are connected to the EcoFlow server for communication and control. In contrast, the rice cooker and electric kettle do not have built-in controllers. Therefore, an external controller was developed to manage and monitor these devices.

4.2.4 DC Bus and Interconnection Setup

The central 12V DC bus serves as the main backbone for energy exchange between all system components. A low-voltage DC distribution line is constructed using 12AWG cables and XT60 connectors to ensure safe and efficient power transfer across the DC MG.

4.2.5 Controllers and Sensors

The Raspberry Pi serves as the main controller and communication hub, running Python scripts to execute the control algorithm. All sensor data, including voltage and current from PZEM-017 modules, is collected via RS-485 serial interface. The system uses Modbus RTU protocol to interact with sensors and relays commands through MQTT and HTTP to end devices. Real-time SoC calculation is based on integrated current over time and voltage thresholds, allowing dynamic decision-making for power routing and load control

The entire setup is housed within a modular and reconfigurable testbench that enables the addition or removal of components for future experimentation. Simulated solar profiles and variable load patterns are used to test the system under different operating conditions, enabling a comprehensive assessment of the control logic, hardware responsiveness, and communication reliability. This hands-on experimental environment bridges the gap between simulation-based validation and real-world deployment, offering a robust platform for intelligent DC MG research.

4.2.6 External Controller for ESS

In this research, an external control system was developed for the ESS, as illustrated in Fig. 4.2. This system enables precise management of power flow between the ESS and the DC microgrid. The control architecture includes a Raspberry Pi that acts as a local control node, connected to a Buck Converter via a USB interface. The Buck Converter regulates the voltage level from the ESS before supplying it to the DC bus. Communication between the Raspberry Pi and a centralized Main Controller is established using the

MQTT protocol, which enables real-time messaging through a lightweight broker. The Main Controller, functioning as an MQTT client, publishes control commands and subscribes to system status updates from all Raspberry Pi nodes deployed in the system. This modular approach allows the external

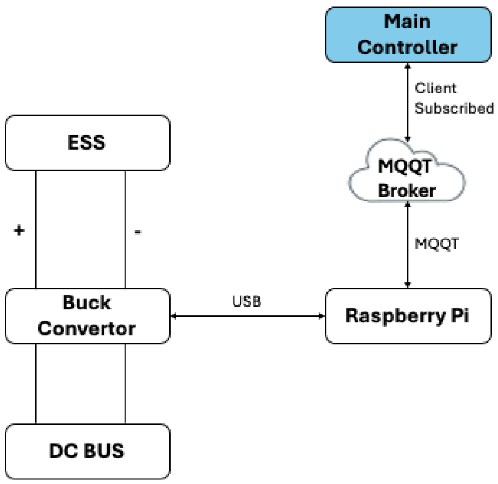

Figure 4.2: Configuration of External Controller for ESSs

controller to receive power-sharing commands, voltage references, or scheduling signals from the Main Controller, based on the system's current state, such as SoC levels or load demands. This structure improves the flexibility and responsiveness of the DC MG by allowing decentralized nodes to act autonomously while remaining coordinated. It also supports advanced features such as time-based scheduling, priority load handling, and SoC-based distribution logic all of which are implemented in Python scripts running on the Raspberry Pi.

4.2.7 External Controller For Loads

This research developed a dedicated External Controller for DC Loads, which facilitates remote monitoring and control of power consumption at the load level. As illustrated in Fig. 4.3, the architecture consists of a Raspberry Pi that serves as the local controller, interfacing with two critical components: the PZEM-017 energy monitoring sensor and the MOSFET D4148 module for switching control. The Raspberry Pi collects real-time current, voltage, and power data from the PZEM-017 via USB, allowing accurate tracking of energy usage for each connected DC load, such as air conditioning units, refrigeration, or cooking appliances.

For actuation, the Raspberry Pi uses its GPIO pins to control the gate of the MOSFET D4148, thereby enabling or disabling the power supply to each load. The switching logic is determined based on system-wide control policies communicated through MQTT messages. Like the ESS controller, the Raspberry Pi subscribes to control commands from the Main Controller, which coordinates the entire MG operation. This setup allows the system to selectively activate or deactivate specific loads based on criteria like SoC levels, priority class, or demand forecasts.

By decoupling the load control from the main system controller and enabling local intelligence at the Raspberry Pi node, this architecture increases the scalability and resilience of the microgrid. It supports the implementation of demand response strategies, user-defined schedules, and emergency cutoffs, all of which contribute to energy efficiency and service quality in the DC MG.

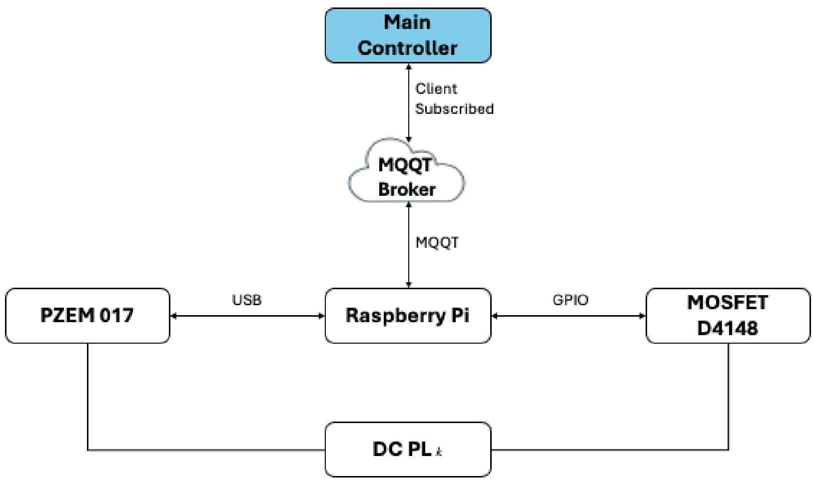

Figure 4.3: Configuration of External Controller for Loads

4.3 Experimental Procedure

This section outlines the experimental methodology employed to design, implement, and validate the proposed DC microgrid system. The objective of the experiment was to establish a functional DC bus infrastructure capable of managing diverse energy sources, storage units, and critical/non-critical loads under real-time control strategies.

The first phase of the experimental setup involved the construction of the physical DC bus. Due to the integration of smart and traditional devices, it was essential to ensure electrical compatibility and safety. EcoFlow devices utilize XT60 connectors for both input and output power interfaces. To accommodate the current levels required by these systems, 12 AWG cables were selected. These cables are capable of safely conducting currents up to 30 A, providing sufficient margin for both charging and discharging operations across various components. The XT60 connectors were securely crimped and soldered to the 12AWG cables to create a robust and efficient DC distribution backbone.

The second stage focused on establishing a communication and control framework among various smart and non-smart devices. For smart appliances such as the EcoFlow ESS units, Glacier (portable freezer), and Airwave (air conditioner), official developer API credentials were obtained from the respective manufacturers. These APIs allowed bidirectional communication via HTTP and MQTT protocols, enabling command-based control (e.g., ON/OFF, mode switching) and real-time telemetry acquisition (e.g., State-of-Charge (SoC), temperature, voltage, and current).

In contrast, traditional devices like the electric kettle and rice cooker lacked built-in communication interfaces. To monitor and control these devices, a hardware-based sensing and actuation solution was deployed. The PZEM-017 DC power meter was installed to measure voltage, current, and power consumption data for each device. For remote actuation, a power electronic switching mechanism using D4148 MOSFETs was implemented. These switches were controlled via a Raspberry Pi, allowing the system to turn devices ON or OFF based on pre-defined power flow logic and priority schedules.

Together, these configurations enabled a comprehensive experimental platform capable of demonstrating intelligent load prioritization, SoC-based power sharing, and real-time DC bus voltage regulation under practical operating conditions.

4.3.1 Problems and Challenges

During the implementation phase of the proposed SoC-Based Power Assignment (SPA) algorithm in the experimental DC microgrid (MG), several technical challenges were encountered. These challenges were primarily associated with the integration of heterogeneous devices, communication protocol design, and ensuring stable and coordinated power flow from multiple distributed energy sources. This section highlights two major issues encountered during the development and testing phases, along with the practical solutions applied.

1. Integration of Smart and Non-Smart Loads

One of the primary challenges was the heterogeneous nature of the load devices. The testbed included both smart and traditional (non-smart) appliances. While smart devices such as the Glacier and Airwave could be controlled directly via developer provided APIs over network protocols, the traditional devices namely the electric kettle (EK) and rice cooker (RC) lacked internal communication or control interfaces.

This presented two key problems:

- The inability to directly measure power consumption parameters such as voltage, current, and energy.
- The lack of built-in control mechanisms to allow remote switching or mode selection.

Solution: To overcome this challenge, an external control system was developed using a Raspberry Pi microcontroller, integrated with a PZEM-017 power monitoring module and D4148 MOSFET switches. This setup enabled both real-time monitoring and actuation of the non-smart PL devices. The Raspberry Pi facilitated MQTT and HTTP-based communication with the central controller, thereby allowing the SPA algorithm to uniformly manage all load types—smart and non-smart—under a unified control framework.

This solution provided:

- Accurate measurement of operational parameters for traditional devices.
- Safe and reliable remote switching using MOSFET relays.
- Seamless integration of legacy devices into the intelligent control system.

2. Uneven Power Sharing Between Dual ESS Units

The second major issue emerged in the context of supplying power from two independent ESS units (ESS1 and ESS2) to shared loads. In scenarios where only one ESS was active, the power flow was stable and well-regulated. However, when both ESS units attempted to supply power simultaneously, the system exhibited undesirable behavior due to internal control interference.

Observed Issues:

- The internal voltage regulation mechanisms of the ESS units were not synchronized.
- This led to asynchronous current flow patterns, resulting in power oscillations between the two units.
- The system alternated power supply back and forth, triggering false ON/OFF switching events in some loads.

Figure 4.4 demonstrates this phenomenon, where the power supply is seen fluctuating due to uneven control interaction between ESS1 and ESS2.

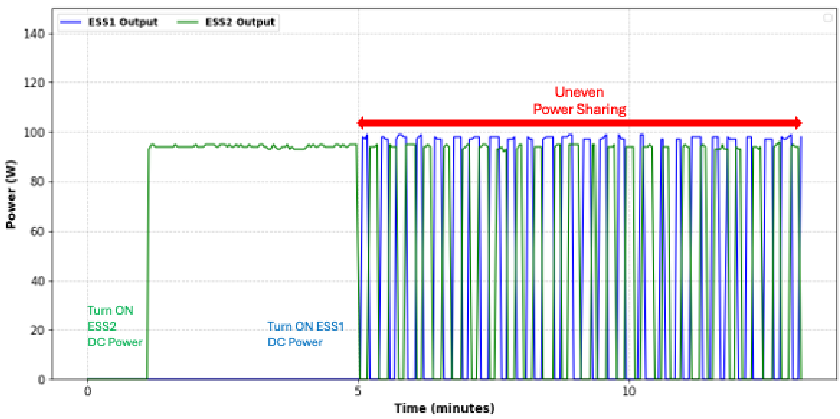

Figure 4.4: Power supply between ESS units uneven sharing

4.3.2 How to Power Sharing from multi ESS

The ESS units, being independently governed by internal BMS and power control logic, did not natively support cooperative power sharing. The lack of a synchronized droop or master-slave control mechanism led to poor load sharing dynamics when both ESSs were connected in parallel to the same DC bus.

Solution:

Design of an External Controller for ESS: One of the key technical contributions of this research is the development and deployment of a custom external control system for managing ESSs within the proposed DC microgrid framework. As illustrated in Fig. 4.2, this control solution enables intelligent and flexible regulation of power flow from ESS units to the DC bus, without relying solely on the internal logic of commercial storage devices.

The proposed external controller is built around a Raspberry Pi, which operates as a decentralized local control agent. It interfaces with a programmable Buck Converter via USB to modulate the voltage and current output of the ESS according to system requirements. Control signals and data are exchanged with a central Main Controller using the MQTT communication protocol, supporting lightweight, real-time messaging across the system network.

This modular architecture permits the Main Controller to issue control directives such as power sharing ratios, voltage references, or schedule based activations based on real-time system metrics like load demand and SoC values. The local Raspberry Pi nodes execute these commands autonomously, maintaining system coordination while enabling distributed intelligence.

This external controller framework significantly enhances the MGs adaptability, particularly in mixed-device environments where traditional appliances lack native communication interfaces. By decoupling power control from hardware specific internal logic, the system achieves both operational transparency and algorithmic flexibility contributing meaningfully to the body of research on experimental microgrid control.

SPA Algorithm: This research introduce external controller for ESS. To address this, the SPA algorithm was enhanced to incorporate a SoC-aware output assignment policy. Specifically, it allocates discharge responsibilities to the ESS unit with a higher SoC at any given time, while the other unit is held in reserve. By controlling discharge flow through the central controller rather than relying solely on internal BMS logic, coordinated and predictable power delivery was achieved. Additionally, internal switching thresholds were adjusted to reduce sensitivity to minor voltage variations, thereby eliminating unnecessary toggling behavior.

Impact of Resolution:

- The issue of fluctuating power flow was resolved, leading to stable multi-ESS operation.
- Load devices received uninterrupted and balanced power, improving overall system reliability.

- The algorithm maintained SoC balancing by alternating discharge assignments in a controlled manner.

These practical enhancements enabled the experimental DC MG to function reliably under mixed load conditions and multi-source supply configurations, validating the real-world feasibility of the proposed SPA framework.

4.3.3 Results and Discussions

This subsection presents the evaluation of the experimental performance of the ESSs in the DC MG, managed using the proposed State-of-Charge-based Power Assignment (SPA) algorithm. Figure 3.4 illustrates the energy profile of both ESS1 and ESS2 over a 24-hour period, highlighting their output power and the dynamic power assignment strategy employed by the Main Controller. The first subplot in Figure 3.4 shows the output power delivered by each ESS. Initially, up to approximately the 15th hour, ESS1—having a higher initial SoC—bears the majority of the load demand. This behavior aligns with the SPA algorithm's prioritization policy, which preferentially allocates power from the ESS with the higher SoC to ensure balanced discharging, protect lower SoC units, and minimize deep cycling stress. During this period, ESS2 remains in standby or contributes minimally, conserving its stored energy.

As time progresses and ESS1's SoC gradually declines, the SPA algorithm adaptively transitions to a shared power delivery mode. Around hour 15, both ESSs begin to contribute to load supply in a more balanced manner. This behavior reflects the algorithm's capability to detect SoC convergence and initiate cooperative power dispatching to avoid over-utilization of a single ESS. By hour 17 onward, the output power from both ESSs becomes synchronized, reflecting successful SoC balancing and effective load sharing—one of the primary goals of the SPA mechanism.

The system thereby addresses the critical issue of uneven power sharing, which was observed in earlier implementations without coordinated SoC-based logic. Previously, asynchronous discharge caused frequent fluctuations and unstable ON/OFF cycles in the ESSs due to internal control mismatches. These fluctuations not only impaired system reliability but also led to inefficiencies in energy utilization.

With the SPA algorithm, the Main Controller dynamically allocates power assignments to ESSs in accordance with their current SoC levels and real-time load demand, as influenced by the QoES hierarchy. This ensures:

Priority loads are always met, Internal batteries of non-critical loads are charged only under surplus conditions, Safety bounds of $\mathrm{SoC}_{\min}$ are respected, And energy delivery is smoothly distributed over available ESS resources. In conclusion, the experimental data validate that the SPA algorithm significantly enhances the resilience and efficiency of the DC microgrid by solving the inherent uneven power distribution challenge and achieving autonomous, balanced energy provisioning.

Airwave Performance Analysis:

The performance of the Airwave (AR), a non-critical yet essential cooling device with internal battery storage, is analyzed based on the results depicted in Figure 4.6. The experimental results are plotted across a 24-hour timescale and are divided into three main aspects: power demand, charging activity and SoC variation, and internal battery output. The top subplot of Fig. 4.6 illustrates the instantaneous power demand of the AR. The demand curve shows clearly defined ON cycles, typically peaking around 250–300 W. These activation periods correspond to scheduled cooling or air conditioning sessions based on both preset runtime intervals and the QoES policy. As AR is classified as a non-critical load with an internal battery, it is scheduled to operate only when sufficient energy is available from either the photovoltaic (PV) system or ESSs, and when higher-priority loads such as the Electric Kettle (EK) and Rice Cooker (RC) are not active.

The middle subplot presents the AR's internal battery charging events alongside the SoC level. The SPA algorithm actively monitors the SoC of AR and initiates charging when SoC falls below the defined threshold typically 50%. According to the control logic defined in the QoES framework, charging commands are issued only when at least one ESS maintains a SoC above 22%, ensuring that critical loads are not compromised. The results indicate that AR charging is opportunistic and coordinated charging starts during intervals of surplus energy and halts once the SoC exceeds 80–90%, avoiding overcharging and preserving ESS reserves.

The lower subplot shows the output power from AR's internal battery. These discharge patterns strongly correlate with the power demand peaks seen in the top subplot. The SPA algorithm leverages AR's internal storage to support load demand during periods of ESS unavailability or peak activity from higher-priority devices. By allowing AR to run on its internal battery, the system offloads stress from the DC bus and avoids unnecessary switching events that could compromise ESS health.

The SPA algorithm ensures that AR does not compete with EK and RC during power-constrained intervals. If both ESSs are low or if critical loads are ON, AR's operation is deferred. Additionally, based on SPA's adaptive control logic, AR may switch between cooling and fan modes depending on power availability and internal temperature settings, as seen in previous code implementations. This dynamic behavior improves energy efficiency while maintaining user comfort.

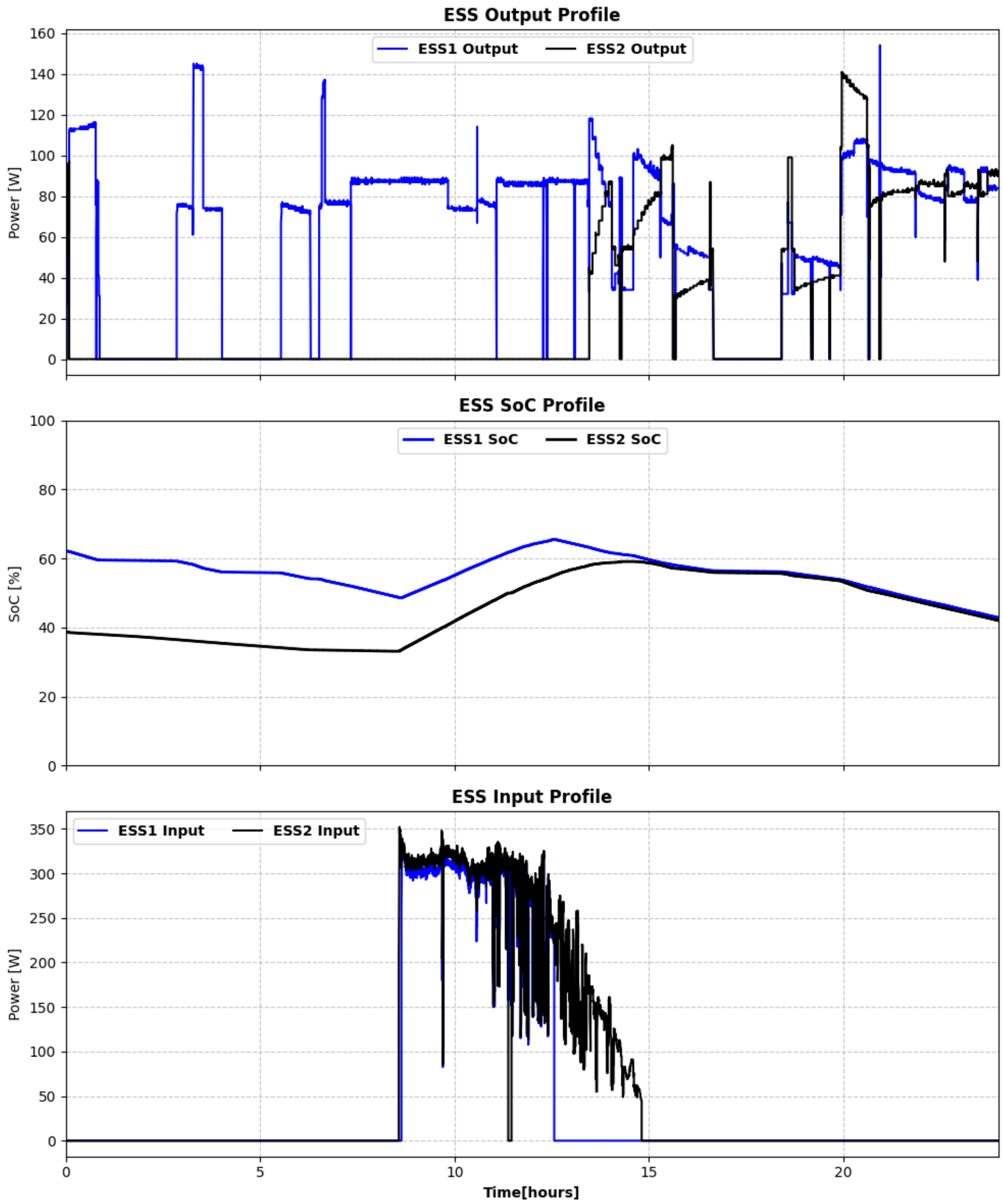

Figure 4.5: Energy Profile of ESS

Glacier Performance Analysis:

The performance of the Glacier device, a non-critical load with an internal battery, is analyzed to assess the effectiveness of the SPA algorithm and QoES prioritization strategies in real-time operation. Figure 4.7 presents

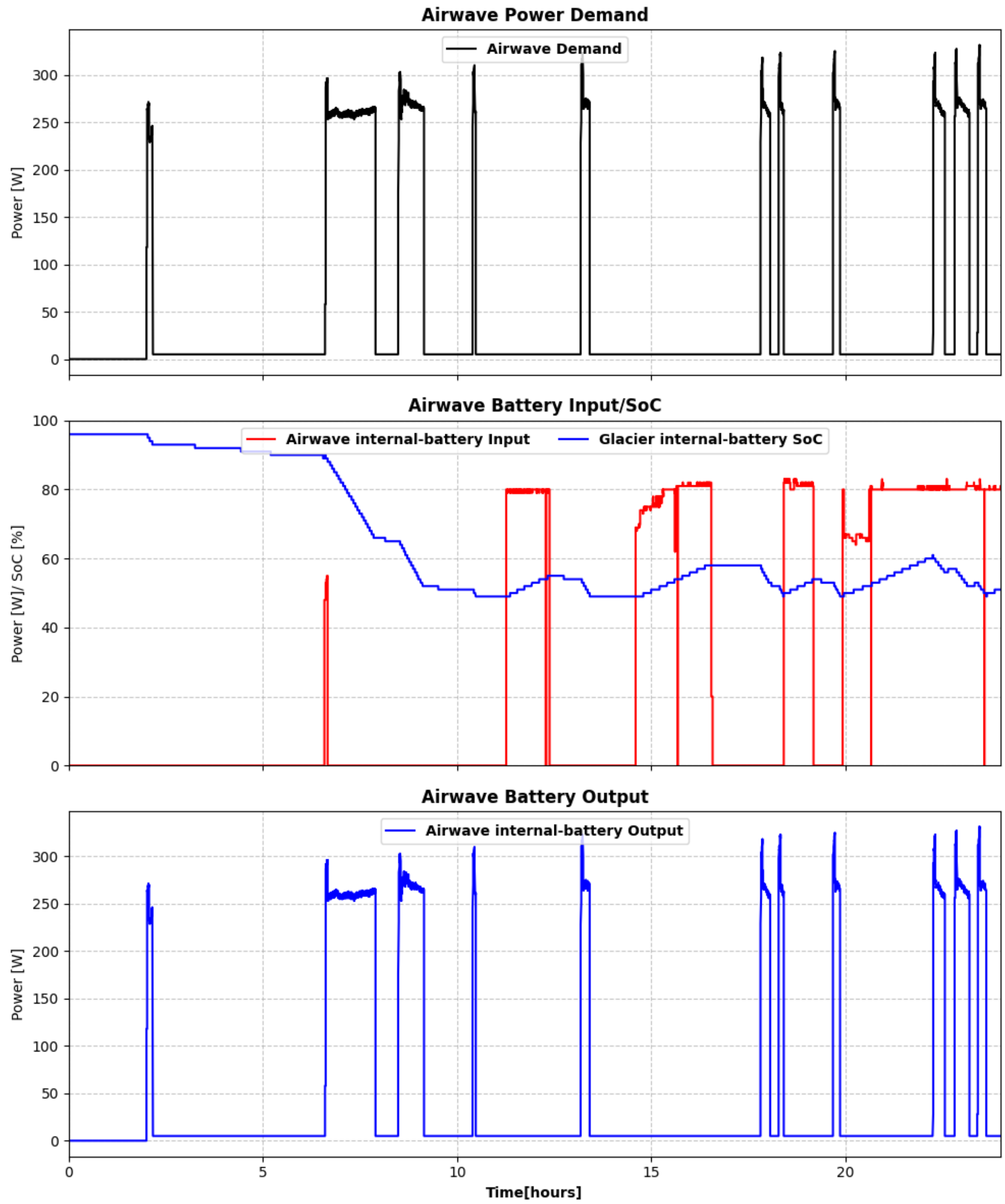

Figure 4.6: Energy Profile of Airwave

three critical subplots: Glacier's power demand profile, its internal battery SoC and input power, and finally, the battery output behavior over a 24-hour period. The first subplot illustrates the Glacier's power demand throughout the simulation period. The load exhibits a highly variable and intermittent demand pattern ranging between 0–80 W. These fluctuations are a direct result of the time-based and SoC-aware scheduling governed by the QoES strategy. Glacier, being a non-critical load, is only permitted to operate or be charged when system conditions are favorable—such as when critical devices like the Electric Kettle (EK) and Rice Cooker (RC) are inactive, and ESS SoC levels are above the minimum threshold 22%.

In the second subplot, the indicates the power input to Glacier's internal battery, while the second represents the SoC trajectory. Initially, Glacier begins with a high SoC close to 95%. As the system operates, the SoC gradually declines, reflecting energy consumption. Charging events are visible as sharp spikes in input power, which correspond to periods when ESS capacity exceeds demand from higher-priority loads. These charging cycles are selectively triggered by the SPA algorithm when Glacier's SoC drops below 50%, and sufficient ESS energy is available. The non-continuous nature of the charging profile indicates the successful enforcement of QoES load control policies, effectively avoiding unnecessary energy allocation to lower-priority devices.

Furthermore, when SoC dips below a critical threshold 20%, the algorithm enforces emergency cutoffs for other devices to preserve refrigeration stability, underscoring the adaptive QoES mechanism that elevates Glacier's priority during emergencies.

The third subplot shows the power output from Glacier's internal battery, confirming that the device actively supports its load through self-discharging when not powered by the grid. This design helps reduce dependency on external supply during peak hours or ESS constraints, contributing to load flexibility and system reliability.

Overall, Glacier's operation highlights how the SPA algorithm, combined with QoES-based load categorization, enables:

Intelligent scheduling of non-critical appliances, Protection of internal batteries through SoC threshold enforcement, Optimized charging from ESS under surplus conditions, and Autonomous operation based on real-time system status. The coordinated charging/discharging pattern confirms that the system efficiently leverages internal energy buffers in non-critical loads, thereby improving energy allocation, reliability, and load stability in the microgrid.

Electric Kettle and Rice Cooker Performance Analysis: Figure 4.8 presents the experimental power demand patterns of the Electric Kettle (EK) and Rice Cooker (RC). Both devices exhibit distinct high-power usage intervals corresponding to their scheduled operation windows within the SPA-controlled DC microgrid. The results show that EK and RC were powered during the early and mid-day hours when sufficient energy was available from the ESS units. Initially, EK operated more frequently, re-

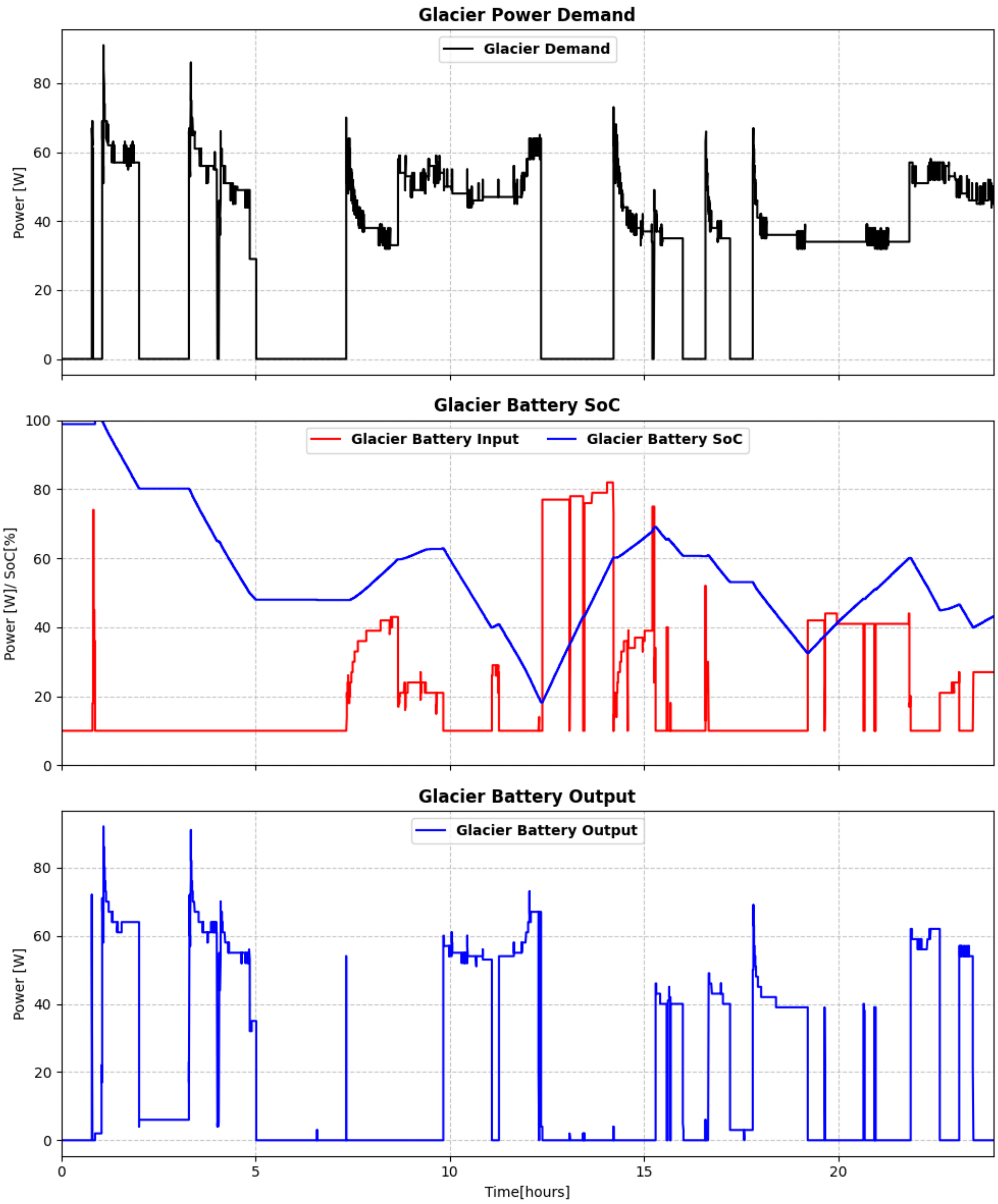

Figure 4.7: Energy Profile of Glacier

flecting its higher QoES priority over RC, especially during periods of constrained energy availability. As the system progressed and energy became more abundant—either from PV generation or SoC balancing between ESS1 and ESS2—RC activation followed to meet additional demand.

A clear pattern of non-overlapping and sequential activation is observed in several instances, confirming that the SPA algorithm actively prevented simultaneous operation of both loads to avoid overloading the system. Additionally, sharp rise and fall in the power traces indicate the effectiveness of real-time control logic using MOSFET-based hardware switching.

Throughout the experiment, the loads were selectively powered based on the availability of energy and SoC thresholds defined by the controller. In periods where Glacier or Airwave SoC fell below the cutoff threshold, EK and RC operations were temporarily suspended, highlighting the dynamic adaptability of the load prioritization framework.

These results confirm that the SPA algorithm successfully manages non-buffered loads in a real-world setup, maintaining reliable operation of critical appliances without compromising overall system stability or exhausting ESS capacity.

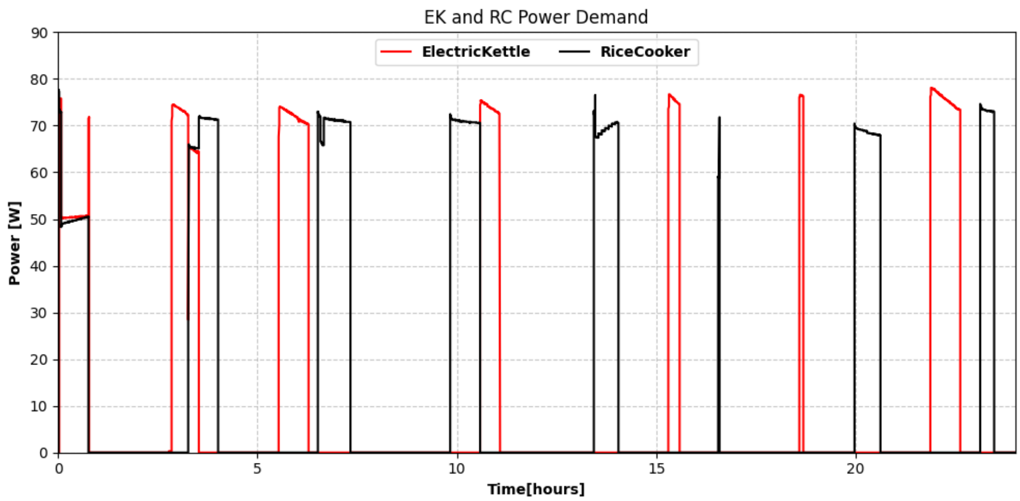

Figure 4.8: Energy Profile of ElectricKettle and RiceCooker

Voltage stability on DC Bus:

Fig 4.9 illustrates the voltage profile of the DC bus over the course of the whole day. The graph confirms that the voltage remained within a stable operating range, validating the effectiveness of the external controllers and the SPA algorithm in maintaining bus stability under dynamic load and generation conditions. Throughout the 24-hour period, despite fluctuations in power demand from EK, RC, Airwave, and Glacier, the voltage on the DC bus did not exhibit any significant deviation or instability. This reflects the system's ability to dynamically regulate power flow from the ESS units, guided by real-time SoC readings and QoES-based load prioritization. In tandem with the SPA algorithm, which optimizes energy distribution across all devices, the system ensures that the bus voltage remains within safe bounds even during peak demand or rapid switching events.

Overall, the results in Fig 4.9 demonstrate a key success of the proposed architecture, achieving high reliability and voltage stability in a decentralized DC microgrid environment through intelligent energy management and modular control design.

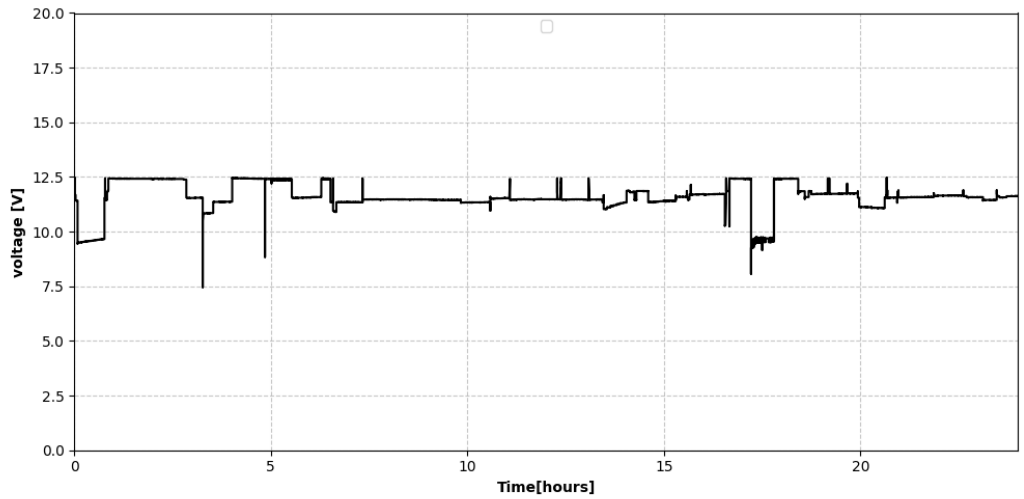

Figure 4.9: Voltage Stability on the DC bus

4.4 Summary

This chapter presented the complete experimental implementation of the proposed SPA-based DC microgrid system. The experimental environment was established using real hardware, including photovoltaic (PV) generation units, dual ESS1 and ESS2, and a variety of smart and traditional power loads such as Glacier, Airwave, electric kettle (EK), and rice cooker (RC). A modular architecture was designed to ensure flexible and scalable deployment of the testbed components. The hardware configuration outlined the integration of key components, emphasizing the use of Raspberry Pi modules as control interfaces, MOSFET switches for traditional load switching, and sensors such as the PZEM-017 for power monitoring. The DC bus design focused on safe, efficient interconnection, employing XT60 connectors and 12 AWG cabling to manage power delivery across the microgrid.

To ensure real-time control and communication, external controllers were developed for both ESS and load units. These controllers interfaced with a centralized main controller using MQTT and HTTP protocols, enabling prioritized power assignment based on SoC and QoES logic.

The experimental procedure section detailed the challenges encountered during the physical implementation, including synchronization issues during dual-ESS operation and control integration with mixed-type devices. These were mitigated through adaptive control strategies and hardware-software coordination.

Finally, the chapter presented and analyzed experimental results showing the power sharing behavior, voltage stability on the DC bus, and individual device performance under SPA algorithm control. The findings validated that the proposed architecture achieved its design objectives: stable power delivery, balanced SoC across ESS units, prioritized load management, and overall system robustness under dynamic real-world conditions.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

This thesis presented the design, development, and validation of a SoC-based Power Assignment (SPA) algorithm implemented in an experimental DC microgrid (MG) environment. The research addressed critical challenges in managing real-time power flow in a decentralized system composed of multiple ESSs, PV input, and a combination of smart and traditional loads.

The proposed DC MG architecture was developed using a modular approach that integrated both smart appliances and non-smart legacy devices via external sensing and control systems. To ensure effective coordination and optimal operation of the MG, a QoES framework was introduced, which prioritized load behavior based on usage criticality, battery status, and system constraints.

One of the central achievements of this study was the practical implementation of the SPA algorithm, which dynamically balances power distribution from ESS units based on real-time SoC, load priority, and system energy demands. The algorithm was evaluated through both simulations and experimental testing, confirming its capability to achieve SoC balancing, maintain DC bus voltage stability, and enforce priority-based load activation under constrained energy scenarios.

The experimental platform, developed using Raspberry Pi controllers, MQTT communication, and auxiliary power electronics, enabled reliable device communication and control across smart and non-smart subsystems. The simulations validated system behavior under variable load and supply conditions, demonstrating robust and adaptive performance of the control strategy.

Overall, this research bridges the gap between theoretical energy management approaches and practical deployment in resource-constrained environments. The framework established here lays the groundwork for more scalable, flexible, and autonomous microgrid systems capable of serving remote or disaster-prone areas with improved energy resilience and service quality.

5.2 Contributions

This research contributes to the field of DC microgrid control and energy management through a combination of novel algorithm development, system integration, and experimental validation. The key contributions of this work are outlined below:

- **Experimental Development of a Small-Scale DC Microgrid:** While previous research on DC microgrids has been largely simulation-based, this study makes a novel contribution by designing, developing, and implementing a functional small-scale DC microgrid in a real-world testbed. The system integrates key components, including PV generation, dual ESS units, critical and non-critical loads, and centralized control logic, thereby providing an experimental foundation for future studies in DC-based energy systems.

- **Power Sharing and Assignment:** In traditional microgrid systems, power loads are allowed to draw energy passively from the available sources without explicit control. This research introduces a power assignment strategy, where energy assign to each load is actively managed by the main controller. The SPA algorithm regulates energy allocation based on system conditions, ensuring controlled, intelligent distribution from multiple ESS units to different prioritized loads.

- **Real-Time Implementation of SoC Balancing Between ESS Units:** Previous studies have only analyzed SoC balancing techniques through simulations. This work advances the field by successfully implementing SoC balancing in a physical microgrid environment. The proposed system dynamically distributes load demand between multiple ESS units based on their SoC levels, ensuring safe operation, extended ESS life, and improved system reliability.

- **Adaptive Load Management Under Power Fluctuations Using SPA:** The proposed SPA algorithm enables real-time adaptation to fluctuations on the load side. When total generation PG_j becomes less than total demand PL_k the system employs QoES logic to prioritize loads. Critical loads continue operation while non-critical ones are curtailed, ensuring system stability during energy shortages or peak demands.

- **Integrated Communication Framework for Smart and Non-Smart Loads:** A major contribution of this research is the development of a robust communication protocol enabling seamless integration between smart devices (e.g., Glacier, Airwave) and non-smart appliances (e.g., electric kettle, rice cooker). The architecture ensures secure, reliable, and prioritized message exchange using MQTT and HTTP APIs, supporting both command execution and sensor feedback, thus enhancing coordination and control across the microgrid.

These contributions provide a comprehensive and modular framework for managing energy in distributed DC microgrids, combining adaptive software control with practical hardware implementation. The research paves the way for smarter, more autonomous microgrids suitable for real-world deployment.

Collectively, these contributions significantly enhance the operational capabilities of cost-effective and resilient DC microgrids by bridging advanced algorithmic control strategies with real-time hardware implementation. The system developed in this research serves as a foundational reference model for future experimental platforms within the domain of decentralized and intelligent energy systems. The successful deployment and validation of this small-scale testbed underscore the practical relevance and feasibility of the proposed approach. Furthermore, the architecture and control framework demonstrated in this work can be scaled and extended to larger systems comprising hundreds of loads and multiple energy sources, even in highly dynamic and fluctuating environments

5.3 Future Work

While this research successfully demonstrates the feasibility and effectiveness of a small-scale DC MG with SoC-based power assignment and real time control, several opportunities remain for future development and enhancement.

First, future work could focus on scaling the proposed system to support a larger number of distributed loads and energy storage units. By introducing more complex and heterogeneous load types including both residential and industrial appliances the robustness of the SPA algorithm under highly dynamic demand conditions can be further evaluated.

Second, one of the most promising extensions of this research lies in the integration of Mobile Energy Storage Systems (MESS) into the microgrid architecture. MESS such as Electric Vehicles (EVs) or portable battery trailers can serve as both flexible loads and dispatchable power sources. Their mobility offers unique benefits in emergency response, grid support during peak hours, and energy trading within interconnected microgrids. Future systems should develop real-time coordination algorithms that can schedule the charging/discharging cycles of MESS based on grid status, location, and mobility constraints.

Third, while this research implemented communication protocols for reliable device coordination, future improvements can explore the application of advanced IoT frameworks, including time-sensitive networking (TSN), wireless mesh topologies, and blockchain for secure peer-to-peer energy exchange. These will be critical in enabling decentralized energy communities with autonomous energy trading capabilities.

Lastly, from a control perspective, more advanced predictive and machine learning-based algorithms can be developed to enhance energy forecasting, SoC prediction, and adaptive load prioritization. Coupling these data-driven techniques with the existing deterministic control strategy will further increase system intelligence and adaptability.

In conclusion, this research lays a strong experimental foundation for resilient DC microgrids, and future efforts should emphasize scalability, integration of mobile storage technologies, and intelligent, decentralized control to realize the full potential of next-generation energy systems.

Publication

1. Sadiq Muhammad, Saher Javaid, Yuto Lim, and Yasuo Tan, "Incremental Power Load Analysis for Distributed Power Flow System in Smart Homes," *IEICE Technical Report; IEICE Tech. Rep.*, 124(420), pp. 371–376, 2025.

2. Saher Javaid, Sadiq Muhammad, Yuto Lim, Ioannou, I.I., and Yasuo Tan, "Performance Analysis of Optimal Energy Storage for Renewable-Powered Nanogrid System," *IEICE Technical Report; IEICE Tech. Rep.*,124(420), pp. 365–370, 2025.

3. Saher Javaid, Ioannou I.I., Sadiq Muhammad, Yuto Lim, and Yasuo Tan, "Adaptive Control Strategy for Peak Shaving Based on Real-Time Power Supply-Demand Conditions," in *Proceedings of the IEEE International Conference on Consumer Electronics – Taiwan*, 2025.

4. Sadiq Muhammad, Saher Javaid, Yuto Lim, and Yasuo Tan, "Incremental Power Load Analysis for Distributed Power Flow System in Smart Homes," *MDPI Energies.* (Under Review)

5. Sadiq Muhammad, Saher Javaid, Yuto Lim, and Yasuo Tan, "Adaptive Load Fluctuation Mitigation in DC Microgrids Using a SoC-Driven Control Framework," *IEEE Transactions on Smart Grid.* (To be submitted)

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