OPTIMAL ENERGY MANAGEMENT FOR A GRID CONNECTED PUMPED HYDRO-BATTERY HYBRID STORAGE SYSTEM SUPPLIED BY RENEWABLE ENERGY

By

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DECLARATION

I, KHANYISA SHIRINDA, student number ________, hereby declare that this research project which has been submitted to the Central University of Technology, Free State, for the degree Doctor of Engineering in Electrical Engineering, is my own independent work that complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State, and has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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ABSTRACT

South Africa is experiencing serious challenges with limited electricity supply and frequent blackouts, leading to a national crisis. In response, there has been growing interest in renewable energy sources like wind and solar power to help meet the increasing demand for electricity. However, the inconsistent nature of these renewable sources leads to a mismatch between the energy available and what is needed. To solve this issue, it is crucial to integrate different energy storage technologies. Therefore, this study fills a significant gap in the existing literature on hybrid energy storage systems (HESS) as it applies to renewable energy-based microgrids, especially in residential, commercial, and industrial contexts. While much of the current research focuses on electric vehicles, the use of HESS in other areas has not been fully explored. Given South Africa's ongoing electricity crisis, marked by frequent load shedding, aging infrastructure, and rising electricity costs, there is an urgent need for innovative solutions that enhance energy security and reduce expenses.

To address this, this research develops an optimal energy management model designed to lower electricity costs for a commercial farm connected to a grid-supported microgrid using a hybrid system of batteries, supercapacitors, and pumped hydro storage. The study includes a thorough review of the current literature, highlighting that while hybrid storage solutions have been well-studied for electric vehicles, their potential in other applications requires further investigation. A control model is developed using a Fuzzy Logic Controller (FLC) to ensure a reliable energy supply and efficient energy exchange within the HESS. This model is validated through simulations in MATLAB Simulink, showing that the FLC can optimize energy flow based on changing load demands and pricing conditions.

The key findings reveal that the proposed energy management strategies significantly improve the resilience and reliability of the system, particularly during variable energy generation and high demand periods. The FLC effectively balances the different energy storage components, optimizing their charging and discharging cycles to meet energy needs

while keeping costs low. Furthermore, the system's operational data is analyzed using both statistical and machine learning methods through real-time validation on the Opal-RT simulator. This analysis identifies patterns among the various energy sources and demonstrates how weather and demand fluctuations impact system performance.

Machine learning techniques were employed to enhance these insights; specifically, anomaly detection captured unusual load patterns, while Principal Component Analysis (PCA) and K-means clustering facilitated the simplification and grouping of system states. Additionally, regression models provided strong predictions of load demand. The economic observations indicate potential savings through reduced dependence on grid electricity, which is imperative amid rising electricity costs in South Africa. Ultimately, this research enhances the understanding of HESS by providing a mathematical framework that promotes the efficient integration of renewable energy systems across different sectors. By tackling the specific challenges faced in South Africa, this work aims to support the transition to a more sustainable and resilient energy future, contributing to broader goals of energy security and economic stability in the country.

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LIST OF SYMBOLS AND ABBREVIATIONS

C_j	Cost of Energy
SOC^{max}	Maximum Soc
SOC^{min}	Minimum Soc
$\Delta t = t_s$	Sampling Time
ANN	Artificial Neural Network
AP	Average Power
ASD	Afternoon Standard Demand
BSS	Battery Storage System
DBC	Droop Based Control
EDLC	Electric Double Layer Capacitor
EOP	Evening Off Peak
EP	Evening Peak
ESD	Evening Standard Demand
ESS	Energy Storage Systems
FBC	Filter Based Control
FLC	Fuzzy Logic Control
GWO	Grey Wolf Optimizer
HC	High Consumption
HEDE	High Energy Density Energy Storage
HESS	Hybrid Energy Storage System
HKT	Hydro Kinetic Technology
HOMER	Hybrid Optimization Model for Electric Renewable
HP	High Power
HPDE	High Power Density Energy Storage
HRES	Hybrid Renewable Energy System
IGDT	Information Gap Decision Theory
J	Sampling Interval
LC	Low Consumption

LP	Low Power
MOP	Morning Off Peak
MP	Morning Peak
MPC	Model Predictive Control
MPPT	Maximum Power Produced Control
MAE	Mean Absolute Error
MSD	Morning Standard Demand
N	Horizon Period
OBC	Optimization Based Control
$P_{b\ (In)}$	Power Flowing into The Battery
$P_{b(Out)}$	Power from The Battery System
G_{rid}	Power Allowed from The Grid
PHS	Pumped Hydro Storage.
PID	Proportional Integral Derivative
P_{mp}	Power Required by The Motor Pump
PP	Peak Power
P_{pv}	Power Generated By The PV System
$P_{sc\ (In)}$	The Power Flowing into The Supercapacitor
$P_{sc(Out)}$	Power from the Super Capacitor
PSO	Particle Swarm Optimization
P_{tg}	Power Generated by the Turbine
PV	Photovoltaic
PCA	Principal Component Analysis
RBC	Rule Based Control
RES	Renewable Energy Systems
SVR	Support vector regression
SAURAN	Southern African Universities Radiometric Network
SMES	Superconducting Magnetic Energy Storage
Soc	State of Charge
ToU	Time Of Use
VDC	Direct Current Voltage

VHC	Very High Consumption
VHP	Very High Power
VLC	Very Low Consumption
VLP	Very Low Power
XGboost	Extreme Gradient Boost

CHAPTER 1 : INTRODUCTION

This chapter establishes the background and context of the research, articulating the motivation that drives the study. It formulates the problem statement and delineates the research aim, objectives, and scope. Additionally, it provides an overview of the methodology employed, emphasizes the unique contributions and innovative aspects of the work, and outlines the overall structure of the thesis.

1.1 Background

1.1.1 Renewable energy based microgrid.

The use of renewable energy in microgrids has increased significantly in recent years due to the demand for sustainable energy and advancements in technology. Microgrids are commonly known to operate in two ways: connected to the main grid and as independent systems (standalone) [1,2]. The latter often relies heavily on renewable sources. However, energy generation from intermittent sources like solar and wind is variable, leading to mismatches between energy supply and demand [3].

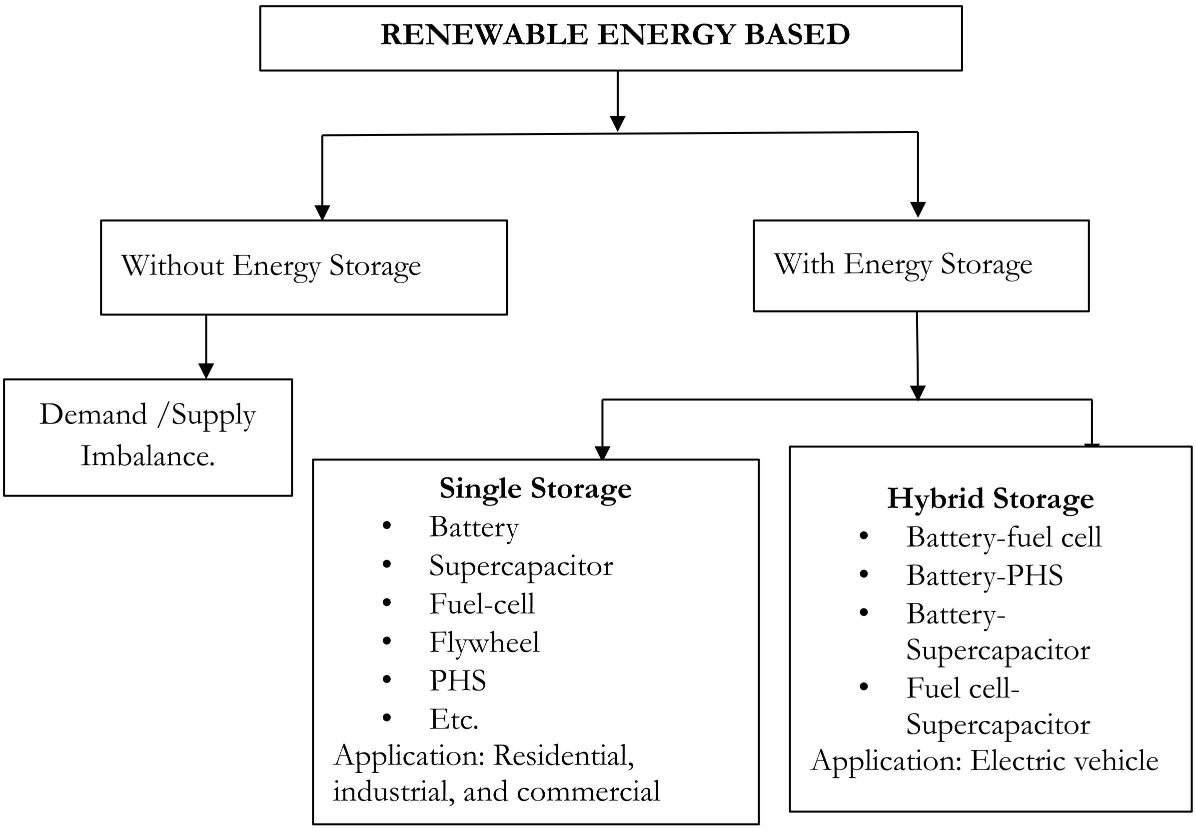

Figure 1.1 Renewable energy based microgrid description

1.1.2 Microgrid without energy storage

In the South African context, the urgency for reliable energy solutions is exacerbated by a burgeoning electricity crisis characterized by frequent load shedding, aging infrastructure, and rising costs. The country's reliance on fossil fuels, coupled with a commitment to sustainable practices, renders the integration of renewable energy sources crucial. For microgrids without energy storage systems, managing the balance between energy demand and supply becomes particularly challenging. When renewable sources produce more energy than is consumed, the excess energy is often wasted, particularly during periods of peak sunlight or wind. This inefficiency is starkly visible in South Africa, where infrastructure limitations hinder the effective storage and redistribution of surplus energy [4].

Conversely, during periods of low energy generation, such as at night or on calm days, the supply often fails to meet consumer demand, resulting in significant challenges. For example, homes may experience dim lights or heating failures, while businesses could suffer losses due to an unreliable power supply [5]. This fluctuation between periods of excess and scarcity creates an unreliable energy supply that complicates microgrid operations. Moreover, such imbalances can lead to instability, causing voltage dips or spikes detrimental to electronic equipment and appliances [6,7].

To address these issues, complex control strategies may be introduced but still may struggle to ensure smooth and reliable energy flow. Without robust energy storage systems, microgrids face significant hurdles in balancing energy supply and demand, ultimately compromising the reliability of electrical supply [8].

1.1.3 Microgrid with energy storage

Energy storage systems (ESS) play a vital role in enhancing the reliability and efficiency of renewable energy microgrids [9]. These systems capture and store excess energy produced during high generation periods for release during peak demand or low generation times, ensuring a stable energy supply [10,11]. They enhance grid stability by acting as a buffer against supply fluctuations, which is critical for preventing outages and ensuring reliable power delivery. Furthermore, they encourage incorporation of renewable energy sources into the microgrid to reduce the use of fossil fuels [12].

1.1.4 Single vs Hybrid storage systems

Both single and hybrid energy storage systems play crucial roles in renewable energy microgrids, but they differ in their configurations, advantages, and applications. A single energy storage system utilizes one type of technology to store and release energy [13,14]. Common examples include lithium-ion batteries, known for their high energy density and efficiency; pumped hydro storage (PHS), which harnesses gravitational potential energy by elevating water; and flywheels, which store kinetic energy through rotation. These systems are typically separated, as each relies solely on its specific technology, offering several advantages such as simplicity in design, installation, and maintenance. They can also be cost-effective for specific applications and are backed by proven reliability due to their established operational history. However, they have limitations, such as limited flexibility in adapting to varying conditions and a trade-off between energy density (the amount of energy stored) and power density (the speed of energy delivery), meaning they typically excel in one area but not both [15].

Hybrid storage systems integrate different energy storage technologies to leverage their individual strengths. This combination allows microgrids to enhance their overall performance by effectively addressing various operational requirements, such as energy density, response time, and lifecycle management. By using multiple types of storage, hybrid systems can provide more flexible and efficient energy solutions [16]. Common combinations include battery-fuel cell systems, where batteries provide quick responses and fuel cells deliver long-duration power; battery-pumped hydro storage, which pairs fast-responding batteries with large-capacity pumped hydro; and battery-supercapacitor systems, which utilize batteries for long-term storage and supercapacitors for rapid energy delivery [17,18]. These systems offer optimized performance by effectively balancing energy density and power density, enhanced reliability through compensatory technologies, and flexibility to adapt to changing energy demands. Additionally, they can be cost-efficient by utilizing the most suitable technology for specific tasks. However, hybrid systems are more complex to design, install, and maintain, and may require a higher initial investment compared to single energy storage systems [19,20].

1.2 Problem statement

Most research on renewable energy-based microgrids with hybrid energy storage primarily focuses on electric vehicles [21]. This leaves a significant gap in the evidence regarding the application of hybrid energy storage systems (HESS) for residential, commercial, and industrial settings. While some studies do address optimal energy management strategies, they often overlook the crucial aspect of effectively controlling power flow between the load and the hybrid storage system [22,23].

In South Africa, persistent electricity shortages, rising tariffs, and grid instability have underscored the urgent need for cost-effective and reliable renewable energy-based microgrids. However, the existing literature reveals a fragmented understanding of various challenges, including control strategy limitations, inadequate coordination models for HESS, and insufficient real-world validation.

Despite extensive investigation into HESS for electric vehicle applications, their optimal integration into grid-connected renewable energy systems for commercial, industrial, and agricultural users remains largely unaddressed. Specifically, there is a lack of comprehensive approaches to coordinate long-term (pumped hydro storage) and short-term (battery and supercapacitor) storage units amid variable renewable generation, fluctuating load profiles, and time-of-use (ToU) tariffs.

Furthermore, the dynamic behavior, control interactions, and performance reliability of such integrated hybrid systems under real operating conditions have received minimal attention. Collectively, these gaps indicate a pressing need for a unified framework that not only enhances energy management strategies but also ensures the stability and efficiency of hybrid energy storage solutions in the South African context.

1.3 Research aims and objectives

The aim of this research is to develop and validate an optimal energy management framework for a grid-connected photovoltaic microgrid integrating pumped hydro, battery, and supercapacitor storage systems. The proposed framework seeks to minimize electricity costs, improve system reliability, and enhance storage utilization under variable renewable generation and ToU tariffs. To achieve this, the study designs a fuzzy logic controller for real-time coordination of energy flow between the hybrid storage subsystems and the grid and formulates a multi-objective optimization model for cost-effective dispatch of energy resources. Furthermore, the research aims to validate the model in real time using Opal-RT hardware-in-the-loop simulations and employ machine learning techniques for system performance analysis, anomaly detection, and predictive reliability evaluation.

To achieve this aim, the following objectives will be pursued:

- Energy Management Model: The primary objective of this work was to develop an optimum algorithm to manage and control the energy exchange between the load and the HESS. Therefore, an optimal energy management model was developed and modelled focussing on effectively allocating energy in the hybrid storage system, as well as ensuring that energy is stored and released in the most efficient manner. It also considered factors such as energy demand, generation variability, and storage capabilities while reducing the overall operating costs of the system.
- Cost minimization: Minimizing the use of grid energy and maximizing the use of renewable energy.
- System lifespan extension: Improving the lifespan of the HESS by taking advantage of the ToU and character of the PHS.
- Results validation on real time using Opal-RT: A comprehensive framework was designed to analyse and model the performance of the proposed system through data analytics and machine learning techniques. The process started with an in-depth examination of the system's operational dataset to reveal key patterns, relationships, and variations among various energy sources and across different time periods.

By meeting these objectives, this work aims to contribute significantly to the field of renewable energy management, enhancing the efficiency and reliability of hybrid energy storage systems.

1.4 Research scope

This research work focused on the development of an optimal energy management model, to minimise the electricity cost of the targeted commercial farm supplied by the grid-connected renewable energy based microgrid with hybrid battery storage system battery/supercapacitor/Pumped hydro storage (BSS/SC/PHS) energy system.

1.5 Research methodology

To achieve the objectives of this research, a structured methodological approach combining theoretical modelling, simulation, and real-time validation was adopted. The methodology integrates both analytical and experimental components, enabling the development, testing, and verification of an optimal energy management framework for a grid-connected photovoltaic microgrid incorporating pumped hydro, battery, and supercapacitor storage systems:

- Stage 1: Literature Review and System Conceptualization
  A comprehensive review of existing literature was conducted to examine HESS configurations and control strategies, with particular emphasis on the limited integration of pumped hydro storage with short-term devices such as batteries and supercapacitors. The findings of this review informed the conceptual design of the proposed hybrid system and established the theoretical foundation for the fuzzy-logic-based control framework.
- Stage 2: Data Collection and System Modelling
  Operational and environmental data were collected from multiple sources to model realistic system conditions. These included:
  - Hourly load-demand data from Nooitgedacht Farm representing commercial load behavior.

- Solar irradiance and temperature data from the Southern African Universities Radiometric Network (SAURAN) for PV generation modelling.
- Eskom time-of-use (ToU) tariff data for economic optimization.
- Component characteristics for the pumped-hydro, battery, and supercapacitor subsystems obtained from literature and manufacturer datasheets. These datasets were used to develop mathematical models representing the PV generator, storage subsystems, and grid interaction. Energy-balance equations and operational constraints were formulated to define the system's objective function.

- Stage 3: Controller Development and System Optimisation
  A Fuzzy Logic Controller was designed in MATLAB/Simulink to coordinate real-time energy exchange between the PV source, hybrid storage units, and the grid. Input and output membership functions were defined based on load level, solar generation, and state-of-charge variables. The controller applied a rule-based inference system to minimize electricity purchases from the grid and to optimize charge/discharge scheduling under ToU tariff conditions. A multi-objective optimisation model was integrated to further reduce operating cost while maintaining energy reliability and extending storage lifespan.
- Stage 4: Simulation and Techno-Economic Evaluation
  The complete system model was simulated in MATLAB/Simulink using the collected datasets. Simulations were performed for both low-demand and high-demand seasons to assess the system's dynamic performance, power flow behavior, and economic benefits. Key outputs such as grid power reduction, energy cost savings, and state-of-charge profiles were analyzed to verify the system's efficiency and stability.
- Stage 5: Real-Time Validation and Performance Analytics
  The developed model was implemented on an Opal-RT hardware-in-the-loop platform for real-time validation. This step enabled assessment of controller robustness, operational reliability, and system response under

actual time constraints. Subsequently, machine-learning techniques including anomaly detection, Principal Component Analysis (PCA), K-means clustering, and regression were applied to the real-time dataset to evaluate system reliability, identify performance patterns, and predict load and storage behavior.

- Stage 6: Synthesis and Interpretation

  The final stage involved consolidating simulation and real-time results to derive techno-economic insights, evaluate the effectiveness of the proposed fuzzy-controlled hybrid framework, and provide recommendations for large-scale implementation and future research.

1.6 Contribution to knowledge

The most notable contribution of this research is the development and real-time validation of an optimal fuzzy-logic-based energy management framework for a grid-connected photovoltaic microgrid integrating pumped hydro, battery, and supercapacitor storage systems. Unlike previous studies that focused on single or dual storage configurations, this work demonstrates for the first time a coordinated control of long-term (PHS) and short-term (BESS–SCES) storage under South Africa's time-of-use tariff environment. The integration of fuzzy logic control with a cost-optimisation objective enabled significant reduction in grid dependence and operating cost while improving system reliability. Furthermore, the model was validated in real time using Opal-RT hardware-in-the-loop simulation, confirming its practical feasibility, and machine-learning techniques were applied to analyse reliability and predict operational behaviour introducing a novel data-driven dimension to hybrid microgrid research.

1.7 Publications

Journal publications from this research are:

- Shirinda, Khanyisa, and Kusakana Kanzumba. "A review of hybrid energy storage systems in renewable energy applications". International Journal of Smart Grid and Clean Energy 11, no. 2 (2022): 99-108.

- Shirinda, Khanyisa, Kanzumba Kusakana, and Mikołaj Ostraszewski. "Combinatorial optimization of a fuzzy logic-controlled grid connected photovoltaic with hybrid energy storage systems using time of use tariff". Journal of Energy Storage 99 (2024): 113251.
- Shirinda, Khanyisa, and Kusakana Kanzumba "Optimal control of an on-grid PV based microgrid integrating a hybrid energy storage using FLC, through Opal-RT validation". *Submitted.*

1.8 Thesis structure

This thesis is organized into six Chapters, each addressing a key stage of the research process, from conceptualization to real-time validation and analytical evaluation.

Chapter 1: Introduction

This Chapter provides the overall background and context of the research. It outlines the motivation behind the study, formulates the problem statement, and defines the research aim, objectives, and scope. It also summarizes the adopted methodology, highlights the unique contributions and novelty of the work, and presents the structure of the thesis.

Chapter 2: Literature Review

This Chapter presents a comprehensive and critical review of existing research on HESS applied to renewable-energy-based microgrids. It examines various hybrid configurations, control strategies, and optimization approaches, identifying the existing research gap concerning the integration of pumped hydro storage with battery and supercapacitor systems in grid-connected applications. The chapter concludes by positioning the proposed research within this gap.

Chapter 3: System Modelling and Fuzzy Logic Control Development

This chapter details the configuration of the proposed grid-connected photovoltaic microgrid integrated with pumped hydro, battery, and supercapacitor storage systems. It presents the mathematical modelling of all system components, defines the objective function and operating constraints, and develops a fuzzy logic controller for optimal energy management. The controller is designed and simulated in MATLAB/Simulink to coordinate energy flow among the different storage units and the grid under varying load and time-of-use tariff conditions.

Chapter 4" Simulation Results and Techno-Economic Performance Analysis

This chapter evaluates the performance of the proposed hybrid system through detailed simulations in MATLAB/Simulink. It analyses the system's dynamic behavior under both low- and high-demand seasons, assessing the contribution of each storage subsystem and the grid to overall power balance. Economic performance is assessed based on electricity cost reduction and improved storage utilization efficiency.

Chapter 5: Real-Time Validation and Machine Learning Analysis

This chapter focuses on real-time implementation and validation of the developed fuzzy-controlled hybrid system using the Opal-RT hardware-in-the-loop (HIL) platform. The real-time results are analyzed to evaluate controller stability, operational reliability, and system responsiveness. Furthermore, machine learning techniques such as anomaly detection, PCA, K-means clustering, and regression are applied to operational data to extract performance patterns, detect anomalies, and develop predictive reliability models.

Chapter 6: Conclusions and Future Work

The final chapter summarizes the key findings of the research and highlights its theoretical and practical contributions to the field of renewable energy and hybrid energy storage systems. It also discusses the limitations of the current work and provides recommendations for future research, including possible extensions of the fuzzy-based optimization framework and real-world deployment strategies.

CHAPTER 2 : LITERATURE REVIEW

This chapter provides a thorough and critical analysis of the current literature on hybrid energy storage systems (HESS) in the context of renewable energy microgrids. It explores different hybrid configurations, control mechanisms, and optimization techniques, highlighting a significant research gap regarding the incorporation of pumped hydro storage alongside battery and supercapacitor systems in grid-connected settings. The chapter concludes by situating the proposed research within this identified gap.

2.1. Introduction

Several studies have been conducted to reduce the use of grid supplied power by introducing renewable energy sources such as wind and solar. This is to close the gap between load demand and supply [24,25] as well as reduce the use of fossil fuel, carbon emissions and operating capital. In most studies, renewable energy (RE) based micro-grids are designed with the aim of reducing the reliance of grid power as well as the cost of energy. However, renewable energy sources come with disadvantages such as unreliability and random power production. Therefore, energy storage may be necessary to avoid frequency and voltage instability [26]. The storage of the generated energy may become a problem due to the nature of RE source and load demand. To this date, there is no energy storage that is said to satisfy all storage requirements [27]. Therefore, hybrid energy storage systems have become a good solution to the problem. HESS consists of various storage systems [28,29]. They all have their unique characteristics and yet complementary to each other in terms of life span, time response, energy, and power density [30,31]. Therefore, the control of hybrid energy storage system is of utmost importance to ensure that there is no fluctuation on the bus voltage and power distribution frequency. It also adjusts the state of charge of the energy storage system to a safe operating range. In overall the process brings the system to balance as well as extend the lifespan as well as its response flexibility [32,33]. This Chapter presents a literature review on hybridization of energy storage and control systems strategies, within the thesis topic. The Chapter provides the literature review on on-site hybrid renewable energy systems (HRES), control strategies and concludes with the discussions and summary.

2.2. Hybrid energy storage systems

2.2.1. Hydrogen (fuel cell) and battery

In most cases, batteries are associated with solar photovoltaic (PV) systems due to their inherent characteristics. However, similar principles apply when combining PV systems with hydrogen subsystems. In this context, excess energy generated by solar PV can be utilized to produce hydrogen, which subsequently feeds a fuel cell during periods of high demand [34,35]. This potential integration has led to increased interest in the incorporation of hydrogen within solar-powered microgrids [36].

Both storage systems exhibit the ability to store solar energy for later use, yet they differ significantly in their respective characteristics. For instance, fuel cells offer high specific energy and reliability compared to conventional batteries, while also providing prolonged operation periods and enhanced durability. In contrast, batteries tend to have shorter operational lifespans [37-40].

The complementary features of both storage systems, paired with the relatively slow dynamic response of fuel cells, pave the way for the development of a reliable and efficient hybrid system. Continuing the exploration of this hybridization, Hongbo Ren et al. [41] developed an optimization model that integrates a grid-connected PV system, fuel cell, and battery as core components. This study aims to establish an effective operating and management strategy for the proposed hybrid energy system, taking into account both economic and environmental considerations. The system is said to be connected to the grid for the ability to sell the energy back and recharging the storage devices during cheap electricity pricing periods. Therefore, the results of this work reveal that having various storage technologies positively affect the load demand as well as using local grid electricity in consideration of ToU electricity pricing method. Using the same system components configuration, Sayyad Nojovan et al [42] presented a performance improvement model of a hybrid energy system using information gap decision theory (IGDT) with consideration of the load uncertainty. The results of this work show that the uncertainty of the load may be solved by either spending more money to buy enough grid power or by a possible decrease in load while considering the system dependency on the total consumed load power.

G. Bruni et al [43] explored the effect of sizing and energy management on the environmental efficiency of a hybrid power system that comprises of PV with battery and fuel cells. From this work, the authors discover that the use of RES is not affected by the management's strategy, however, it may be influenced only by the sizing of the component. The result also reflects on the improvement of the fuel cell's convention efficiency as well as its life span due to proper choice of thresh hold voltage. Ying han et al [44] presented a hierarchical energy management system that features PV and battery-hydrogen energy storage device. With the system depending on the energy of a non-dispatchable RES. The excess energy is absorbed by the electrolyzer to produce hydrogen gas to fill the demand gap.

Juan P. Torreglosa et al [45] presented an energy dispatching model using model predictive control. The standalone hybrid system comprised of PV and wind as source of renewable energy generator, where battery and hydrogen are used as a storage device. The results of this work show a higher global efficiency of the modeled hybrid system, where the operating limits of both the battery state of charge (SOC) and hydrogen tank level are kept at the desired state. Abla khiareddine et al [40] presented a similar optimization model with the aim of sizing the system's components. The results of this work revealed an increase in life span of a battery as well as reduction on the cost of the system through hybrid energy sources. Almed A. kamel et al [46] proposed a control strategy for an energy management of a DC microgrid. With PV as the only energy source accompanied by fuel cells, battery as well as the super capacitor to operate as a hybrid storage system. In this work, the characteristics of the system's components were used to the system's advantage. Based on the results the PV covers the load demand during day, while the fuel cell compensates for the PV's failure to meet the load. This allows the battery to maintain a healthy SOC as well as the direct current voltage (VDC).

Manuel Castaneda at al [47] presented a sizing method as well as control strategies for managing the energy of an off-grid hybrid energy system. The system integrated a battery and a hydrogen subsystem with PV as the source of Renewable energy. The results of this work show that the system successfully meets the load energy demand while keeping healthy energy reserves in the battery as compared to using conventional batteries and sole hydrogen system. Rihab jalloulic and lotfi Krichen [48] analyzed generation management of an off-grid PV system with the aim of finding the best component sizes as well as choosing the most economical storage device to store excess energy should it be there. The hybrid energy system (HES) consists of a battery and a hydrogen subsystem. With consideration of the variable load demand as well as intermittent irradiation, the developed system's results give an optimal solution to the gap between generation and supply.

2.2.2. Battery and supercapacitor

Most of the PV powered micro grid systems are re-designed to feature hybrid storage that consists of a battery with any other storage depending on the nature of the load or terrain, with the aim of improving the service life of the battery [49]. Apart from the hydrogen (fuel cell) and battery, there is supercapacitor storage system in the family of the electrochemical storage category [50]. Unlike the fuel cell, the supercapacitor has a faster charge/discharge rate as well as high power density [51] and is known to have longer life cycle as compared to the conventional battery [52]. Therefore, hybridization of supercapacitor and battery stands out due to its unique bus configurations i.e., four various topologies that are mostly used include the basic parallel, passive, active and semi-active [53]. While some of these configurations are used to control the power flow as well as the voltage of the system, the passive topology is found to be the most common use due to being cheap and easy to apply phenomenon. However, it comes with drawbacks such as disability to control the power flow [49,53]. More research has been conducted with different configurations being used to fit specific systems and scenarios. For example,

Wenlong Jing et al [49] presented a study of a battery-supercapacitor based hybrid energy storage system for a stand-alone PV power system. This work discusses factors that affect the efficiency of a battery as well as different hybrid configurations to relieve stress from the battery. With the use of a three level HESS configuration compared to both passive and semi active HESS. The results of this work reveal that the three-level configuration is the best solution for off-grid rural application. With the same configuration, Lee wai Chang et al [54] proposed an optimal control strategy with the aim of extending the battery's life span as well as reduction of the dynamic stress. In this work, a low pass filter was used together with fuzzy logic controller instead of the usual filtration buffed controller or FLC alone. The results of this work show an improvement in the batter's life, while allowing the super capacitor to operate within the healthy SOC range. Tao Ma et al [52] developed battery-supercapacitor energy storage with hybrid renewable energy sources (PV-wind). With the aim of accommodating long hours of charge/discharge as well as short peak power surges, the authors used passive configuration which also prolongs the battery's life. Using the same renewable resources for an off-grid system with hybrid storage system (battery-supercapacitor). Abbasi Abdelkader [55] proposed a multi objective generic algorithm using a different approach of optimization with the aim of sizing the system components. Discrete Fourier transform is used to manage the frequency as well as the power supply system. Therefore, the simulation results prove the proposed algorithm to be the best option to explore renewable energies.

Zineb Cabrane et al [56] have analyzed the behavior of a battery-supercapacitor hybrid energy storage system for PV installation. With the aim of reducing the battery's stress, the authors have explored all available configurations of a Battery-supercapacitor storage system. However, they opted for a fully active configuration to take advantage of the controllable voltage topology for both battery and capacitor. The results of this work show a decrease in the current charge/discharge rate as well as reduction on the battery's stress level. A dynamic power allocation of a battery-supercapacitor energy storage system for an off-grid PV power system is proposed by Wenlong Jing et al [51]. With the aim of solving the problem of charge/discharge stress of a battery, a novel hybrid storage system topology is used. The work was conducted with consideration of the financial and technical viability. The simulation results have shown that the proposed system may positively change the life span of the battery as well as lower the operating costs of the conventional PV-battery system.

2.2.3. Hydrogen and supercapacitor

The hybridization of the fuel cell and supercapacitor has similar operations as that of battery and fuel cells. In that kind of a configuration the fuel cell is used as a battery to store the renewable anergy when the resource is available and the capacitor to store excess generated energy to accommodate the high transients and rapid load fluctuations [57]. However, in some research work, the fuel cell is used as the source and the supercapacitor as the main storage to supply and absorb the power during load transients [58,59]. The integration of these two-energy storage systems obeys the required parameters of an energy storage system, i.e. high energy and power density [60-66]. Where the fuel cell delivers high energy density and the capacitor with high power density [67]. Moreover, the main drawback of the fuel cell is its inability to respond fast to charging that is caused by limited power slope to further prevent fuel shortage and improve its service life. While the super-fast response of a supercapacitor compliments most of the fuel cell's characteristics [68]. The following reviews advocate for the mentioned principles as well as the configurations of the fuel cell-supercapacitor hybrid systems.

Doudou N Luta and Alanda K Royi performed [57] an optimal sizing of hybrid fuel cell with supercapacitor storage system for off-grid renewable applications using PV as the source of renewable energy. The authors choose the components sizes based on the system's technical feasibility and its cost effectiveness. With the supercapacitor used to cover the transient peak and rapid fluctuation demand, the results show how the integration of both systems will affect the overall cost of the proposed system. However, the system is found to be expensive to be implemented for a commercial load. N.S. Jayalakshmi et al [58] has also used the same configuration with PV and Fuel cell as the main sources, the supercapacitor used as load power stabilizer in a power control hybrid system for stand-alone applications. Three control strategies are used i.e., maximum power produced tracker (MPPT) used for PV, inverter controller to regulate voltage and frequency variations as well as current control for total power balancing. The results of this work prove the control strategies to be positively effective on the voltage and frequency. Therefore, the end user receives constant voltage with less distorted frequency.

A hybrid power system based on fuel cells, photovoltaic (PV) systems, and supercapacitors is proposed by Seydali Ferahtia et al. [59]. The system is designed to manage power delivery effectively, ensuring high-quality energy supply to accommodate variable load demands while accounting for fluctuating solar irradiance and the operational state of the fuel cell. In this configuration, the supercapacitor (SC) is utilized to respond effectively during peak transient periods. The results of this study indicate that stability of the DC bus voltage was successfully achieved. Onar O.C et al [68] proposed dynamic modeling, design and simulation of a hybrid power generating system that comprises of wind turbine, fuel cell as well as a supercapacitor. The authors aimed to reduce voltage variation on the equipment. The system accommodates the variable energy generated by the wind by charging the fuel cell to meet the load demand. While the supercapacitor is used to meet the peak powers that are above the fuel cell limits. The system is recommended for stand-alone application as well as remote located areas with non-ideal wind speed since it is found to be successfully accommodative to variable wind speed.

Phatiphat Thounthong et al [67] proposed an energy management of a hybrid power source that is composed of fuel cells as the main source, solar cell and supercapacitor as the storage device. The capacitor bank is charged by the fuel cell as well as the solar cell when the solar is available. To validate the proposed system, a test bench was developed. The results show an improvement in the system performance due to SC's fast response and controlled fuel cells. Idoia San Martin et al [69] analyzed the energy and frequency of a microgrid based on fuel cell and supercapacitor. With the idea of replacing a lead acid battery as well as the components of the developed microgrid in the Navarre university labs. The complete system comprises of a wind turbine and PV hybrid renewable energy systems and a lead acid batter (which is to be replaced) as the storage device. The behavior of the FC and SC was characterized under both steady state and dynamic modes of operation. Further comparison was made between sole use of FC as well as the combination of FC and SC. The results of this work prove the integrated storage system of FC and SC to be more efficient that the FC alone by at least 8.5 percent.

2.2.4. Battery and pumped hydro storage

The current trend in the energy storage system research field has shown an increased interest in the use of pumped hydro storage systems (PHSs). This ESS is well known, requires low maintenance, has a long lifespan, can produce high energy density, is environment friendly and has high roundtrip conversion efficiency; these characteristics make PHS well suited to support the fluctuation of RESs such as isolated hydrokinetic (HKT), PV and wind energy conversion systems [70-76]. However, some of the challenges observed when operating existing PHSs are the fairly low power and energy density, which necessitates either large water flows and/or large net height between the upper and lower reservoirs, as well as the slow response rate when balancing lower power deficits [77]. Therefore, PHSs can be used in hybrid configurations with other ESSs to take advantage of the resultant energy storage capabilities and further support the stochastic power generated from RES. Like renewable energy systems, the different storage technologies currently available have their own technical properties. Therefore, they can also be combined in hybrid storage system (HSS) topologies this hybridization provides excellent characteristics which cannot be offered by a single ESS [78]. Much research works published in the last decade looked at the operation control of hybrid storage systems with topologies such as battery-supercapacitor, fuel cell-battery-supercapacitor, fuel cell-supercapacitor or battery-pumped hydro storage.

The subsequent compiled literature reveals that very few studies have analyzed the optimal energy management of integrated PHSs with other ESSs to support RESs. Guezgouz et al [79] presented an energy management model for an HES composed of a PV and wind supported by a HSS (PHS-BES). The work opened a path to the concept of HSSs operating in conjunction with non-dispatchable RESS such as PV or wind supplying isolated loads. Bhayo et al [80] analyzed a HES composed of a PV, a BSS, a hydro system and a PHS for optimal energy management, considering the excess generated power. The results have demonstrated that integrating a rainfall-based hydropower system with an optimally sized water storage situated at a specific net water head resulted in a substantial reduction of the PV size as compared to system without rainfall-based hydropower system. Javed et al [81] proposed a novel operating strategy for a hybrid PHS-BSS operating with an isolated RES. The results obtained based on energy output analysis have shown that during peak power demand periods, PHS comes into operation when the minimum SOC is almost reached, while low power shortages are met by the BSS. Abdelshafy et al [82] presented an energy management model to minimize the cost as well as the CO2 emissions of a grid-connected double storage system consisting of a PHS-BSS supplied by a HES. The research findings have demonstrated the techno-economic and environmental effectiveness of the proposed model.

Kumar and Biswas [83] studied the feasibility of combining a PHS and a BSS supplied by a PV. The results revealed that utilizing a small BSS with PHS can significantly reduce the upper reservoir size, which can subsequently decrease the excess energy generated. Ma et al. [84] analyzed the combination of BSS and PHS for the RES suppling a microgrid in an isolated island in Hong Kong. Several options have been analyzed i.e. advanced deep cycle

BSS, conventional BSS, PHS without BSS, and PHS combined with BSS. Sensitivity analysis revealed that PHS becomes even more cost-effective by increasing the upper reservoir capacity. Bento et al [85] proposed an optimal dispatch model for a grid connected/stand-alone HES, supplying power to an industrial prosumer using a HES made of BSS and PHS. Different scenarios were analyzed to highlight the techno-economic effectiveness of the developed model. Reza Hemmati and Hedayat Saboori [86] reviewed the emergence of hybrid energy storage systems I renewable energy and transport application. The Authors focused on the concept, principles, control topology as well as management strategies. They have also explored various energy storage categories to discover suitable technology that can cover all the needs and ideal characteristics of renewable resources for optimization purposes. Therefore, hybridization remains the optimum solution to most systems' reliability and efficiency problems.

Mohammed Guezgouz et al [87] proposed an optimal hybrid pumped hydro-battery storage scheme for standalone renewable energy systems. With the grey wolf optimizer used as the sizing methodology, the results reveal an increase in reliability at a low cost. However, special attention is considered during design phase to accommodate the meteorological variations of the future. Bilawal A. Bhayo et al [88] presented a power management optimization model of a hybrid solar PV-Battery with PHS system for off-grid electricity generation. Instead of the common PHS system with two reservoirs, this system features one storage tank that is fed by water from the roof and gutters. The system analysis was conducted with comparison of various configurations i.e. PV-battery-hydro, PV-battery-PHSS and PV-battery. The findings of the work show a reduction on the installed PV capacity by at least 13.12% from the conventional PV-battery configuration integrated with rainfall based hydro power. This system is recommended for tropical areas with climate of high potential of solar and rain annually. Alaaeldin M. Abdelshafy et al [89] proposed a grid connected hybrid optimized energy management strategy powered by renewable energy resources (Wind-PV). The battery is used to store excess energy and meet the load demand when the PHS is defeated. The cost of electricity is reduced by at least twenty-two percent, which also affects the grid energy exchange by five percent of annual demand. The components sizes increase with an increase in load demand.

Alok Kumar and Agoimitra Biwas [90] presented a techno-economic optimization of a standalone PV/PHS/Battery system for a low load demand. The authors prioritized sizing the components as well as optimizing the RES using the levelized cost of energy as the objective function at hundred percent reliability. Firefly algorithm and grey wolf optimization method were compared for sizing both the RES components as well as the storage system. The outcome of both performances exposes the GWO method as the best based on the cost of energy and system reliability. While on the other hand the overall results reveal that integrating a small battery bank with the PHS reduces the capacity of the upper reservoir as well as improving the power supply reliability by at least ten kilowatts. Junhui Zhao et al [91] proposed a hybrid electric hydro storage solution to remote located areas. With the idea of solving the energy and water crisis in remote locations that have enough solar. The system features solar PV as the RES, while the PHS system is used as support energy storage/generator as well as a water storage system. The results of this work concluded that the turbine generator works when there is not enough energy to charge the battery to a level of handling heavy load. That is, for as long as the battery can charge to safe working limits, then the turbine does not operate. Therefore, the PHS guarantees a reliable system operation. Nicola Destro et al [92] designed components as well as optimized a system that features a hybrid storage sub-system. The system is comprised of PV, diesel engine and a reversible heat pump plus a boiler. Battery and PHS are used as storage. The authors used the PSO methodology to size the components and optimize the system operation. The performance of the traditional cooling system and that reversible pump was compared, where the reversible heat pump was found to be more feasible by reducing the size of internal combustion engine and boiler. on the contrary this solution increases the number of installed PV and required extra space for cooling tanks.

2.3. Control strategies for hybrid energy storage system

Amongst the available combinations of HESS, the control strategies that are already available are mainly associated with the combination of battery and supercapacitor. There are few articles that have worked on other combinations excluding PHS. As for PHS, limited evidence is available on it being used as part of hybrid energy storage system. Therefore, the same is true about its control. The HESS control strategies may include three categories i.e., centralized, decentralized, and distributed control [93]. When using the centralized control, the local controller (LC) of the HPDE and HEDE are adjusted by the central controller by means of collecting local data to decide [94]. Where the opposite is true for the decentralized system. The local controller of the decentralized system focusses on the dedicated converter, where it only receives the local data and has no means of communicating with the central controller or any other controllers including their working conditions [95]. On the other hand, on the distributed multi-agent control, all central controllers are identified as individual agents which are deployed to collect local data as well as neighboring agents for a final coordinated control.

2.3.1. Filter based control

For a filter-based control (FBC), the current of SC and battery are referenced by means of separating the total current into high and low frequency currents using a low pass filter. Where the high frequency may be deployed to reference the current of high-power density storage and the low frequency deployed to reference the current of high energy density storage. This control method is usually associated with single HESS such as SC and battery instead of multiple HESS. Furthermore, the FBC requires a communication system to coordinate the data collected from both storages. Therefore, a delay may be expected. This control method has been used for managing and controlling various HESS. Manandhar et al [96], proposed a management scheme for grid-connected hybrid energy storage systems combining batteries and supercapacitors. This work focuses on the challenge of controlling power sharing under various operating modes. The system aims to regulate DC link voltage quickly and balance battery use with grid input based on battery charge, reducing battery stress especially during power fluctuations. FBC is once again used by Ramos et a [97], to manage energy in hybrid storage setups that mix batteries and supercapacitors. It focuses on tweaking filter-based control methods to better share power, protect devices from wear, and keep everything running smoothly.

2.3.2. Fuzzy logic control

Instead of decoupling the storage current, the FLC generates reference power through a low pass filter to achieve average and transient power to distribute actively to the HSS. Furthermore, this method may reduce the peak current of the high energy density storage. However, it may also be restricted to single HESS. If more systems are added the system may suffer communication delays since the control design would get to be more complex as compared to a single HESS. This control method has also been used for HESS based microgrids. Sun et al [98], explores a novel fuzzy logic control design for a hybrid energy storage system that uses both superconducting magnetic energy storage (SMES) and batteries. It focuses on managing fluctuating power demands by combining the strengths of SMES's high power density with the battery's energy capacity. The study aims to also extend the battery life by reducing the frequency of charging and discharging, while adapting to the SMES's state of charge automatically.

2.3.3. Rule-based control

This method has several predefined control rules, these rules are in the controller to generate control signal to communicate with the controller of the storage devices through communication network. This control method is attained via the formulation of a sequence of empirical and predetermined rules of the control [99]. Ahmed m et al [100], introduced a controller for a supercapacitor/battery setup in a DC microgrid that incorporates solar and wind systems. This controller addresses the issues of RES variability and load changes, ensuring that the DC voltage level stays within a 5% limit. Additionally, Hou J et al [101], utilized Rule-Based Control (RBC) to minimize energy losses, extend battery life, and lower costs for the HESS. In Reference [102], RBC was employed to manage power flow, maintain power balance, and reduce fluctuations in the system's power output.

2.3.4. Model predictive control

This control technology depends on the online optimization to allocate power and current references in a particular HESS based on different constraint conditions. In the control system, the allocated parameters are referred to as inputs of the model predictive control (MPC). Therefore, the MPC determines the power allocation in the HESS with reference to the constraint condition and produces modulated signal. This method may additionally not be recommended for multiple HESS since there may be more constraints to consider. Lim et al [103], proposed a smart energy management system to improve how multiple grid-connected microgrids (MGs) work together using MPC. The authors use mixed-integer quadratic programming to tackle the complex energy flows and power exchanges in the network. They test the system across different weather conditions and with prediction errors, showing that the cooperative approach reduces external resource use by nearly half and cuts operating costs significantly. The same control method is further used to optimally manage the power in a PV based microgrid with hybrid energy storage with the aim of delivering high quality power to the loads, while achieve seamless power transfer among the generation, storage, and consumption [104].

2.3.5. Optimization based control

This control method is used to optimize power distribution among system components. As a result, less damage is caused to the storage and the investment cost of HESS as well reduces. Like the FBC, a low pass filter is used to divide the total power into high and low frequency power for optimal power reference of both storage systems. Furthermore, this method of control is associated with multi-objective optimization such as consumption of energy, operating and investment costs [105]. However, the more the optimization targets increase, the more constraints condition becomes complex which creates a computational burden to the controller.

2.3.6. Artificial neural network

This is an intelligent algorithm that trains and verifies collected data for optimization purpose of the HESS. The back propagation network forms part of supervisory control. It trains measured data such as current and voltage to successfully generate a reference to their controller. This control method is mainly used in control systems due to their nonlinear and adaptive structure, as well as their ability to generalize, while their design is independent of system parameters [106]. Singh p et al, proposed a power managing system in low voltage DC microgrids that combine batteries and supercapacitors as energy storage. This study is based on balancing power sharing, keeping battery charge healthy, and stabilizing voltage using a hybrid of bat search algorithm and neural networks. The system tested on a real time simulation to show its performance against conventional methods. It was also used in [107] to extend the lifespan of batteries in an off-grid photovoltaic power plant using lithium-ion batteries and a supercapacitor HESS, while also lowering costs for the battery and fuel cell.

2.3.7. Droop based control

This control method is based on adjusting the reference voltage of the HPDE storage system by changing the output power. In this method, the integral droop control is based on the characteristics of the capacitor. Where they are used to regulate the converter of the SC to accommodate transient power. While voltage and power control applied to adjust the battery's converter power for average output power [108].

2.4. Related literature of similar systems

There is little evidence available on the application of hybrid energy storage system that combines pumped hydro storage with a battery or supercapacitor on a microgrid system that is grid connected, as well as analyzing its response to load based on factors such as response time, energy, and power capacity. Therefore, related literature based on the control method, hybrid combination and modelling methods have been conducted as follows:

Jacques B. J. et al. [109], present a method to improve the performance of PV/wind hybrid microgrids by integrating a SMES/BES system and employing fuzzy logic control for energy management. This paper demonstrates improvements in energy quality and stability under various disturbances, such as wind gusts and sudden shading, through MATLAB/Simulink simulations, ensuring continuous DC bus voltage regulation and preservation of AC load voltage and frequency.

H Shao et al. [110], use FLC algorithm for HESS in microgrids, with the aim of minimizing power fluctuations between the microgrid and the external grid. By optimizing the charge and discharge processes of the SCES/BES system, the proposed method balances peak loads, reduces power exchange fluctuations, and prolongs the lifespan of the HESS. The performance of the FLC was validated, showing superior results compared to a rule-based controller.

FLC is further used together with hysteresis current method to control of HESS that combine BES and SCES, for energy management to improve the performance of standalone PV systems. This approach focusses on ensuring the share of power between BES and SCES, preventing deep discharge and overcharging, thereby improving system stability, and extending the useful life of storage devices. The simulation results presented confirm the effectiveness of the proposed strategy in maintaining regulated DC bus voltage and managing load fluctuations [111].

R Zahedi et al. explored power management for an autonomous HRES using optimally designed FLCs for storage mechanisms, including BES, SCES and hydrogen fuel cells. The study demonstrates that optimized FLCs using methods like particle swarm optimalization reduce operational and maintenance costs, improve reliability, and manage power fluctuations, with simulations showing increased hydrogen storage, reduced battery current fluctuations, and improved system stability. The integration of supercapacitors along with batteries and hydrogen storage contributes to peak power reduction and overall efficiency [112].

SMES device is once again used, however integrated with a shunt active power filter for off-grid, PV-supplied microgrids on this study. The proposed system addresses harmonic, unbalanced currents, and power fluctuations using a multi-objective control technique and FLC, demonstrating superior active filtering and power fluctuation suppression compared to traditional methods [113].

N Mousavi et al. introduced a real-time energy management strategy for PHS systems in farmhouses, with the aim of efficiently managing the surplus renewable energy of PV systems. The proposed system integrates a scheduling method with a real-time controller using ANN and FLC to handle forecast errors and optimize pump and turbine operations. Results demonstrate reductions in electricity costs and improved system performance, highlighting the potential of the strategy for economically and environmentally effective energy storage in agricultural settings [114].

In [115] the authors investigated the sizing and operation of PHS for isolated microgrids, focusing on integrating PHS with existing renewable energy sources to enhance stability and reliability. It details a mathematical model to size the PHS based on physical dimensions and a governor-excitation control system to maintain stable microgrid frequency and voltage under various load changes. The study demonstrates that the proposed control strategy manages power fluctuations efficiently and ensures a continuous power supply in the absence of wind power. More article comparison is presented on table 1:

Table 2.1Related literature of similar systems

Reference	Utilized RESs			ES technologies in HESS	Control Methods	System modelled in terms of:						
	PV	WT	Grid			RES maximum power point tracking	Energy tariff	State of Charge (SOC)	Load (U, f) control	Response time	Power density	Energy storage capacity
[109]	✓	✓	off	BESS, SMES	PI, FLC	✓	x	✓	✓	✓	✓	✓
[110]	✓	x	on	BESS, SCES	FLC	x	x	✓	x	✓	✓	✓
[116]	✓	✓	off	BESS, SMES	FLC	✓	x	✓	✓	✓	✓	✓
[117]	✓	x	on	BESS, SMES	PI, FLC	x	x	x	x	✓	✓	x
[111]	✓	x	off	BESS, SCES	PI, FLC	✓	x	✓	✓	✓	✓	✓
[112]	✓	✓	off	BESS, SCES, Hydrogen	FLC	✓	x	✓	x	x	✓	✓
[118]	✓	✓	off	BESS, Hydrogen	FLC	✓	x	✓	x	✓	x	x
[113]	✓	x	off	BESS, SMES	PI, FLC, SMC	✓	x	x	✓	✓	✓	✓
[119]	✓	x	off	BESS	FLC	x	x	✓	✓	x	x	x
[120]	✓	✓	off	BESS	FLC, SMC	✓	x	✓	✓	x	x	x
[121]	✓	✓	off	SMES	PI, FLC	x	x	x	✓	x	x	x
[122]	✓	x	off	BESS, SCES, Hydrogen	PI, FLC	✓	x	✓	✓	✓	✓	✓
[114]	✓	x	on	PHS	FLC	x	✓	✓	x	x	x	x
Current study	✓	x	on	BESS, SCES, PHS	FLC	x	✓	x	x	✓	✓	✓

2.5. Chapter discussions and conclusion

This chapter reviewed the available literature published on the hybridization of various energy storages and control strategies of hybrid energy storage system for electric microgrids applied to both standalone and grid connected systems. Based on the review conducted on the available publications on hybrid storage systems, the following were observed:

- With reference to the available energy storage systems, the PHS system has gained a lot of attention as a single storage due to its low maintenance, long life span and high energy density. However, it is accompanied by challenges such as low power density which makes it necessary to either have large water flow or large net height between the reservoirs.
- HESS systems are commonly known for electric vehicles rather than residential, commercial, and industrial areas. Therefore, many research works have concentrated on combinations such as battery-supercapacitor, fuel cell-battery and supercapacitor-fuel cell. However, the compiled literature reveals that a few studies have analyzed optimal management of PHS integrated with other storage to support RES's in this area.
- Several studies have developed an optimal management algorithm of hybrid renewable energy systems to ensure optimal power flow. However, these studies considered optimal energy management solely. from economic perspective without the inclusion of optimal sizing as well.
- Several authors have analyzed the use of hybrid renewable energy systems to improve load satisfaction with one energy storage device applied to a standalone system. However, due to the unreliable nature of the resource, a gap still exists between demand and supply.
- Other studies have concentrated on the use of hybrid energy storage systems instead of single storage to improve the reliability of hybrid renewable systems. This proved to improve the security of load supply for the standalone system. However, none of these studies have developed an optimal energy management and power control algorithm for a grid

connected hybrid energy storage system applied to residential, commercial, and industrial areas.

- The hybrid energy storage system may positively enhance the reliability and resiliency of a microgrid system featuring a battery as part of the hybrid energy system as well as improve the life span of the battery since it depends on the number of charges and discharges.
- Majority of the studies develop energy management strategies in which they exclude sizing and operation control in their objective. Therefore, the combination is rarely analyzed as a joint operation.
- Most energy management systems usually do not obtain accurate results due to losses such as electrical, mechanical, hydraulic and precipitation which are not taken into consideration. Therefore, available literature demonstrates that considering precipitation as well as optimally sizing the water storage of a PHS may result in subsequent reduction in PV size as compared to a system that ignores such losses.

Therefore, it can be said that a hybrid energy storage system may be usefully considered for renewable energy based microgrid for application in either residential, commercial, and industrial area. While considering the behavior of the storage system given the dynamics of the load and all system losses to achieve accurate results. Furthermore, several studies have developed an optimal energy management algorithm of hybrid renewable energy system to ensure optimal power flow. However, these studies considered optimal energy management solely from economical perspective without the inclusion of optimal sizing as well. Hence, to ensure optimal operation both technically and economically, the combination of both sizing and control optimization needs to be taken into consideration. Nevertheless, to improve the reliability of the hybrid renewable energy system, several studies have concentrated on the use of hybrid energy storage system instead of using single energy storage system. This proved to improve the security of load supply for the standalone system. However, none of these studies have developed an optimal energy management algorithm for a grid-connected hybrid energy storage system. Hence, to ensure optimal operation of a grid-connected hybrid energy storage system, an optimization approach needs to be developed to ensure optimal operation of the integrated short-term and long-term energy storage capacity devices. The reason being that the lifespan of the integrated storage devices is not the same.

CHAPTER 3 : OPTIMAL CONTROL AND MODELING OF THE PROPOSED SYSTEM

This chapter outlines the design of the proposed grid-connected photovoltaic microgrid, which integrates pumped hydro, battery, and supercapacitor storage systems. It includes the mathematical modelling of all system components, establishes the objective function and operational constraints, and formulates a fuzzy logic controller for optimal energy management. The controller is designed and simulated using MATLAB/Simulink to manage energy flow between the various storage units and the grid, adapting to changes in load and time-of-use tariff conditions.

3.1. Introduction

This study is designed with the purpose of accommodating three different loads i.e. commercial, industrial and residential load. Therefore, adequate and reliable electricity is very important to continuously satisfy the load demands. Due to the electricity shortage and the underproduction of conventional power stations in South Africa, blackouts and load shifting have become more frequent [123]. This has led to an increased focus on using variable renewable energy sources, such as solar and wind, for local energy generation, particularly in standalone microgrid systems. However, the intermittent nature of these renewable sources requires the integration of various energy storage systems to balance the demand-supply mismatch [124]. The currently available energy storage technologies have different characteristics, such as power capacity and response time. To leverage these differences and improve grid stability management, a combination of these technologies, known as HESS, is recommended [125]. Furthermore, to ensure the reliability and adequacy of electricity supply from a microgrid-connected renewable energy system, proper control of the implemented energy storage is necessary.

Several optimal control techniques, such as MPC, PID, RBC, and FLC, are available for different systems. Research has shown that PID and FLC are widely used in industrial applications due to their reasonable cost and reduced operation faults. As a result, FLC is selected for this work due to its ability to solve complex non-linear problems related to multidimensional systems and parameter variation problems, and its potential to outperform the standard PID control by at least 70% more control period [126].

The primary purpose of this chapter is to fulfil the two stages of the proposed combinatorial model by designing and developing both the fuzzy and optimal model. Where stage one is the development of the controller that optimizes the HESS's daily operation to assist the microgrid in receiving the appropriate power rate to guarantee an adequate energy supply. The control strategy involves the supercapacitor responding during high-demand transients, while the pumped hydro storage and battery respond to low and standard demands, respectively, while maximizing the use of renewable energy to recharge the respective storages. The optimal energy management controller is developed using the fuzzy toolbox, with input and output variables, membership functions, rule development, and surface design, as well as the design of switching times, load variation, and modelling of a microgrid-connected PV-PHS with HESS. Stage two is the system's optimization process, where a mathematical and computational model is developed with a well-defined objective function, constraints, limitations, and variables. Lastly will be the component sizing that will be based on the collected data.

3.2. System configuration

Figure 3.1. shows the schematic diagram of the proposed fuzzy controlled grid-connected PV-PHS based microgrid connected to a HESS. The performance of each storage will be modelled in terms of flexibility (response time) and load demand. The arrows represent the direction of the power flow and the control signal. The system is composed of the PV system and pumped hydro Storage (PHS) as the primary source of the system during the day and early morning/night respectively, while on the other hand the Grid, SCES, and the BES as a back up to maintain a balance system and correct response to the various load demands. i.e. Taking the advantage of each energy storage characteristics, the PHS will be used for low demand due to its nature of slow discharge and high energy density to accommodate the long hours of low energy demand in a day, BES for standard demand due to its high energy density and slow charge/discharge rates and SCES for high load demand transients due to its fast charge/discharging rates. More characteristics of the HESS are compared based on power density, energy density,

discharge time, response time, number of discharge cycles and life span on Table 3.1. Therefore, the controller will send signals to each component, commend how it should react based on time and load demand, by optimizing the power flow of the entire system. During off-peak hours, where the load is usually lower. The controller will send a signal for the PHS to discharge and supply the load whilst the grid act as a backup. Whereas during peak hours, where the load demand is higher, the PHS storage act as a backup whilst the SCES discharges to accommodate the high load demand transients. Lastly, during daytime, the PV will be instructed to supply the load with the battery as a backup for cases where conditions are unfavourable for the PV to operate. Therefore, the hybrid energy storage system will be recharged by the excess energy generated by the PV system when the load demand is lower than the PV output power during the day and by the grid when the price of the electricity is at its lowest at night.

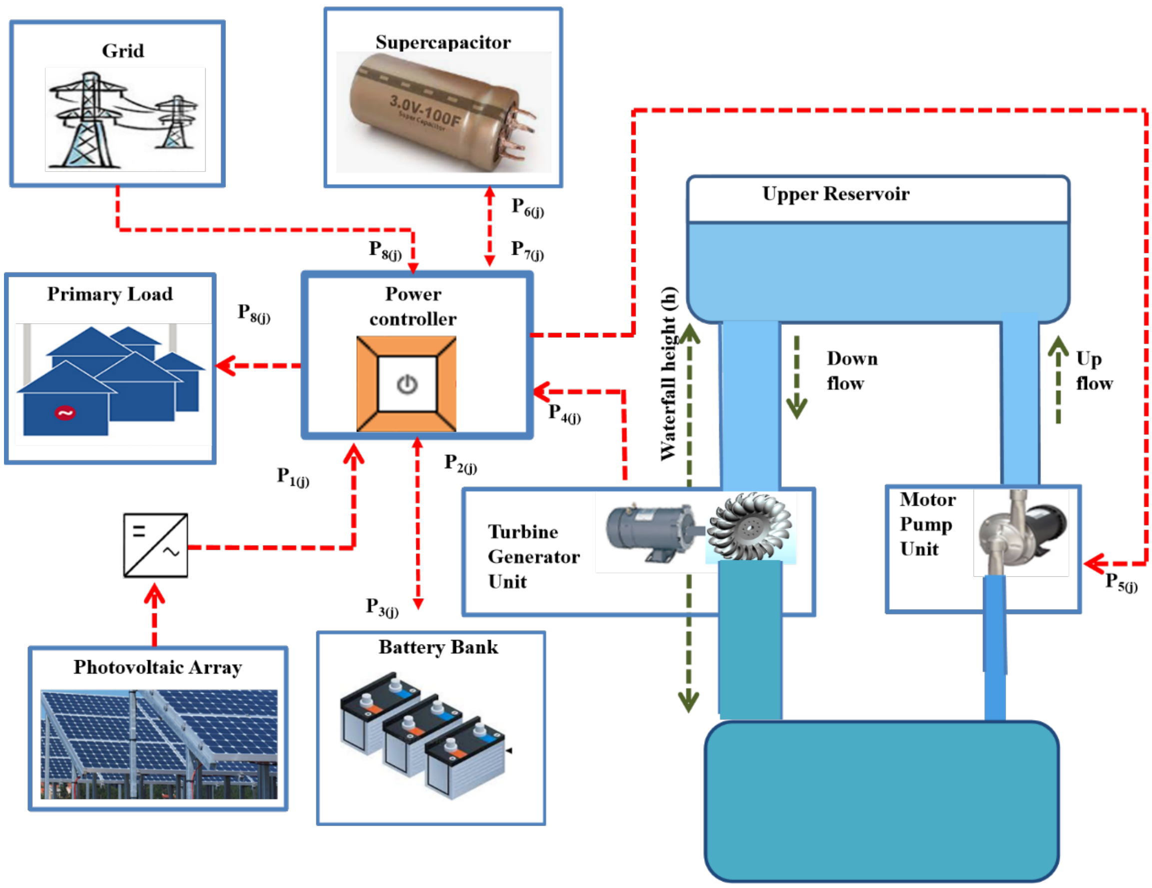

Figure 3.1 Proposed schematic diagram

Table 3.1 Related energy storage comparison

Variable	BESS (Li-ion)	SCES	PHES	REFERENCES
Power density, W/kg	360	500 - 5000	N/A	[127]
Energy storage capacity, MWh	10-5 -100	10-6 -10-2	4·10-3 - 1000+	[128, 129]
Discharge time	Mins - hours	Milisecs - 1 h	1 - 24 h	[127]
Response time	Milisecs	Milisecs	≈3 min	[128]
Number of discharge cycles (if DOD 80%)	2000 - 5000+	>100,000	N/A	[128]
Lifetime	5 to 15 yrs	> 20 yrs	30 to 60 yrs	[127]

3.3. Flow diagram of the proposed system

Figure 3.2 depicts the two-stage combinatorial flow diagram of the proposed system. The first stage consists of a control system, while the second stage is an optimal system. The second stage can only be fully completed after the first stage is well operational.

Stage 1: Fuzzy Logic Control System

- A fuzzy logic control system is developed and modelled based on the desired operation of the overall system.
- This is achieved by introducing a set of rules which are initialized to meet the aims and objectives of the study.
- Upon completion of the control system, the resultant operation must reflect the behavior set in the rules. If not, the initialization process must be repeated until it is correct.

Stage 2: Optimal System Design

- In the second stage, all the system's components are modelled and sized based on the load demand.
- This stage can only be completed once the control system in stage one is fully operational.

System Integration

- Once both stage one (control system) and stage two (optimal system) are completed, the resultant systems are integrated to create one overall system.

- This integrated system is then simulated in MATLAB Simulink to achieve the desired results.

This approach allows for a structured development process and ensures that the control system and optimal system design are both well-aligned to achieve the overall objectives of the study.

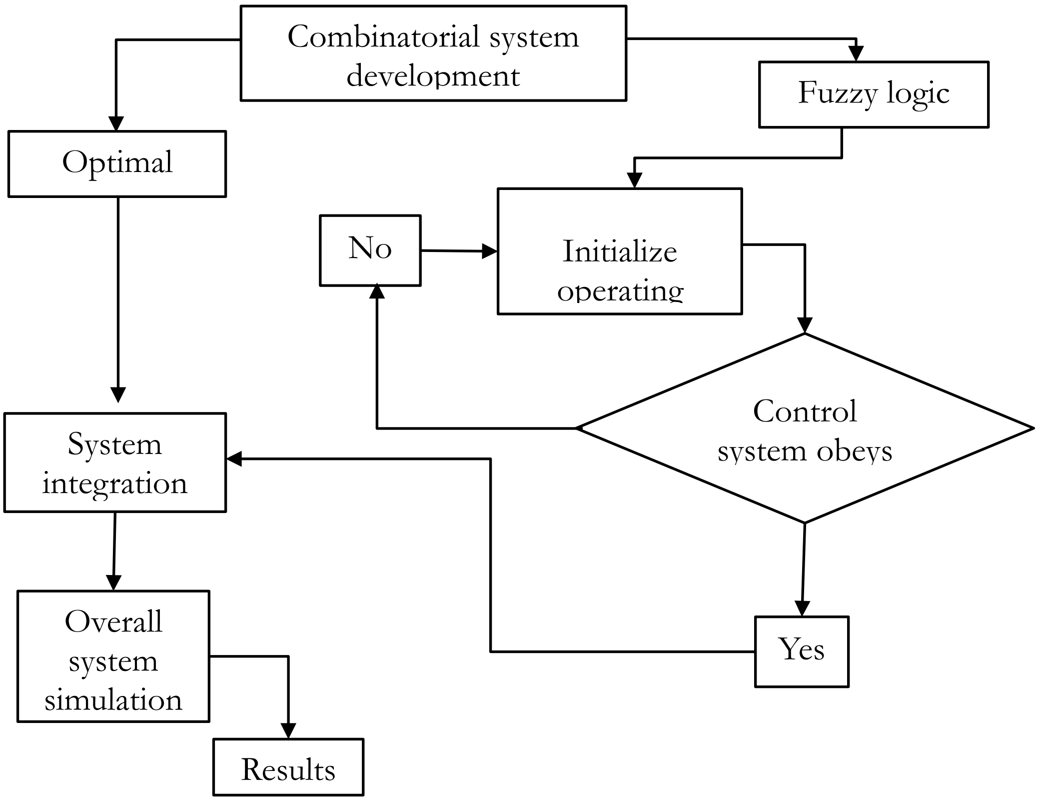

Figure 3.2 Combinatorial flow diagram

3.4. Mathematical system modelling

3.4.1. Objective function

The primary objective of this work is to develop an optimum algorithm to manage and control the energy exchange between the load and the HESS. The key aims of this algorithm are:

- Reducing the overall operating costs of the system
- Minimizing the use of grid energy and maximizing the use of renewable energy

- Improving the lifespan of the HESS by taking advantage of the ToU tariff

Therefore, the total cost of the system's operation will be formulated as follows:

$$F = [min \sum_{j=1}^{N} C_j.\left(P_{8(j)}\right) - max \sum_{j=1}^{N}\left(P_{1(j)}\right)]\Delta t \qquad 1\leq j\leq N) \qquad (1)$$

Where $P_{8(J)}$ is the power from the utility Grid and $P_{1(j)}$ is the power from the PV.

3.4.2. System Constraints

3.4.2.1. Equality constraints

A. Power balancing

The constraint of power balance is important to guarantee that the primary load is always covered without shortage. Therefore, the sum of the power supplied by the HESS, PV and the Grid should equal to the total load demand. The power flow is controlled by the Fuzzy Logic intelligence to balance the power through the expressed Equation below:

$$P_{load(j)} = P_{1(j)} + P_{2(J)} + P_{4(j)} + P_{6(j)} + P_{8(J)} \qquad (1\leq j\leq N) \qquad (2)$$

Where $P_{1(j)}=P_{pv}$ is the power generated by the PV system, $P_{2(j)}=P_{B(out)}$,is the power from the battery system, $P_{4(j)}=P_{TG}$ is the power generated by the turbine, $P_{6(j)}=P_{SC(out)}$, is the power from the super capacitor and $P_{8(j)}= P_{Grid}$ is the power allowed from the grid.

B. Fixed final state conditions

For smooth operation of the proposed system, the final state of the energy stored in the HESS should match the initial state for a specific simulation period. Therefore, this may be modelled as follows:

$$\left.\begin{array}{l} \sum_{j=1}^{N}\left(P_{5(j)}\right) - \sum_{j=1}^{N}\left(P_{4(j)}\right) = 0 \qquad (3) \\ \sum_{j=1}^{N}\left(P_{3(j)}\right) - \sum_{j=1}^{N}\left(P_{2(j)}\right) = 0 \qquad (4) \\ \sum_{j=1}^{N}\left(P_{7(j)}\right) - \sum_{j=1}^{N}\left(P_{6(j)}\right) = 0 \qquad (5) \end{array}\right\} \quad (1\leq j\leq N)$$

Where $P_{5(j)} = P_{MP}$ is the power required by the motor pump, $P_{3(j)} = P_{B\ (in)}$ is the power flowing into the battery and $P_{7(j)} = P_{SC\ (in)}$ is the power the power flowing into the supercapacitor.

C. Control variable limits

The power generated by the PV system, turbine generator as well as the HESS are assumed to be adaptable sources which may be kept between zero and their maximum rated output for the total simulation period of 24 hours. Therefore, these constraints will depend on the characteristics of each source as expressed below:

$$\left.\begin{aligned} &0 \le P_{1(j)} \le P_1{}^{max} && (6)\\ &0 \le P_{2(j)} \le P_{2(j)}{}^{rated} && (7)\\ &0 \le P_{3(j)} \le P_{3(j)}{}^{max} && (8)\\ &0 \le P_{4(j)} \le P_{4(j)}{}^{rated} && (9)\\ &0 \le P_{5(j)} \le P_{5(j)}{}^{max} && (10)\\ &0 \le P_{6(j)} \le P_{6(j)}{}^{rated} && (11)\\ &0 \le P_{7(j)} \le P_{7(j)}{}^{rated} && (12)\\ &0 \le P_{8(j)} \le P_{8(j)}{}^{rated} && (13) \end{aligned}\right\} \quad (1 \le j \le N)$$

3.4.2.2. Inequality constraints

The inequality constraints are important factors to be considered for generation/discharging limits of the subsystems system. So that, at any given sampling period, the total energy supplied by a source/storage must never exceed the expected maximum output of that system. Therefore, the inequality of the PV, grid and the HESS is expressed as follows:

$$\left.\begin{array}{l} P_{1(j)} \le P_{PV(j)}{}^{max} \quad (14) \\ P_{2(j)} \le P_{B(j)}{}^{rated} \quad (15) \\ P_{4(j)} \le P_{TG(j)}{}^{rated} \quad (16) \\ P_{6(j)} \le P_{SC(j)}{}^{rated} \quad (17) \\ P_{8(j)} \le P_{G(j)}{}^{rated} \quad (18) \end{array}\right\} \quad (1 \le j \le N)$$

3.5. Fuzzy intelligent control

Lately, FLC has been the most applied and feasible control under the fuzzy set theory in research. This control function is widely used in many research topics, such as autonomous systems and control theory [130]. Its priority of use is due to the associated characteristics like simple and non-dependent solutions to complex mathematical problems, quality power flow management in hybrid applications, low current fluctuation, and adaptability [131,132]. This control method is based on the translation of the input variable to a simpler language of measure such as peak, off-peak, standard, low, very low, high, medium, and very high etc. and formulation of control rules to achieve the desired output [130].

Recent literature shows the application of fuzzy based integral controller on an isolated microgrid system to eliminate frequency fluctuations. The results of the work revealed that the system has a dynamic performance when compared to other low frequency controllers [133]. FLC is as well applied on a tourist ship for energy management strategy on a hybrid power system. It was further improved by incorporating the small wave analysis and Proportional-integral (PI) control to analyses the optimal power distribution. The results show approximately fourteen percent of hydrogen reduction and improved balance in the battery's state of charge [134]. Furthermore, FLC was used to neutralize the variability of active and reactive power of the smart home energy storage [135]. Therefore, in this case the fuzzy logic energy-based control is explained in detail under this section, the controller will be used to command the correct source/ storage for supply or load satisfaction by sending a signal to at the right time.

3.5.1. Optimization technique

The proposed fuzzy intelligent controller has six inputs and four outputs, as illustrated on Figure 3.3. The inputs (shaded in yellow on the left) is the time schedule of the sources, power consumption rate (load demand scale), PV output, as well as the supercapacitor, battery, and pumped hydro storage's state of charge. The outputs (shaded in blue on the right) consists of power sources (grid, SCES, PV, BES, and PHS). The control is programmed to determine the status of all sources' state of charge, to manage and control the power required at a specific time. This power controller, sends/receives signals to/from both primary sources and back-up systems, respectively, to determine when specific source or back-up should operate to continuously meet the load demand without shortages.

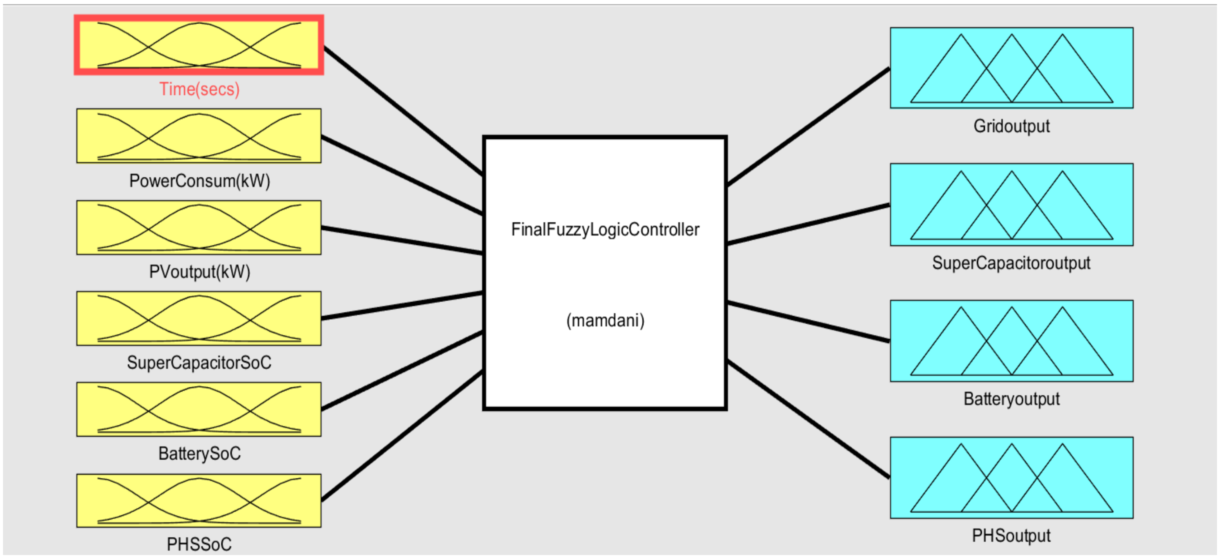

Figure 3.3 Block diagram of the proposed FLC system

3.5.2. Fuzzy logic application

Figure 3.4 demonstrates of the FLC process i.e. Inputs, fuzzification, application criterion and fuzzy processing, defuzzification as well as the desired output. The fuzzification module decodes the standard values of the control input to fuzzy values. These values are defined in terms of any desired measure. The developed fuzzy values are further associated with the criterion of choice based on the desired factors such as system performance requirements, constraints, reliability, and interpretability. They are then processed through fuzzy sets, where they are individually defined by adjusting the membership functions of between "0" and "1" rather than binary membership of "0" and "1". Then lastly, is the defuzzification process which translates the fuzzy output of a fuzzy interference system into a clear decision or control action.

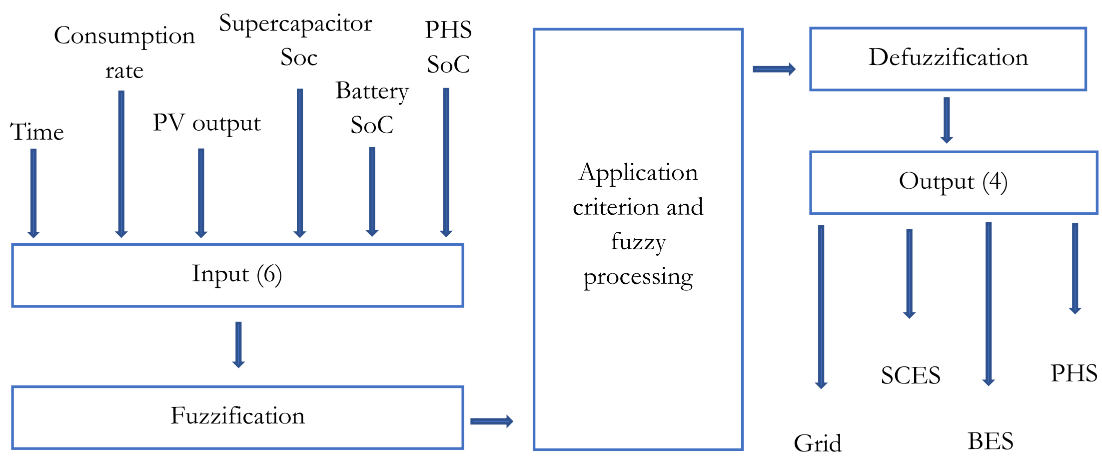

Figure 3.4 Block diagram of the FLC development process

3.5.3. Time frames definitions

Six categories are used to describe the tariff types of a specific time frame in twenty-four hours. These time frames were designed with reference to South African public electric utility company's (Eskom) weekdays ToU tariff 2023/24. The process of input 1 fuzzification is explained in the details on Table 3.2.

Table 3.2 Fuzzification of time frames

Description of input 1 (Time)		
Time range (24 Hours)	**Tariff type**	**Abbreviations**
00:00-05:59	Morning Off Peak	MOP
06:00-08:59	Morning Peak	MP
09:00-16:59	Morning/Afternoon Standard Demand	M/ASD
17:00-18:59	Evening Peak	EP
19:00-22:59	Evening Standard demand	ESD
23:00-23:59	Evening Off Peak	EOP

3.5.4. Power consumption definition

Table 3.3. shows the overall energy consumption range, where the consumption is categorized in six different sets. Ranging from zero to a maximum of thirty kilowatts hour (kWh). The peak load demand is assumed to be thirty kWh per day for a household that consumes energy that is above average during high demand season.

Table 3.3 Fuzzification of consumption rate

Description of input 2 (Consumption rate)		
Consumption range (kW)	**Consumption type**	**Abbreviation**
0-1	Very low consumption	VLC
1.1-10	Low consumption	LC
10.1-20	High consumption	HC
20.1-30	Very High consumption	VHC

3.5.5. PV output definitions

Table 3.4 shows the amount of power generated/ produced by the PV system. The production is categorised in six different sets, ranging from zero to a maximum of 50 kW. The system size is designed to be above the primary load.

Table 3.4 Fuzzification of primary power sources

Description of input 3 (PV output)		
Power generation (kW)	**Generation rate**	**Abbreviation**
0-5	Very low power	VLP
5.5-10	Low power	LP
10.5-20	Average power	AP
20.5-30	High power	HP
30.5-40	Very high power	VHP
40.5-50	Peak power	PP

3.5.6. Storage SOC definitions

Table 3.5 shows the charge status of power stored by the storage systems. The storage statuses are categorised in four different sets, ranging from zero to hundred percent. With zero as the lowest or empty and 100% being the storage at full charge.

Table 3.5 storage state of charge fuzzification

Description of input 4-6 (storage SOC)			
Storage	Charge range (%)	Status	Abbreviation
	0%-30%	Very low	VL
Supercapacitor/	31%-40%	Low	L
Battery/	41-70%	High	H
PHS	71-100%	Very high	VH

3.5.7. Power source definitions

Various sources and their combinations are expected to satisfy the load demand without shortage throughout the day. Based on the size of the load at a specific time, the corresponding source or combination must take over accordingly as show in Table 3.6.

Table 3.6 Fuzzification of primary power sources

Description of Output 3 & 4 (Primary power sources)		
Time range (24 Hours)	Source type	Abbreviation
00:00-05:00	Pumped Hydro Storage + Grid	PHS+grid
04:30-10:00	Pumped Hydro Storage	PHS
08:00-17:00	Photovoltaic	PV
16:00-20:30	Pumped Hydro Storage	PHS
20:00-23:59	Pumped Hydro Storage + Grid	PHS+grid

3.5.8. Fuzzification of input and output of the controller

Table 3.7. depicts the input and output variables of the controller's complete configuration. Where there's Time (h) and Consumption rate (kWh) as selected input variables, whilst on the output side we have two outputs as the primary sources (PV & PHS) rated in Kilowatts and the other three outputs as the backup system which consist of the grid (kW), supercapacitor (kW), and the battery (kW).

Table 3.7 Fuzzification of input and output of the controller

Description of FLC variables			
Input 1 Time(H)	Input 2 Consumption (kWh)	Output 4 & 5 Primary Sources (kW)	Output 1-3 Backup (kW)
00:00-05:30	VLC (0-5)	PHS	Grid
05:00-09:00	HC (20-25)	PHS	SC
08:30-13:00	LC (5-10)	PV	BT
13:00-17:00	AC (10-15)	PV	BT
16:30-20:00	VHC (25-30)	PHS	SC
20:00-23:59	AAC (15-20)	PHS	Grid

3.5.9. Membership functions

A membership function (MF) serves as a quantitative representation of the degree to which a given input is associated with a specific set. MFs facilitate the conversion of non-fuzzy input values into corresponding fuzzy linguistic terms [136]. In fuzzy logic systems, various forms of membership functions are utilized, including triangular, trapezoidal, piecewise linear, Gaussian, and singleton functions. The choice of a specific MF is contingent upon the nature of the data or information that is being interpreted from its geometric representation. Triangular and trapezoidal MFs are frequently employed due to their simplicity and their ability to yield values within the range of zero to one, making them particularly advantageous for applications where the shape of the MF is not a primary concern. Conversely, when the shape of the MF is critical, triangular, or Gaussian MFs are often preferred, as they have demonstrated superior performance relative to other available options. In this study, a trapezoidal MF has been selected. Each membership function is distinctly labelled in the associated plots. The initial plot encompasses six functions identified as MOP, MP, MSD, APD, EP, and EOP, as illustrated in Table 3.2 and Figure 3.5.

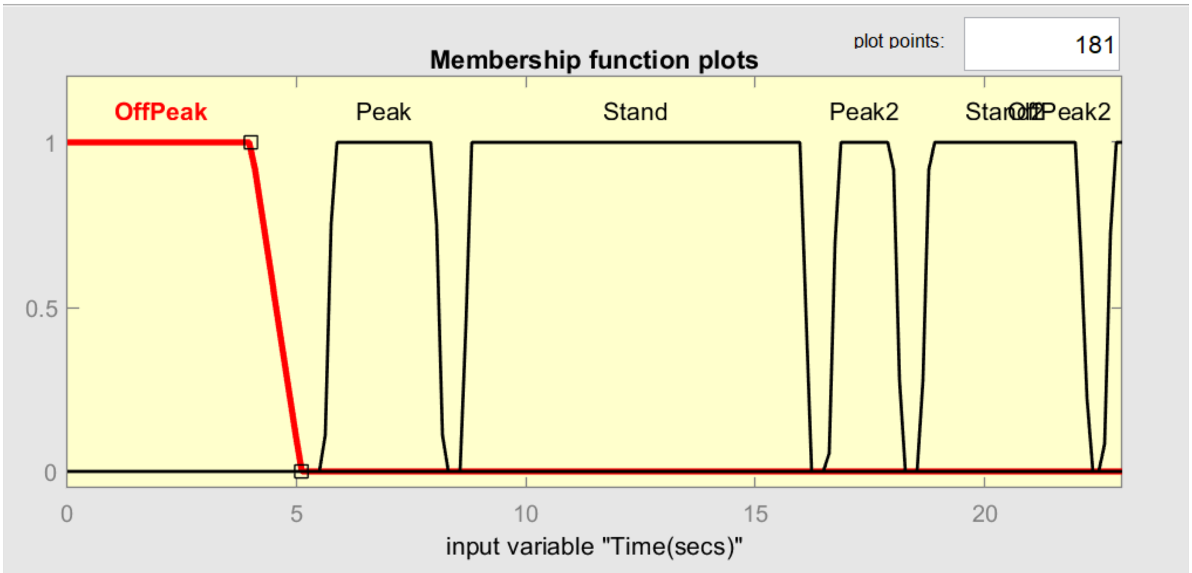

Figure 3.5 Time membership function

The second plot is represented by functions labelled VLC, LC, HC, and VHC, which denote varying levels of energy consumption, ranging from very low to very high, as depicted in Table 3.3 and Figure 3.6.

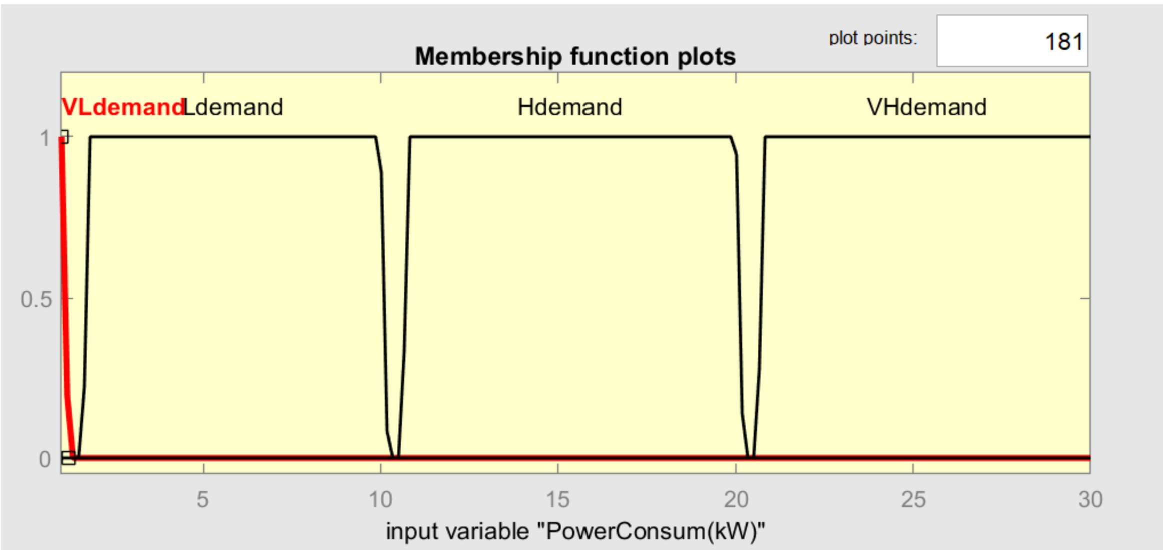

Figure 3.6 Consumption membership function

The third plot quantifies the power output of the photovoltaic (PV) system, with the function labels VLP, LP, AVP, HP, VHP, and PP, as shown in Figure 3.7.

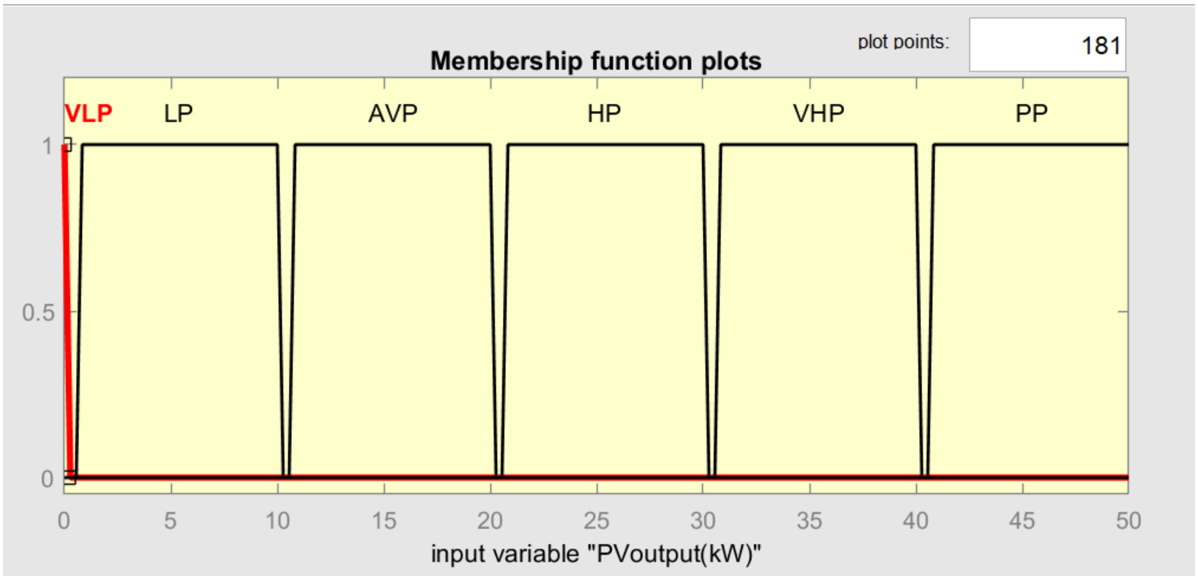

Figure 3.7 PV membership function

The remaining three inputs are illustrated in Figures 3.8 through 3.10, employing function labels for each state of charge in the storage systems: $Sc_{VLsoc}/Batt_{VLsoc}/PHS_{VLsoc}$,$Sc_{Lsoc}/Batt_{Lsoc}/PHS_{Lsoc}$,$Sc_{Hsoc}/Batt_{Hsoc}/PHS_{Hsoc}$, and $Sc_{VHsoc}/Batt_{VHsoc}/PHS_{VHsoc}$. The system's output comprises of four membership plots, three of which each contain three functions.

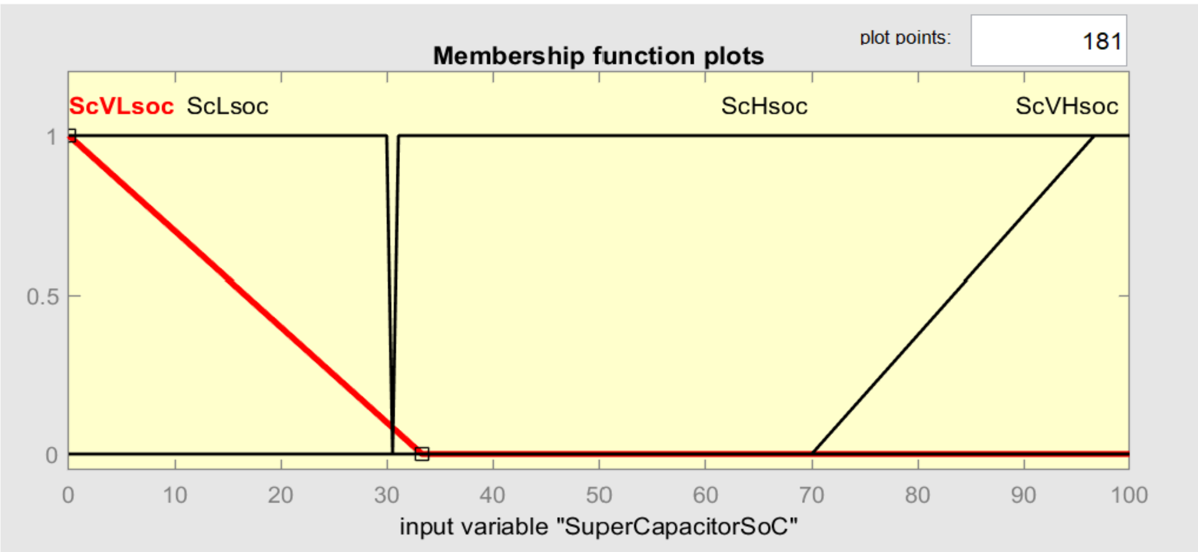

Figure 3.8 Supercapacitor SoC membership function

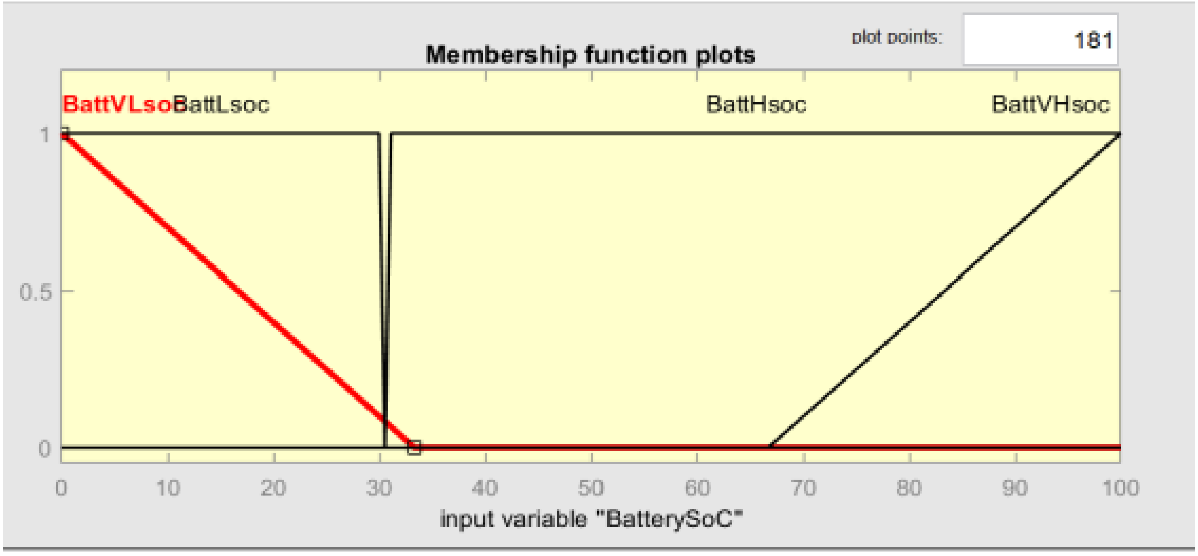

Figure 3.9 Battery SoC membership function

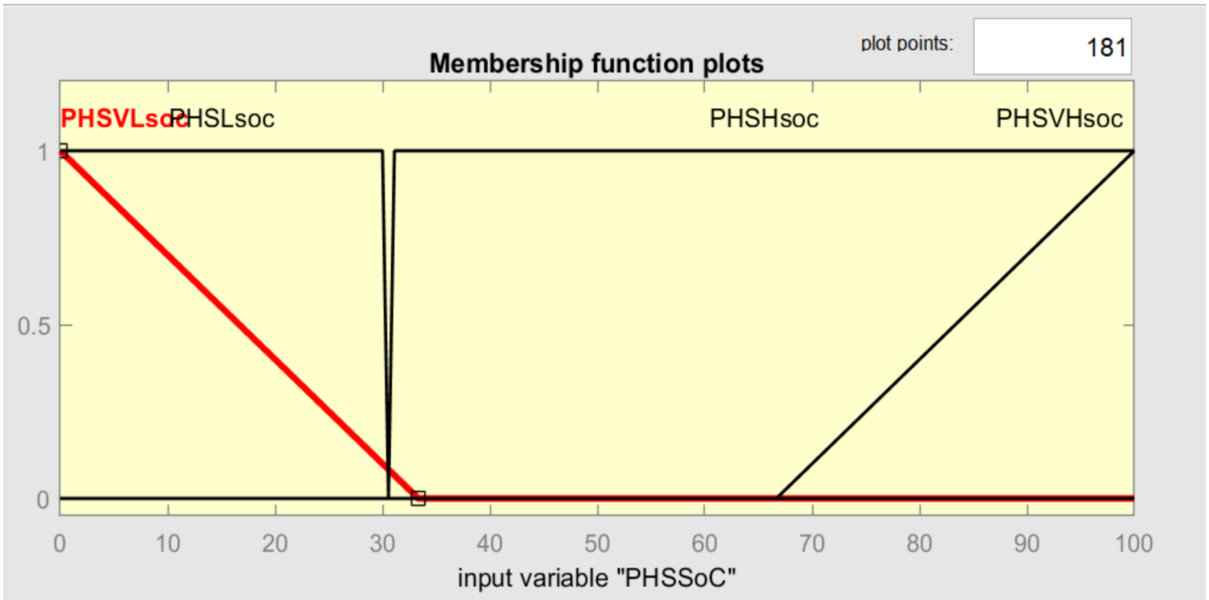

Figure 3.10 PHS SoC membership function

The first output, corresponding to the grid, includes only two membership functions labelled Gridoff and Gridon, as represented in Figure 3.11.

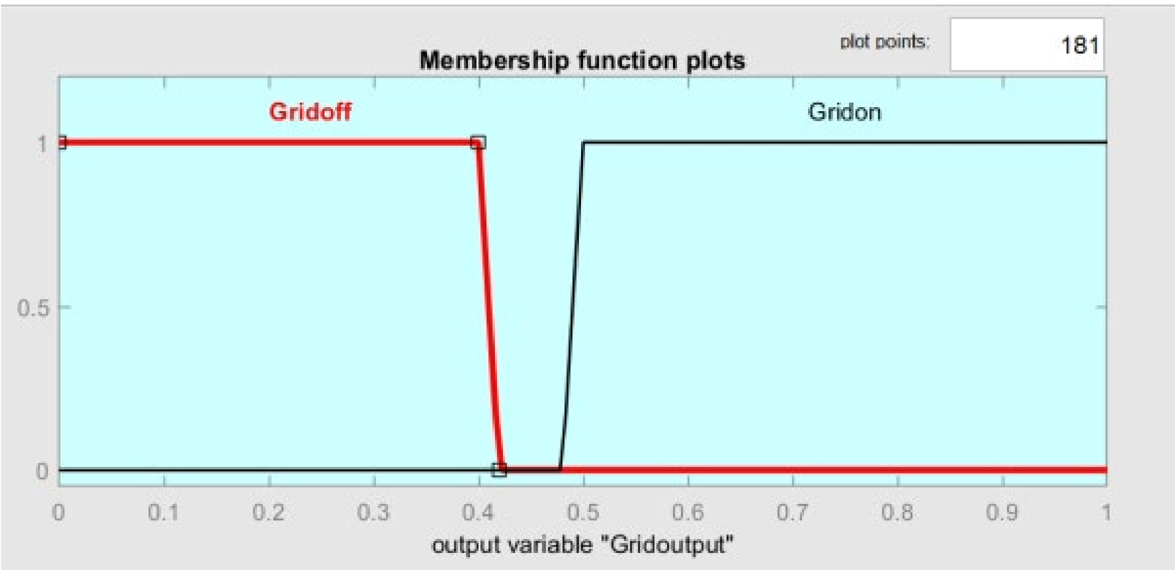

Figure 3.11 Grid membership function

The final three plots are designated with the following labels: $Sc_{off}/Batt_{off}/PHS_{off}$, $Sc_{Charge}/Batt_{Charge}/PHS_{Charge}$, and $Sc_{Discharge}/Batt_{Discharge}/PHS_{Discharge}$. These representations effectively demonstrate the operational states of the storage systems, indicating whether they are in an off, charging, or discharging state during specified periods, as illustrated in Figures 3.12 through 3.14.

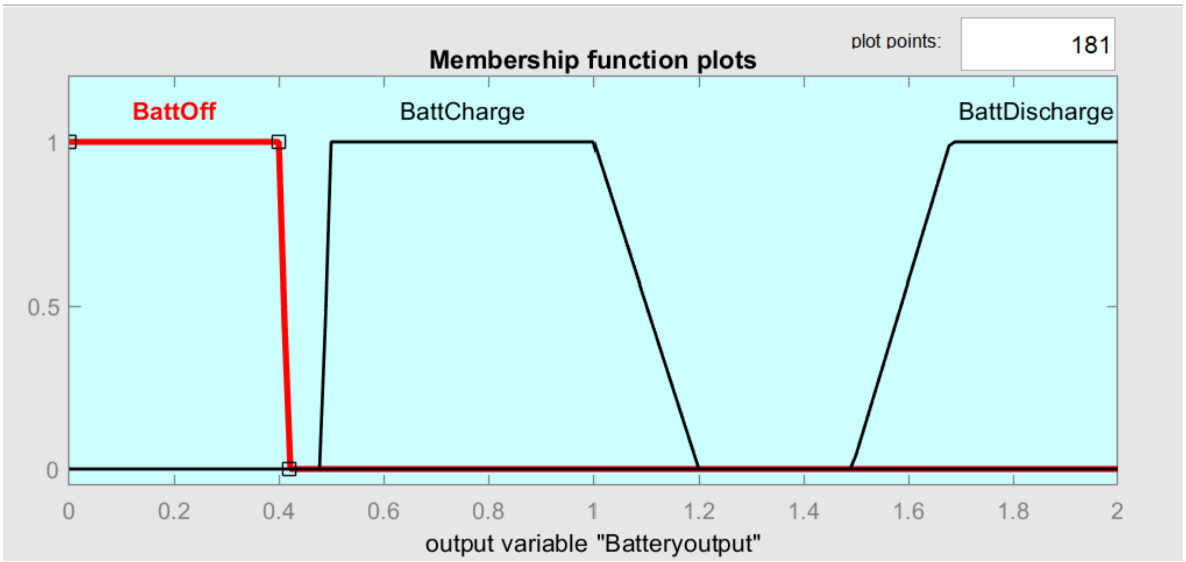

Figure 3.12 Battery membership function

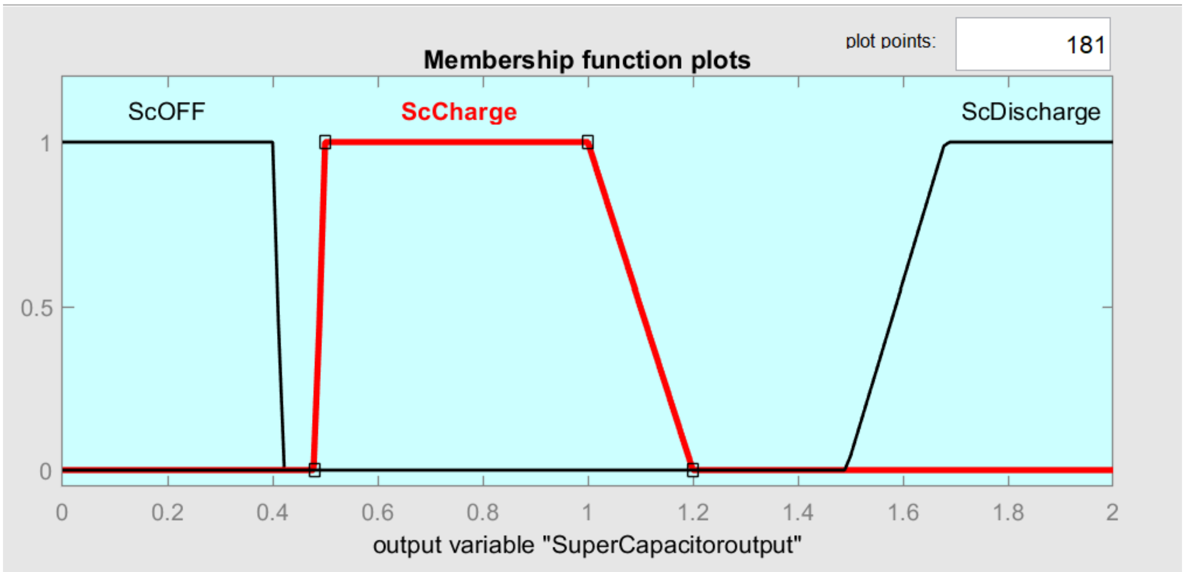

Figure 3.13 SC membership function

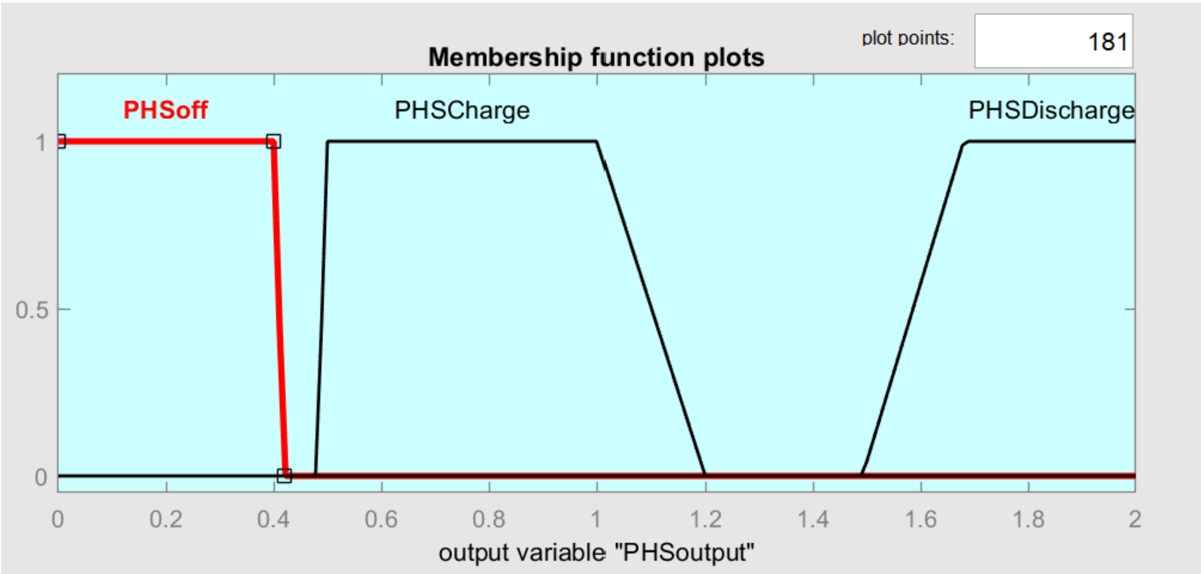

Figure 3.14 PHS membership function

3.5.10. Fuzzy logic rules

Fuzzy controller rules can be the brain of a control system. These rules are based on simple instructions using 'if-then' notation with a choice of 'or' / 'and' combinations. These instructions are derived from the objectives and constraints of the designed system presented in chapter. 1152 rules are designed to manage six sets of input variables and four sets of output variables to prepare the modelling of the designed microgrid system with hybrid storage in MATLAB Simulink. Table 3.8 lists the main 27 rules that manage the proposed control system with fuzzy logic.

Table 3.8 Main governing rules of the proposed system

Rule number	Description
1.	If the time is MOP, the tariff type is off-peak, and consumption is (average/high) then prioritise PHS (no grid)
2.	If the time is MOP, the tariff type is off-peak and consumption is (exceptionally low/ low) with no PHS, then output is Grid.
3.	If the time is MOP, the tariff type is off-peak, and consumption is (remarkably high) then prioritise SC (no grid).
4.	If the time is MP, the tariff type is Peak, and consumption is (exceptionally low/ low/ average) then prioritise PHS (no grid).
5.	if the time is MP, the tariff type is Peak, and consumption is (high/remarkably high) then prioritise SC (no grid).
6.	If the time is MSD, the tariff type is standard, and consumption is (exceptionally low/low/ average) then prioritise PV (no grid and battery).
7.	If the time is MSD, the tariff type is standard and consumption is (exceptionally low/ low/average) with no PV, then prioritise battery (no grid)
8.	If the time is APD, the tariff type is peak, and consumption is (exceptionally low/low/ average) then prioritise PHS (no grid).
9.	If the time is EP, the tariff type is peak, and consumption is (high/remarkably high) then prioritise SC (no grid).
10.	If the time is EOP, the tariff type is standard, and consumption is (exceptionally low/ low/average) then prioritise PHS (no grid and SC).
11.	If the time is EOP, the tariff type is standard, and consumption is (remarkably high/high) then prioritise SC (no grid).

3.6. Optimal system modelling

The analyzed overall microgrid system incorporates a hybrid energy storage configuration, integrating components such as batteries, supercapacitors, and pumped hydro storage as backup solutions. These components are managed by FLC, implemented within the MATLAB/SIMULINK environment, as illustrated in Figure 3.15. The system is engineered to mitigate power flow imbalances that may arise due to variable load demands. The fuzzy logic controller ensures timely and accurate signal transmission to the appropriate energy storage component in response to specific load consumption scenarios. In instances where the PV system or grid supply is insufficient to meet the load demand, the FLC activates the backup system by sending a signal to fulfil the required energy demand. Thus, the fuzzy intelligent controller assumes a pivotal role in the energy management of the hybrid energy storage system, facilitating optimal operation under fluctuating conditions.

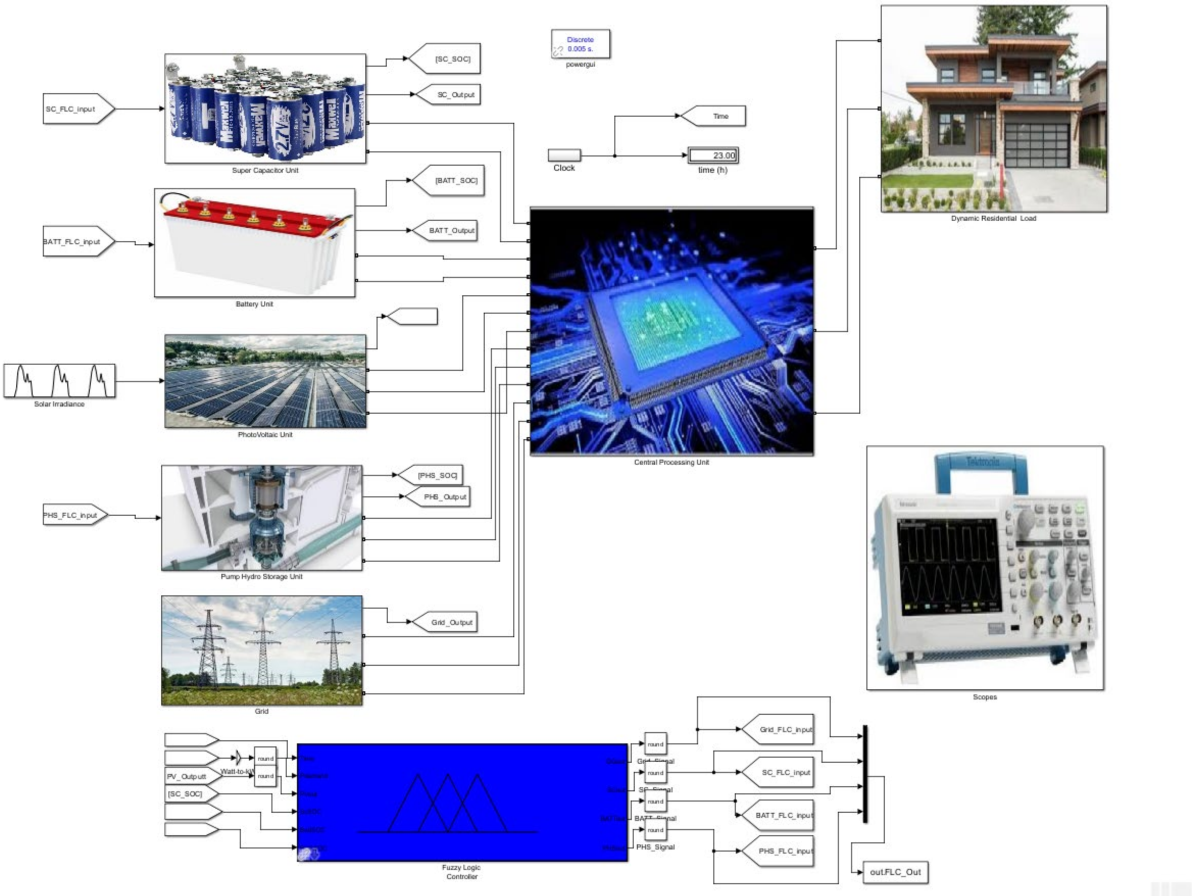

Figure 3.15 Simulink model of the overall proposed system

3.6.1. Solar PV system

The output power of a PV system is influenced by the incident global solar radiation, the operational temperature of the PV panels, and the derating factor. The derating factor quantifies the impact of various losses that reduce the module's actual power output relative to its theoretical maximum performance Li et al [137]. Therefore, the designed mathematical model for the PV array implements a PV system that can generate a maximum power of 50 kW, while accounting for a derating factor of 85%. The system consists of 167 solar panels (300W each) connected in series strings of 10 panels each. Therefore, using equation (19) as documented by HOMER technical library Khosravani et al [138], the system is modelled on Simulink using block diagram as shown on figure 3.16.

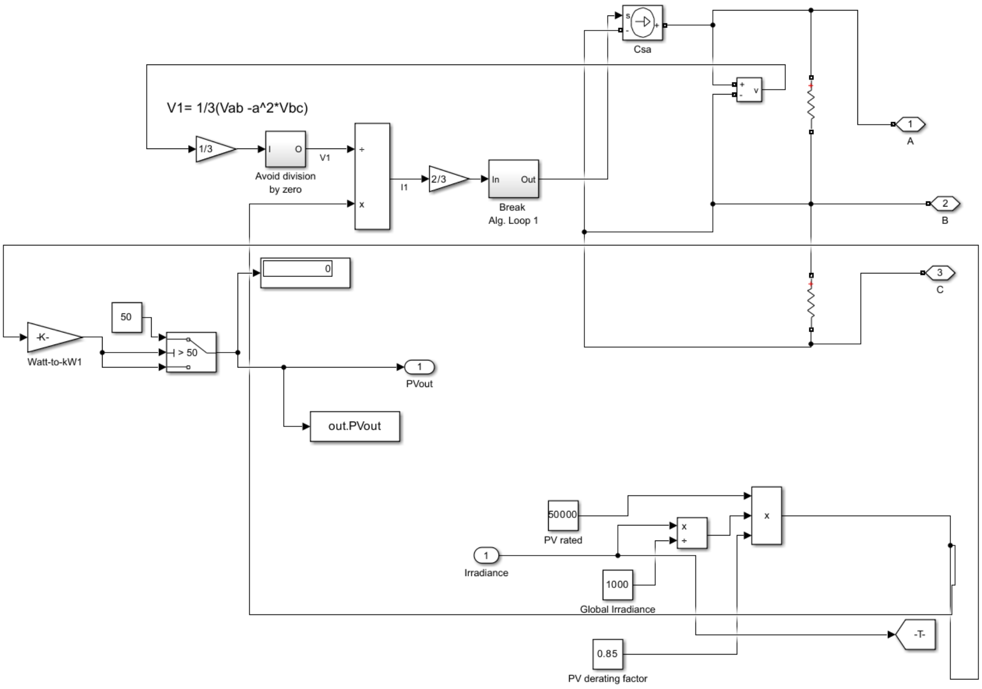

Figure 3.16 Simulation diagram of solar PV system generation

$$P_{PV} = Y_{PV} \times f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_C - T_{STC} \right) \right] \quad (19)$$

Where, Y_{PV} (kW) is the rated capacity of the PV array (power output at standard test conditions), f_{PV} (%) is the derating factor, $\bar{G}_T$ (kW/m2) is the solar radiation incident on the PV array, $\bar{G}_{T,STC}$ (1 kW/m2) is the incident radiation at standard test conditions, α_p (%/°C) is the temperature coefficient of power, which is a negative number that indicates the decrease of PV power output with an increase on cell temperature, T_C (°C) is the PV cell temperature, and $T_{C,STC}$ (25 °C) is the PV cell temperature under standard test conditions.

3.6.2. Pumped hydro system

In this section the mathematical model of a Pumped hydro storage is presented in figure 3.17 the system was modelled by combining an existing Simulink block and an equation that expresses the charging and discharging by means of a motor pump input power and turbine generator output power respectively. The system features a 3-phase synchronous machine that is connected to a hydraulic turbine, governor, and excitation system. The stator's winding is wye connected to a 31,3kVA, 400V and 50H internal neutral point. Assisted by hydraulic turbine model that was designed by the IEEE working group for use in MATLAB simulation. Therefore, the operating principles of both turbine and motor pump depends on the following equations modelled on Simulink as shown on equation (20).

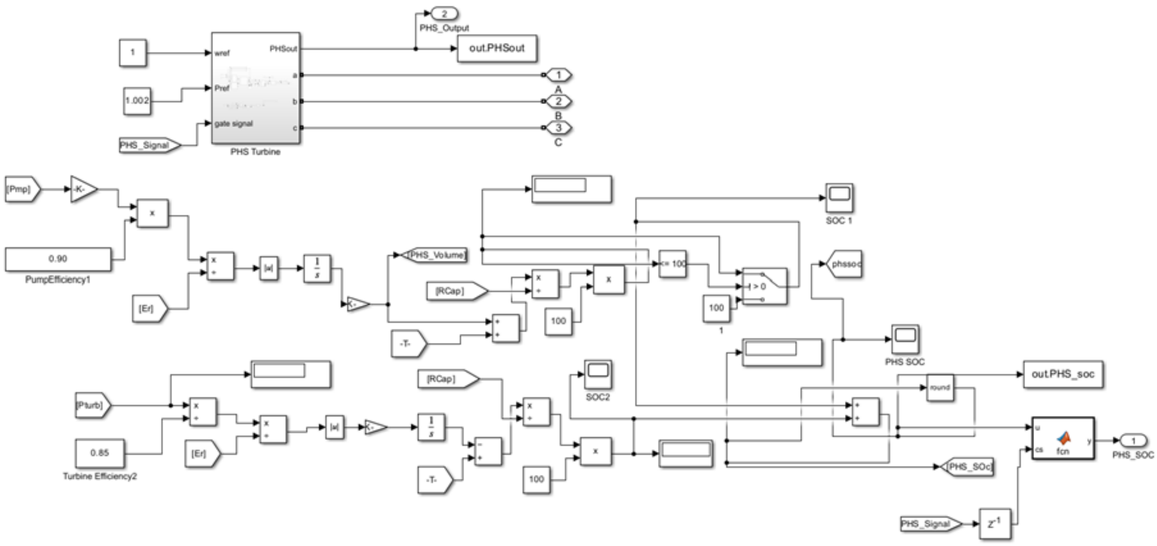

Figure 3.17 Simulation diagram of PHS system

$$P_{PHS_{OUT}} = \rho_W \times g \times h \times Q_{TG} \times \eta_{TG} \tag{20}$$

3.6.3. Battery system

Figure 3.18 Implements a generic battery model for most popular battery types. Temperature and aging (due to cycling) effects can be specified for Lithium-Ion battery type. With a nominal voltage of 48V, 208Ah, 50% initial state of charge (SoC) and battery response time of 15 seconds. The battery's state of charge is modelled separately to ensure that the battery operates when its condition is favourable to operate. Furthermore, Due to the nature of the renewable energy source, a boost converter is essential for efficiently utilizing battery storage and providing voltage regulation, improving power delivery, as well as enabling smooth integration of renewable energy sources.

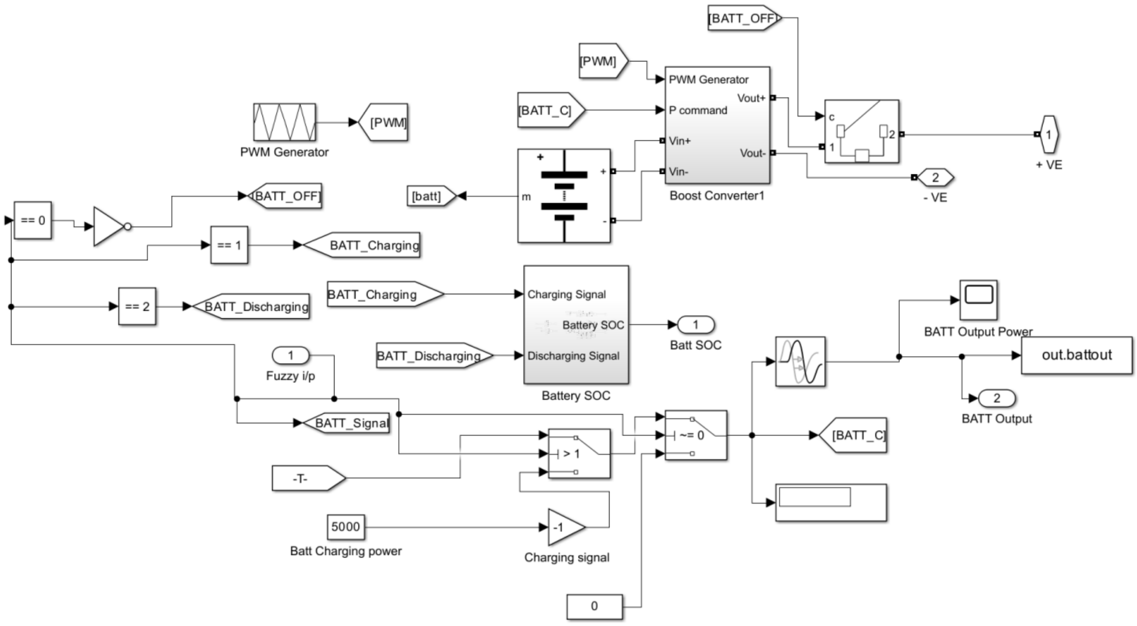

Figure 3.18 Simulation diagram of BT system generation

3.6.4. Supercapacitor System

Figure 3.19 implements a generic supercapacitor model which allows the simulation of Electric Double Layer Capacitors (EDLCs). The capacitor's rated capacitance is 8.9 Farads, DC series resistance of 0,0021 ohms, rated voltage of 48 volts at 25 degrees Celsius. The capacitor is connected to a buck booter converter to regulate voltage, energy management and maintain flexible output. Supercapacitors have a voltage range that can vary significantly as they charge and discharge. A buck-boost converter can maintain a stable output voltage regardless of whether the supercapacitor's voltage is above or below the desired level. It can further optimize the energy transfer from the supercapacitor to the load, ensuring that energy is used efficiently, which is critical in applications where power supply stability is needed.

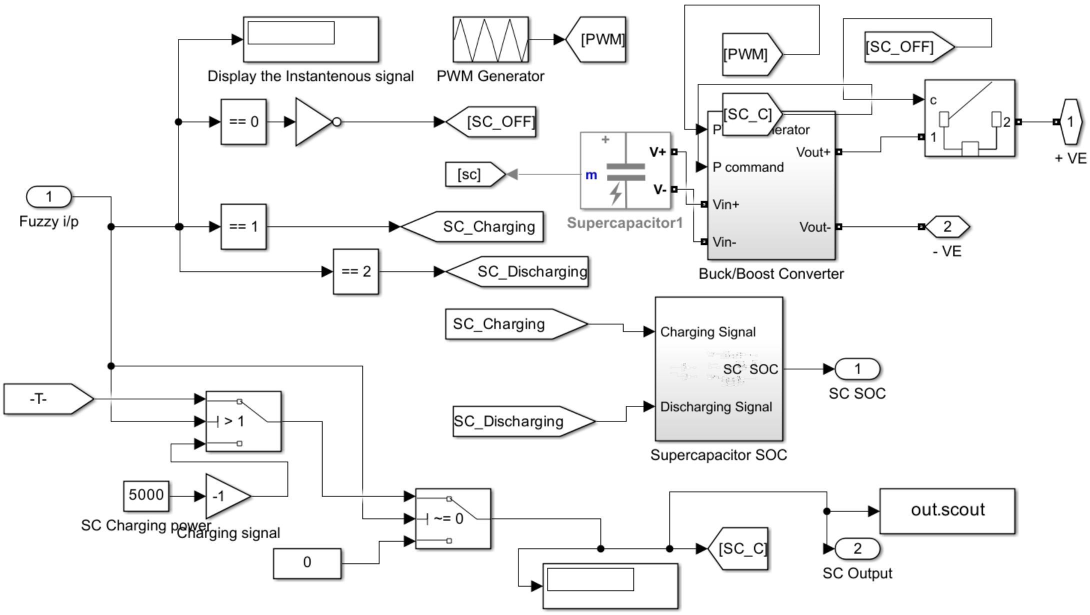

Figure 3.19 Simulation diagram of SC system generation

3.6.5. Grid system

Figure 3.20 demonstrates a three-phase voltage source in series with an R-L branch, a star-delta configuration is used to accommodate the three phases. The phase-phase voltage is set to 400Vrms, zero degrees phase angle for phase A at 50 hertz frequency. The source resistance is set to 0,89 ohms with an inductance of 0,0168 Henry and lastly the base voltage of 380 Vrms. The source is the then connected to a three-phase transformer through a three phase power measuring tools. The transformer block implements a three-phase transformer by using three single-phase transformers. The winding connection was set to 'Yn' to access the neutral point of the Wye. This simple model demonstrates the basic components of a power grid in Simulink, allowing for analysis of power flow and system behaviour. The system is expanded by combining it with a hybrid storage system in a PV supplied microgrid to represent grid electricity that is allowed to feed the load only when the price is affordable.

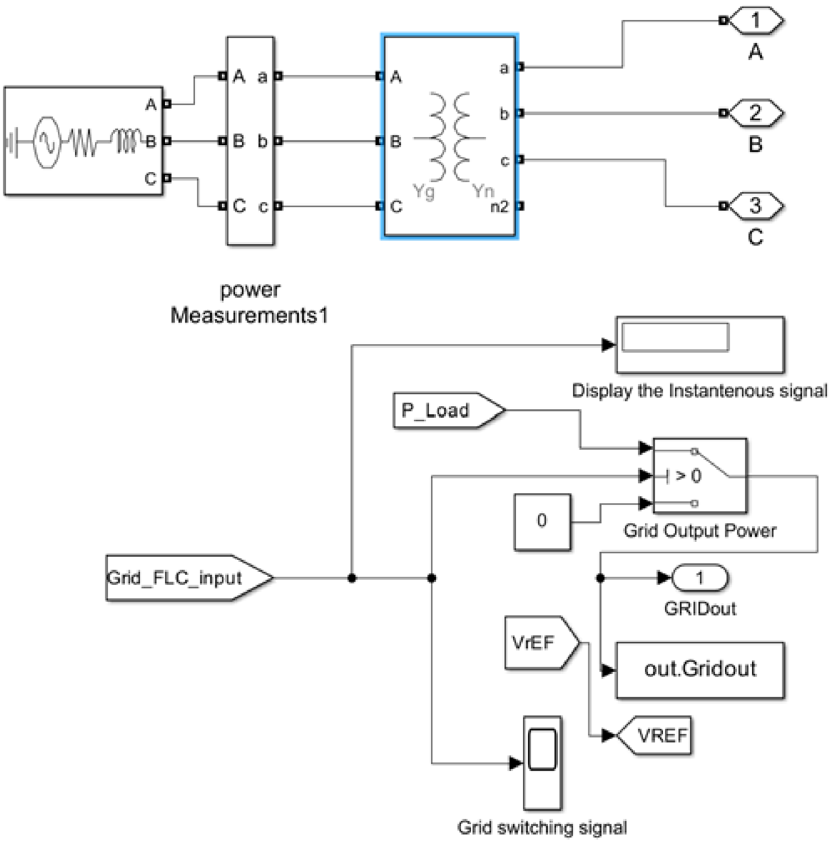

Figure 3.20 Simulation diagram of grid system

3.6.6. Load

Figure 3.21 demonstrates a mathematical configuration that helped connect to the rest of the microgrid, therefore, after configuring the load demand component and establishing the necessary connections, the simulation can was executed by clicking the "Run" button within the Simulink interface. This step allows for the observation of how the load demand influences the overall system dynamics, including energy flow and stability. The load demand component consists of time values which could describe at what time is the load demanded and output values which may describe the load in terms of power (W) or energy (kWh).

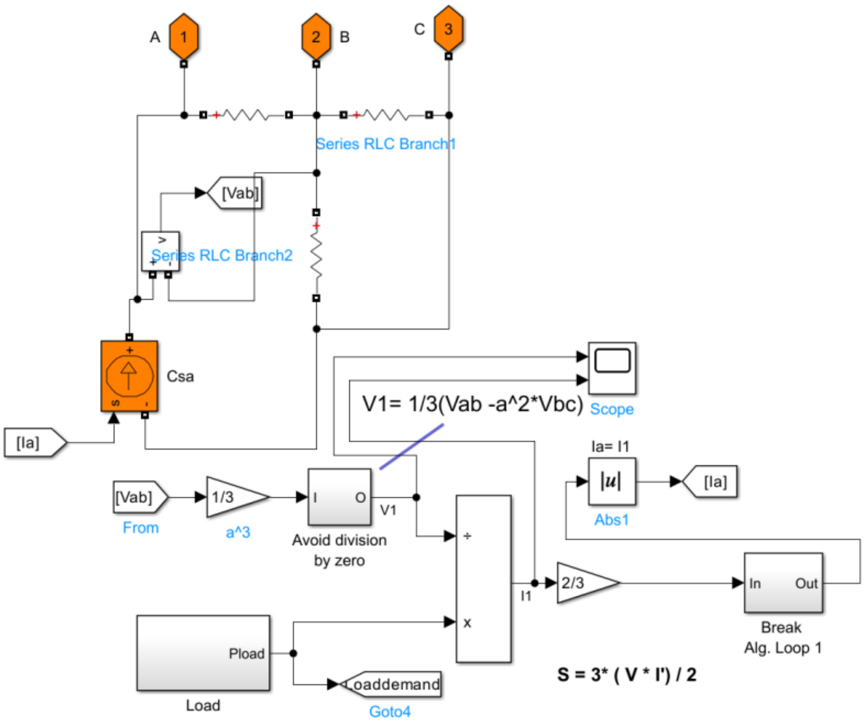

Figure 3.21 Simulation diagram of load system

3.7. Chapter discussions and conclusion

The primary objective of this section was to establish a robust and efficient control model designed to ensure both reliability and adequacy in the energy supply to the load, as well as to facilitate the effective interchange of energy within the HESS. To achieve this, the first stage of this section involved the modelling of the control system using a FLC. This methodology enabled the accomplishment of the foundational goals set forth at the outset. Subsequently, the second stage was achieved through the development of a comprehensive mathematical model that encapsulated the fundamental operations of various energy storage components, including batteries, supercapacitors, and pumped hydro storage systems. This modelling was executed within the MATLAB Simulink environment, which allowed for a detailed simulation of the interactions and functionality of these components within the context of a HESS. The subsequent chapter will delve into a thorough discussion of the results obtained from these developed models, as well as an analysis of their behavior under various operational scenarios. This discussion will provide insights into the effectiveness and efficiency of the control strategies implemented, as well as the overall performance of the HESS.

CHAPTER 4 : SIMULATION RESULTS AND ANALYSIS

This chapter assesses the performance of the proposed hybrid system through comprehensive simulations conducted in MATLAB/Simulink. It examines the system's dynamic behavior during both low- and high-demand periods, evaluating the contributions of each storage subsystem and the grid to the overall power equilibrium. Additionally, the economic performance is analyzed in terms of reduced electricity costs and enhanced efficiency of storage utilization.

4.1. Introduction

This chapter provides a comprehensive analysis of a Fuzzy Intelligent Controller (FIC) applied to a fluctuating alternating current (AC) load within a HESS based microgrid, aimed at achieving optimal energy management and control algorithms. The simulated results and data derived from the patterns established in Chapter 3 are scrutinized, utilizing a commercial AC load as the representative case for analysis, although the framework is adaptable to various load types, including residential and industrial applications. Considering the constraints delineated in the preceding chapter, this section meticulously reports on the behavior of the FIC in accordance with the established rules governing the management of power generation from PV sources, as well as the permissible grid-supplied energy that flows to the load through each storage element. Given the inherent complexities associated with controlling the power output from solar energy systems, MATLAB/SIMULINK software is employed to facilitate the monitoring and management of continuous power flow signal behaviour within the proposed HESS-based microgrid system.

The utilization of MATLAB's Fuzzy Intelligent Controller as an integral input to the developed Simulink model enables a detailed observation of its efficacy in regulating and managing the supply to the load, thereby mitigating issues related to fluctuating energy production and insufficient supply to meet demand. This analysis underscores the capabilities of the FIC in maintaining system stability and reliability, ensuring that energy is delivered seamlessly to the load without shortages, despite the variable nature of the energy sources involved.

4.2. Overall system specification

4.2.1. Typical load demand

Table 4.1 represents the appliances used by Nooitgedacht farm on a day-to-day operation. This commercial farm is in Mpumalanga in an area near Delmas. The farm primarily focuses on maize and cattle farming; however, it as well accommodates ducks and sheep. The farm has a peak load demand of 34,75 kW.

Table 4.1 Typical load demand of Nooitgedacht farm

Appliances	Wattage (kW)	Quantity	Daily usage (h)	Operation interval
Borehole1	1.25	1	5	08:00-12:00
Borehole2	2	1	6	08:00-13:00
Meps security system	5	1	24	24 hours
Cold room	2.5	1	10	08:00-17:00
Maize cruncher	7.5	1	9	09:00-17:00
Feed mixer	7.5	2	9	09:00-17:00
Security lights	0.5	6	12	00:00-06:00/19:00-23:00
Workshop electric tools	1.5	1	10	08:00-17:00

The graph presented in Figure 4.1 illustrates the total load values of the farm over a 24-hour period, with data displayed as vertical bars for each hour. From 00:00 to 07:00, the load remains low and stable, fluctuating between 5 kW and 5.5 kW, indicative of minimal energy demand during the early morning and night-time hours. A notable increase in load commences at 08:00, aligning with the anticipated start of daily farm operations. The load escalates from 5 kW to 12.25 kW, subsequently reaching a peak of approximately 34.75 kW between 09:00 and 11:00, which indicates a significant demand during morning hours. This peak load of 34.75 kW is sustained until around 12:00, at which point it decreases slightly to 33.5 kW. Following this, the load continues to decline gradually to approximately 31.5 kW from 13:00 to 16:00, reflecting typical daytime energy usage patterns associated with commercial activities. Finally, at 17:00, the load experiences a sharp decline to 5 kW, signifying the conclusion of the high-demand period and the transition to low-demand conditions in the evening.

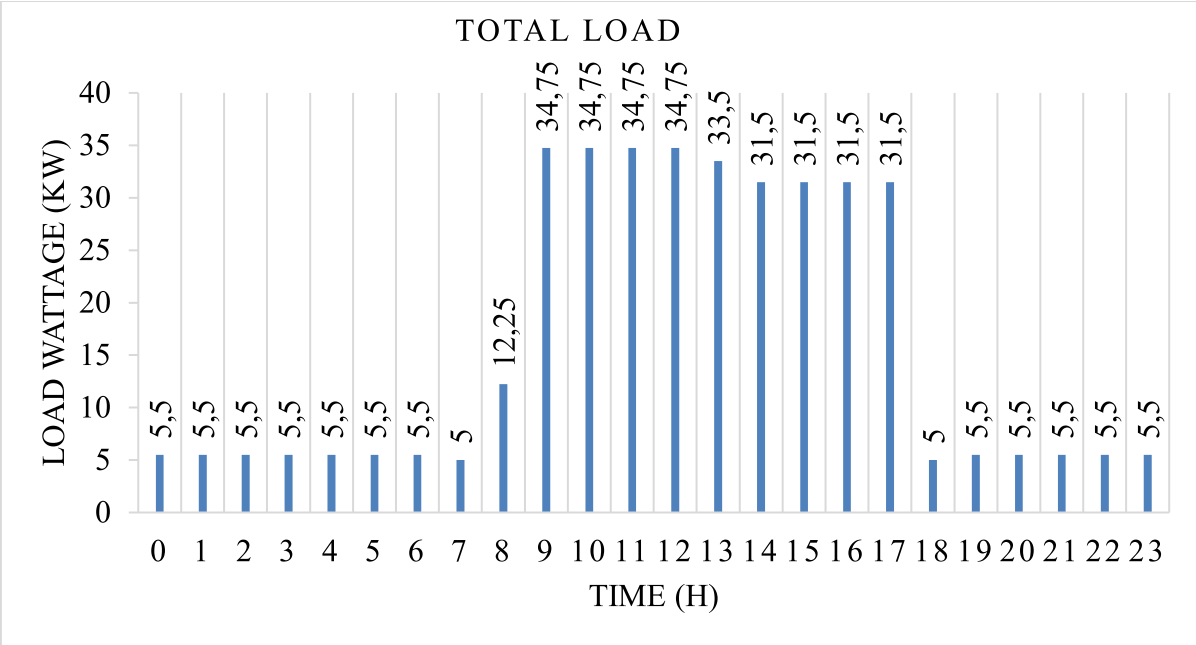

Figure 4.1 Graphical presentation of the load demand

4.2.2. System specifications

The specifications and parameters of the proposed system are shown in Table 4.2. The components include one renewable energy source (PV), three storge systems which are individually characterised as well as the grid. The parameters of the system are comprised of Solar PV system of SunPower SPR-300-WHT-D of a 16-module in series strings and one parallel string. The synchronous machine with hydraulic turbine governor represented the PHS of the proposed system, an 8.9 F supercapacitor and 4 lithium-ion batteries with up to 50% SoC and 0.003s response time.

Table 4.2 Specification and parameters of the proposed system

Component	Description	Specifications
PV	SunPower SPR-300-WHT-D	16-module in series strings and one parallel string
PHS	Synchronous machine with hydraulic turbine and governor	3-phase machine, 31.3 kVA, 400V,50Hz
SC	Electric Double Layer Capacitors (EDLCs)	8.9 F, 48V, 0.0021 Ω equivalent DC series resistance. response time
BT	Lithium-Ion	48V,208 Ah,50% SoC, 0.003s response time

4.3. Results Analysis

4.3.1. Fuzzy logic results

Figure 4.2 demonstrates the 3D output surface of the fuzzy logic controller, which has four expected outputs. The X and Y axes of the surface correspond to the input variables of time (h) and power consumption rate (kW), respectively, while the Z dimension depicts the value of an output (A-battery, B-supercapacitor, C-pumped hydro storage, and D-grid). The surface viewer is governed by the set of fuzzy logic rules developed for the controller design. Analysing the shape and characteristics of this output surface provides valuable insights into the controller's decision-making process and priorities. A closer examination of the surface reveals that the controller is prioritizing the use of renewable energy sources over the grid. This can be observed through the undulating, non-linear nature of the surface, which suggests the controller is dynamically adjusting the output based on factors like time of day and consumption rate, rather than relying solely on the grid. This prioritization of renewable energy is further reinforced when examining the individual output graphs shown in Figure 4.3. Each of these graphs, representing the different energy sources and storage components, actively demonstrates the controller's focus on maximizing the use of renewable energy. It further describes the daily behaviour of the various energy storage and generation components in the system.

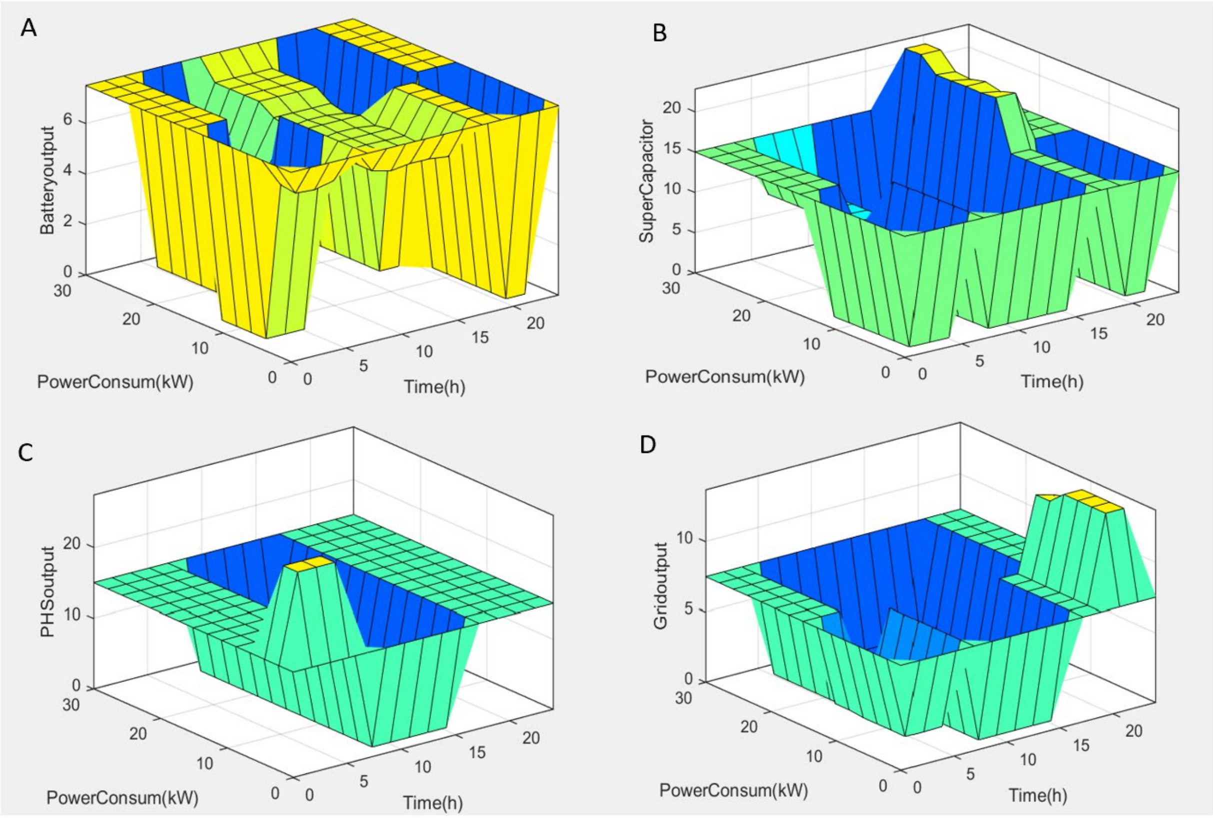

Figure 4.2 Surface view of the last four outputs

Figure 4.3 A shows the Pumped Hydro Storage (PHS) system. The PHS is available to provide up to 15 kW of power between 00:00-09:00 and 15:00-00:00. Figure 4.3 B represents the Battery Energy Storage (BES) system. The BES is available to provide up to 7.5 kW of backup power from 00:00-05:00 and 19:00-00:00. During the day, the BES can provide up to 6.2 kW to back up the Photovoltaic (PV) power generation. Figure 4.3 C depicts the Supercapacitor Energy Storage (SCES) system. The SCES is available from 00:00-04:00 at up to 15 kW, then decreases to a maximum of 9 kW from 05:00-10:00. It is offline from 10:00-15:00, then restarts from 15:00-19:00 at up to 22 kW, before decreasing to 16 kW from 21:00-00:00. Furthermore, when we compare the shape of the PHS and a typical PV output graph, the graphs show an inverse relationship. This complementary behaviour indicates that the controller is effectively managing the HESS (hybrid energy storage system) to ensure the load is always covered. The PHS is used to supplement the PV generation when it is low, and vice versa. Similarly, the SCES (supercapacitor) and BES (battery energy storage) outputs in Figure 4.3 B and 4.3 C reveal an interesting coordination strategy employed by the controller. The supercapacitor is available throughout most of the day, except for a gap between 10am and 3pm. This gap is covered by the battery storage, which shows increased utilization during this period. This coordination between the SCES and BES is a result of their different characteristics. Supercapacitors are well-suited for handling rapid fluctuations in power demand and providing short-term bursts of energy, while batteries are better for longer-duration energy storage and discharge. By strategically managing these two storage components, the controller can optimize the use of both technologies to meet the varying load requirements. Figure 4.3 D is the demonstration of periods that would be highly recommended to use since the electricity is usually reasonable at those times. Therefore, the overall analysis of the output surfaces and individual graphs demonstrates the effectiveness of the proposed fuzzy logic control system in managing the hybrid energy storage system to prioritize renewable energy utilization and ensure reliable power supply to the microgrid, even in the face of fluctuating load demands.

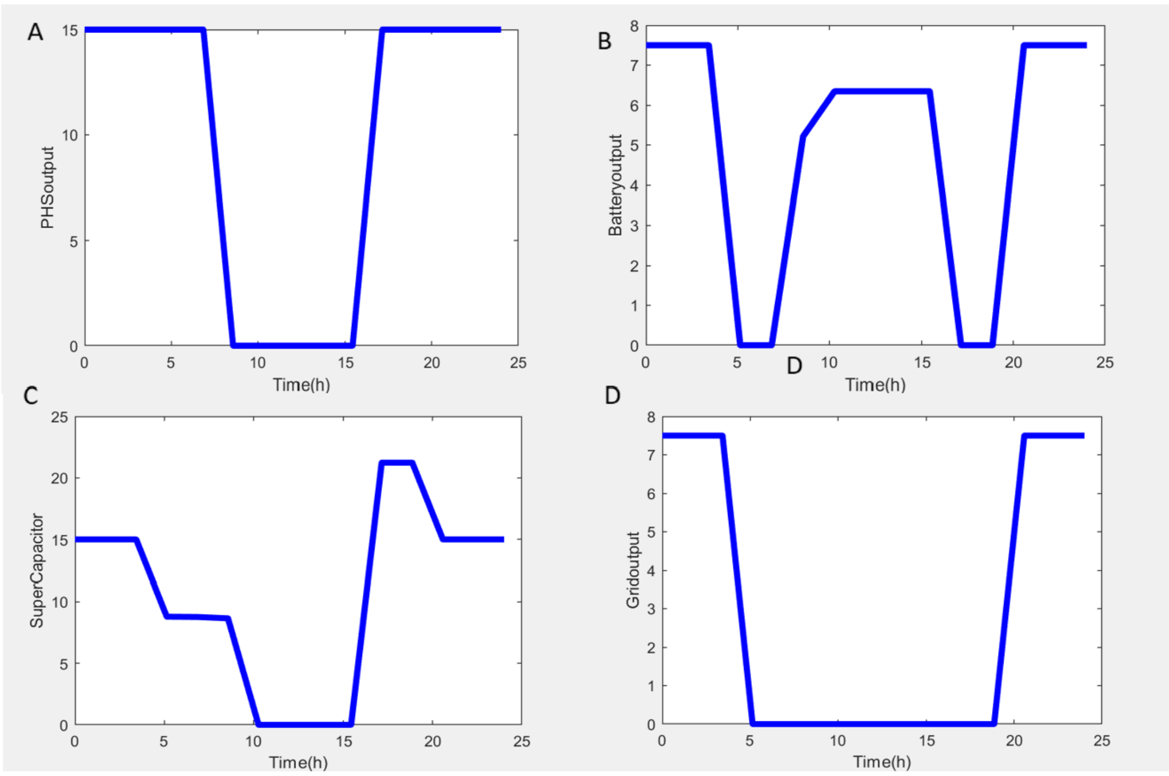

Figure 4.3 Operating pattern of the control's output

4.3.2. Simulink results

4.3.2.1. Case Study

The case study is based on the farm discussed above; however, the winter season (high demand) is used as the worst-case scenario, while summer season (low demand) is used as the best-case scenario. Therefore, the irradiation of the coldest day (30 June) and warmest day (07 February) of 2024 is used. Therefore, the overall system is simulated for 24 hours, and the results are analysed based on the specified charging and discharging conditions. Each storage system has a discharge limit set at 30%. This means that when the SOC falls below 30%, that storage unit cannot deliver power until its SOC rises above 30%. In such cases, an alternative storage unit can be used, provided its SOC is also above 30%. The order of priority for power discharge follows this sequence: first the battery, then the PHS, and SC. The SC will only be charged if it couldn't take advantage of the lower electricity prices available in the morning to charge quickly.

4.3.2.2. Switching times

Figure 4.4 describes the switching times of the overall system components during low demand season. The x-axis represents the duration of the simulation, indicating how the control signals change over time. And the y-axis displays the status of various control signals, indicating whether specific components are active/charging (1) or inactive (0) and discharging (2). In this design, all energy storage systems work together to provide power, each contributing in its own way. The grid supplies power to the system only when electricity prices are reasonable. The battery is set to operate mainly during peak demand hours. Meanwhile, the PHS acts as a backup during the day when the solar system is the main power source. Finally, the supercapacitor serves as a buffer, quickly responding to sudden changes in energy demand, whether it increases or decreases. However, the opposite is true about the high demand season as shown in figure 4.5, the grid is found operating during standard demand period due to the less production of solar energy to sufficiently recharge the energy storage devices. As for the PHS, the storage is only charging because of the switching conditions and minimum charging and discharging factor of 30%. Lastly the super capacitor is responding ton sudden changes in load demand.

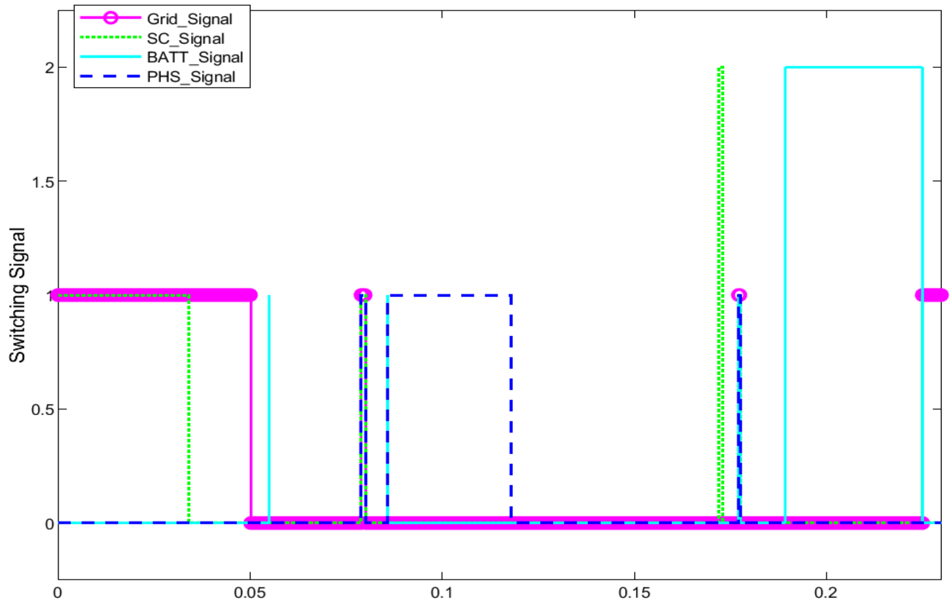

Figure 4.4 Switching times for low demand season

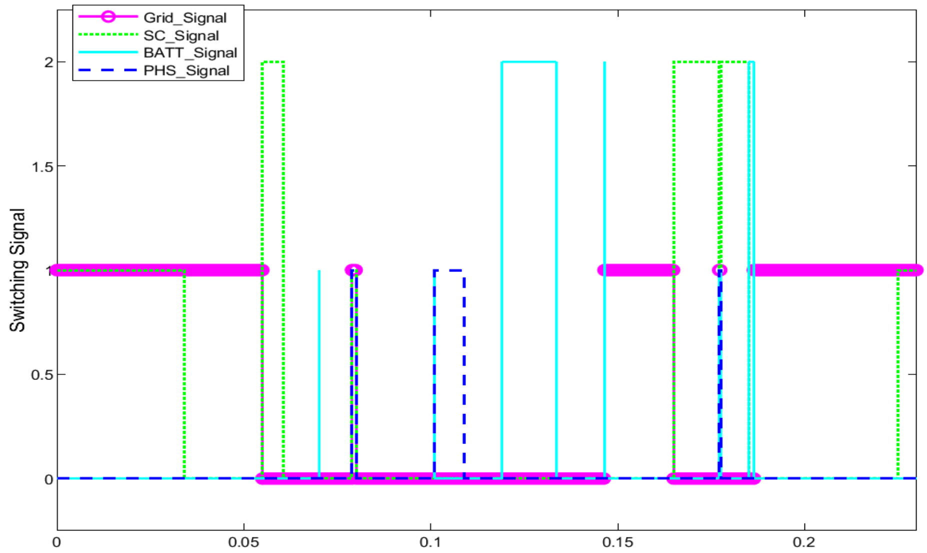

Figure 4.5 Switching time for high demand season

4.3.2.3. Demand Response

Figure 4.6 demonstrates the overall response of the energy storage systems to the load demand at specific times during the best-case scenario. The grid is only active when electricity prices are low or during off-peak hours. This is based on the Eskom ToU tariff Specifically.

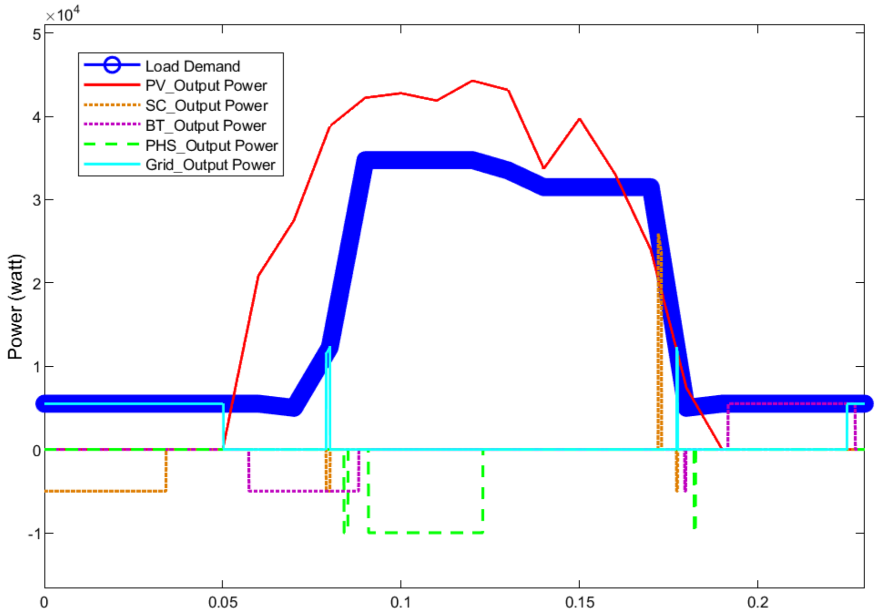

Figure 4.6 Overall system response to load demand (low demand season)

The grid operates from 10:00 PM to 5:00 AM and briefly before and after peak times at 9:00 AM and 5:00 PM delivering a minimum of 5 kW in the morning as shown on figure 4.7.

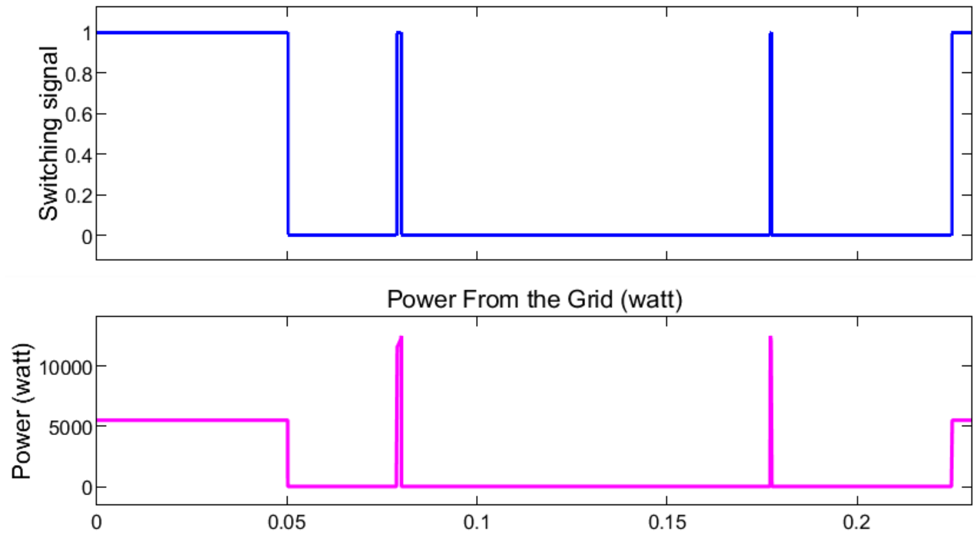

Figure 4.7 Grid output power for low demand

Looking at figure 4.8, it is evident that the supercapacitor behaves similarly, it starts charging from midnight to 3:00 AM, then stays off until 9:00 AM, when it charges for a short time in preparation to quickly discharge at 5:00 PM delivering a maximum of 26 kW taking over from the PV and then recharge to 100%.

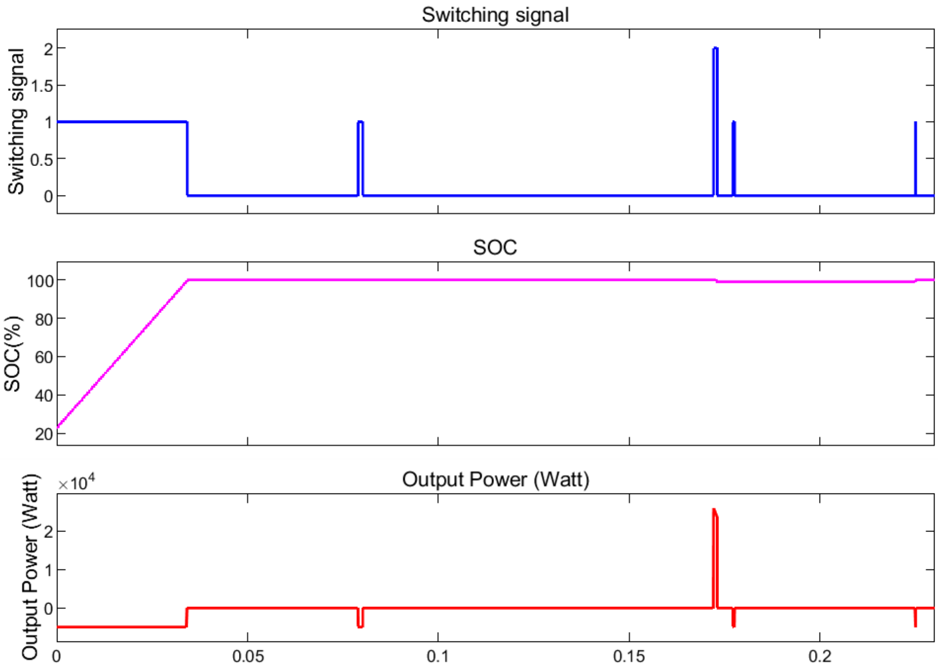

Figure 4.8 Supercapacitor output power for low demand

From figure 4.19, we see the battery takes advantage of low electricity prices and sunlight, charging up to 60% from 5:00 AM to 8:00 AM. It then remains off for most of the afternoon before charging to 100% at 5:00 PM. After that, it discharges a maximum of 5 kW from 6:00 PM to 10:00 PM.

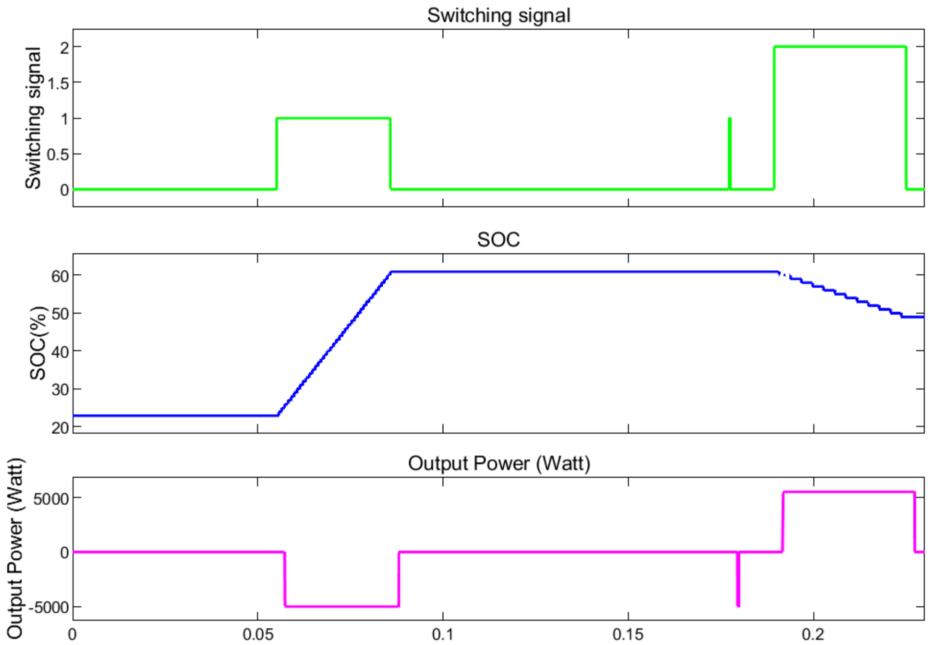

Figure 4.9 Battery output power for low demand

Lastly, on figure 4.10 PHS acts as a backup for the solar system when weather conditions are not good for generating power. It also uses solar energy, starting to charge from 8:00 AM for a few minutes and then continuing to charge until 11:00 AM. This is archived by obeying to the charging/charging sequence.

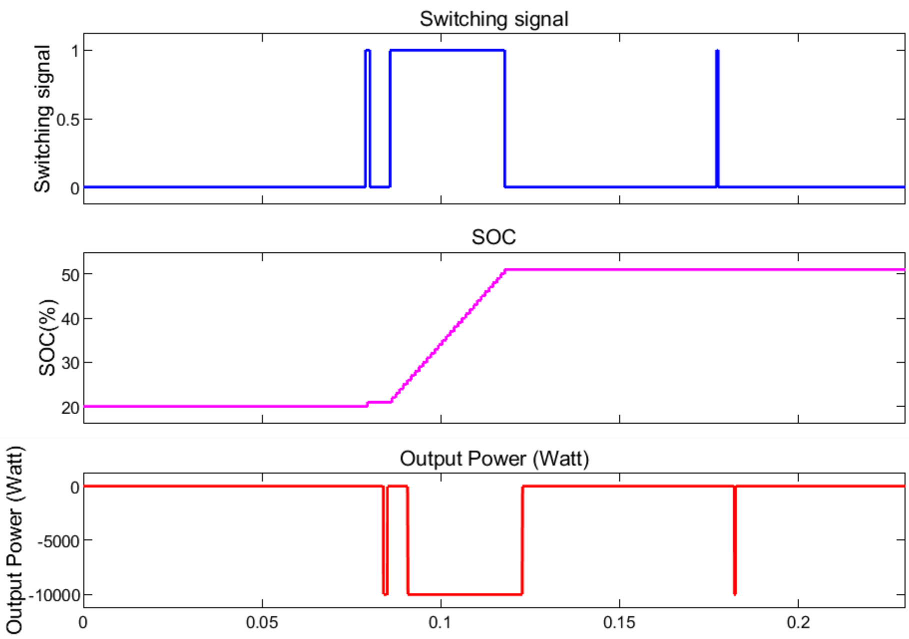

Figure 4.10 PHS output power for low demand

Figure 4.11 illustrates how the energy storage systems respond to load demands in the worst-case scenario. The graph shows that the responses differ between winter and summer seasons.

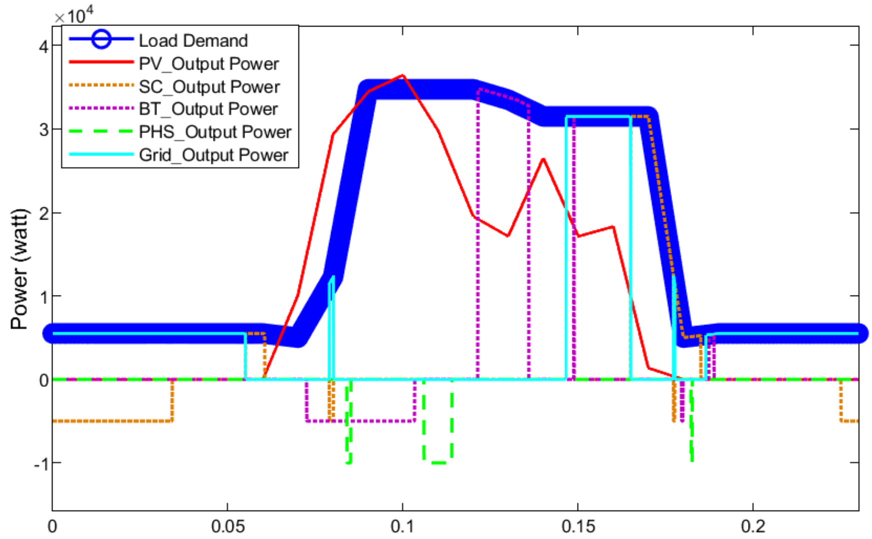

Figure 4.11 Overall system response to load demand (High demand season)

Figure 4.12 the grid operates during the night and early morning as expected. However, it also activates during sudden load changes at 08:00 and 17:00. Additionally, it responds to a peak demand of 32 kW around 15:00 to 16:00, which occurs due to insufficient energy stored at that time.

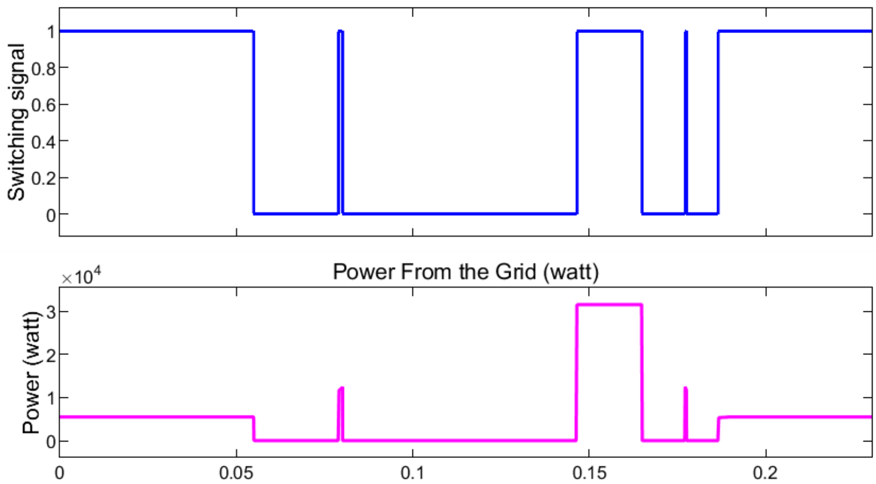

Figure 4.12 Grid output for high demand season

The supercapacitor behaves differently; instead of responding to the sudden load demands, it uses the opportunity to charge from midnight as planned. Later, it takes over from the grid during the second sudden load change, discharging between 32 kW and 5 kW, as shown in figure 4.13.

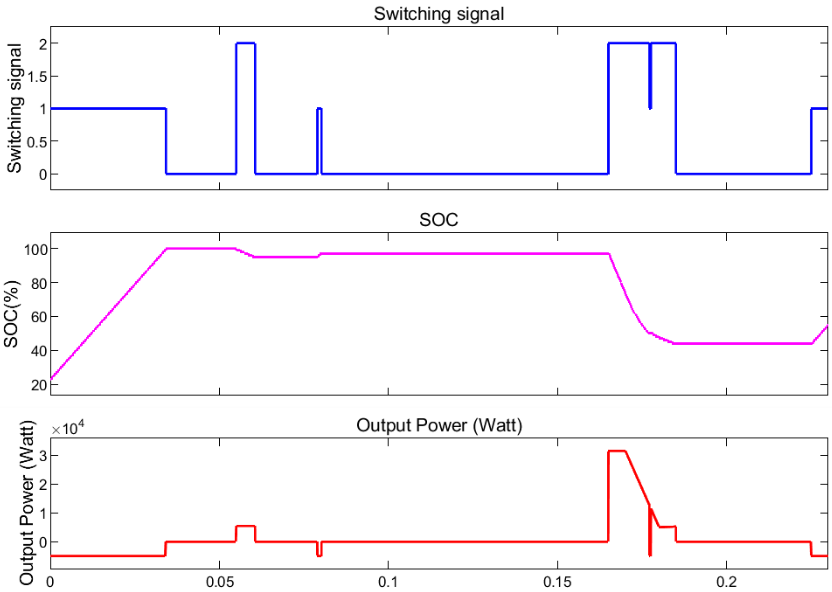

Figure 4.13 SC output power for high demand

The battery effectively uses sunlight to charge up to 60% from 6:00 AM to 8:00 AM. It remains inactive between 1:00 PM and 2:00 PM, then begins discharging right after 2:00 PM as shown on figure 4.14.

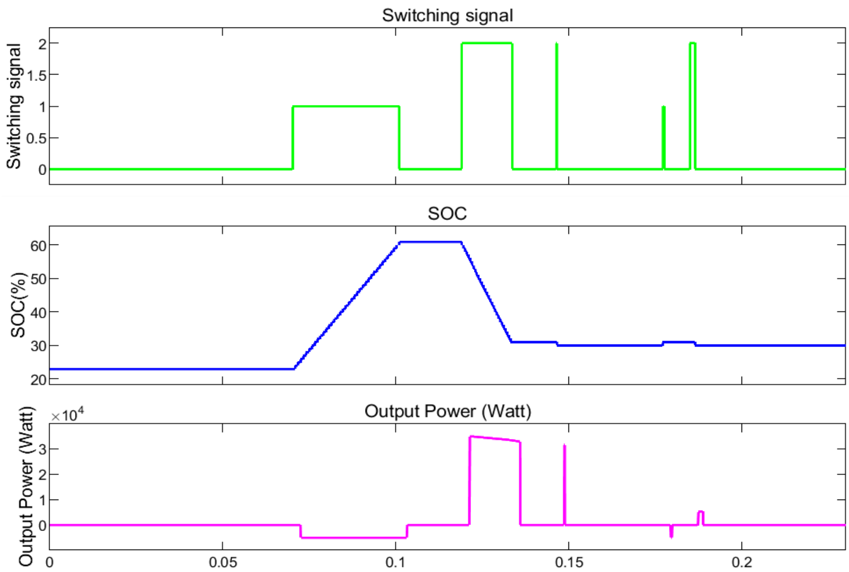

Figure 4.14 Battery output power for high demand

Lastly, the pumped hydro storage (PHS) does not respond until it starts charging around 12:00 and 2:00 PM, and again at around 7:00 PM as seen on figure 4.15. Therefore, it remains inactive all day because it does not have enough stored power. This behaviour is influenced by the charging sequence and the insufficient solar energy generated throughout the day.

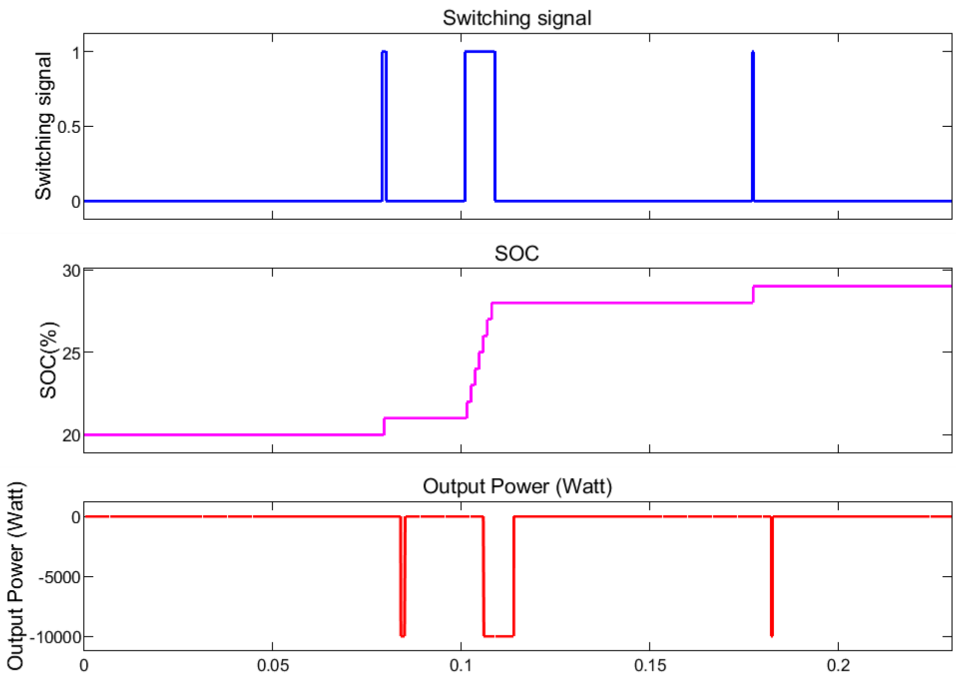

Figure 4.15 PHS output power for high demand

4.4. Chapter discussions and conclusion

The objective of this Chapter was to provide a thorough examination of the performance of a FIC within a HESS based microgrid, focusing on both optimal energy management and the response to varying load demands in different scenarios. The Optimal energy management of hybrid system for a commercial farm has been studied and investigated based on the time of response, time of use and the SOC. The strategy aimed to minimise the cost of electricity purchased from the grid, and maximised the surplus energy generated by the PV system during the best-case scenario. During the best-case scenario, the results show a well-coordinated response of the energy storage systems to load demands, particularly during low electricity price periods. The effective operation of the supercapacitor, battery, and PHS demonstrates the FIC's ability to optimize energy flow. The supercapacitor efficiently charges during off-peak hours and discharges at peak demand, while the battery maximizes charging during low-cost electricity periods. The PHS acts as a reliable backup, reinforcing the system's resilience against fluctuations in solar energy generation.

Conversely, the worst-case scenario highlights the system's challenges during periods of insufficient energy storage. The distinct seasonal responses reveal how load demands can exceed available energy, particularly during high-demand times. The supercapacitor's strategy of charging rather than discharging during sudden load changes exemplifies the need for careful management. The battery's reliance on sunlight underscores the importance of weather conditions, while the PHS's limited response indicates potential areas for improvement in energy storage strategies. Nevertheless, the optimal energy management of the proposed system under ToU minimised both the grid consumption and the consumer's bill. The main benefit of reduced electricity purchased from the grid is the reduced electricity bill for the commercial consume

CHAPTER 5 : REAL TIME RELIABILITY AND PERFORMANCE ANALYSIS OF THE PROPOSED SYSTEM DYNAMICS USING OPAL-RT

This chapter centres on the real-time implementation and validation of the fuzzy-controlled hybrid system utilizing the Opal-RT hardware-in-the-loop (HIL) platform. The real-time results are analysed to assess the stability of the controller, the operational reliability, and the responsiveness of the system. Additionally, machine learning techniques including anomaly detection, principal component analysis (PCA), K-means clustering, and regression are employed on operational data to identify performance trends, detect anomalies, and create predictive reliability models.

5.1. Introduction

This chapter presents a framework for analysing and modelling the performance of a hybrid microgrid system using data analytics and machine learning. The process begins with a detailed examination of the operational data to identify significant patterns, relationships, and variations among different energy sources over time. Initially, pairwise correlation and normality tests are conducted to ensure the data's reliability and to understand how the variables interact with one another. The analysis then focuses on changes in power generation and storage for components such as the PV system, batteries, supercapacitors, pumped hydro storage, and the grid, both within single days and across multiple days. This helps reveal how the microgrid reacts to fluctuations in renewable energy supply and demand, highlighting connections between components and areas of variability. Building on these findings, the chapter introduces machine learning techniques to enhance the system's reliability and performance predictions. Anomaly detection is first employed to identify unusual load patterns that may indicate faults or inefficiencies. Following that, Principal Component Analysis and K-means clustering are used to simplify and organize the data into meaningful groups, uncovering hidden operational patterns. Lastly, four regression models, Random Forest, Extreme Gradient Boost, Support Vector

Regression, and Artificial Neural Networks are utilized to forecast power output and assess their accuracy. Collectively, these methods create a practical framework for improved control, early fault detection, and better energy management in the microgrid system.

5.2. Daily simulation analysis

Figure 5.1 shows how the main energy sources, which include the photovoltaic (PV) array, battery bank, supercapacitor, pumped hydro storage, and the grid, perform over four days in the grid-connected hybrid renewable energy system. The 50 kW PV array provides most of the energy during the day, and its output closely follows load demand. This shows us that the fuzzy logic controller (FLC) effectively aligns renewable generation with consumption patterns while reducing the impact of solar fluctuations. When there’s extra solar power, the controller automatically switches the battery bank and pumped hydro storage (both rated at 10 kW) into charging mode. This appears as negative or near-zero power outputs, showing that energy is being stored. When solar production drops, both units discharge in a controlled way to keep up with the load, while the supercapacitor quickly manages small fluctuations to keep the voltage steady. The grid mainly supports the system in the early morning and late evening, acting as a backup to maintain balance.

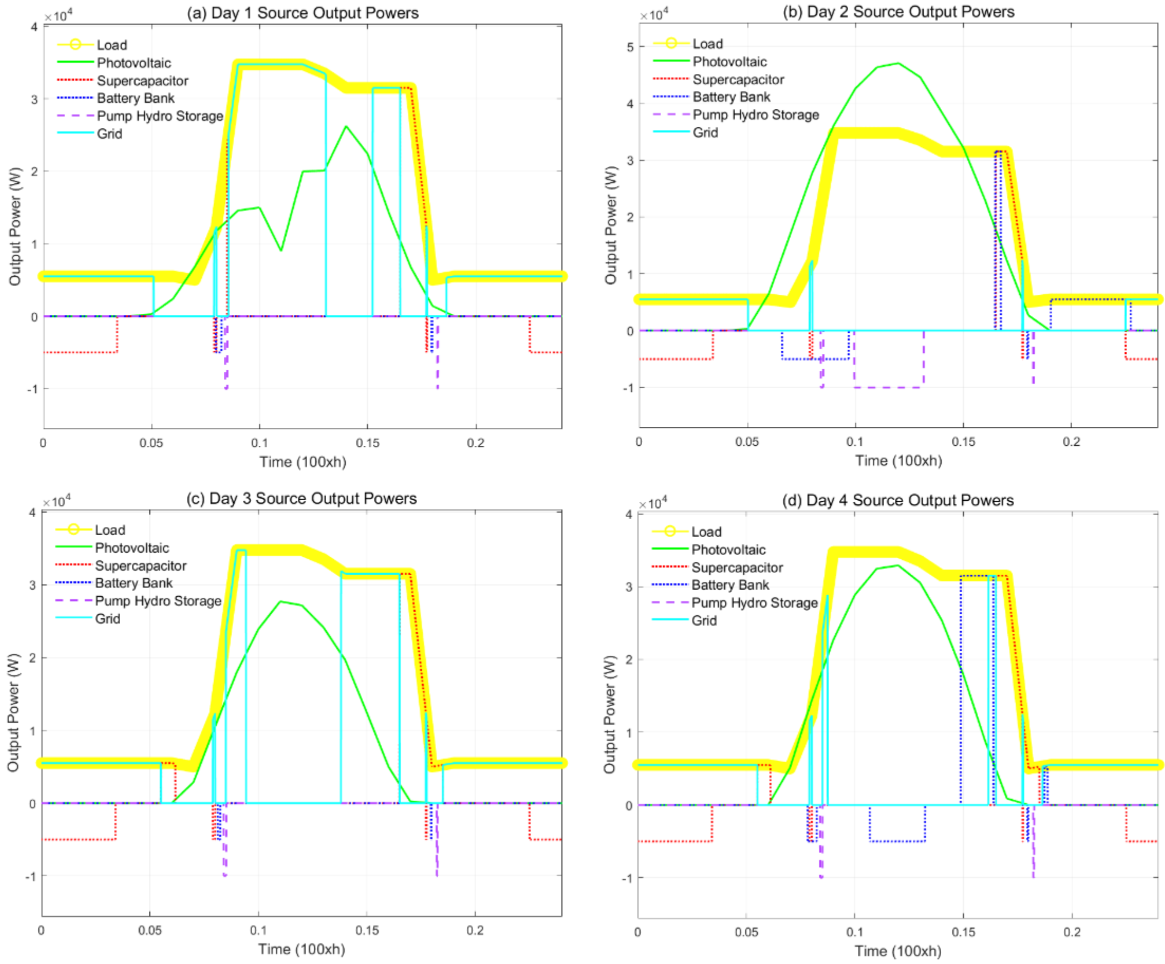

Figure 5.1 Sources Energy Output for Different Days

Across the four days, the results highlight how adaptive and reliable the FLC is under different weather and load conditions. Day 1 shows moderate PV output (~35 kW) with smooth coordination between sources. Day 2 performs best, reaching around 50 kW and showing less grid use due to good sunlight. Day 3 has weaker PV output (~30 kW), so the system depends more on the grid and battery, showing how the controller adapts when conditions aren't ideal. Day 4 sits in between, with storage systems helping to keep power steady as sunlight fades. Overall, these results show that the FLC can manage charging and discharging effectively, reduce the system's dependence on the grid, and increase renewable energy use.

5.3. Analysis of system performance data

The simulation of microgrid based on real data was performed to study the dynamic behaviour of the system. The summary of Microgrid Performance is given in table 5.1. Therefore, the analysis of the microgrid's performance over four days reveals significant differences in renewable energy contribution, system stability, and storage behaviour. Day 2 stands out as the best performer, with the highest renewable energy share at 63.02%, the lowest power balance Mean Absolute Error (MAE) of 4144.01, and a notable battery SOC variation of 38, indicating that energy storage was crucial for maintaining system balance. In contrast, Day 1 had the highest load at 16,344.30 kW and a moderate renewable share of 30.82%, but it also exhibited the largest power imbalance, with a MAE of 6389.67, suggesting a greater reliance on non-renewable sources or less efficient power management. Day 3 recorded the lowest renewable share at 24.64% and minimal battery SOC variation of 2, indicating poor use of renewables and limited energy storage engagement, despite moderate load and balance errors. Day 4 demonstrated a better balance with a renewable integration of 31.79%, an acceptable power balance of 4481.86, and strong storage activity, highlighted by a battery SOC variation of 36 and supercapacitor activity of 32.99%. This indicates improved responsiveness and stability compared to Days 1 and 3. Overall, Days 2 and 4 exhibited the most stable and efficient operations, highlighting the advantages of higher renewable integration and effective storage use in enhancing the microgrid's reliability and energy balance.

Table 5.1 Microgrid Performance Summary

Day	Load Mean	Renewable Energy Share Mean	Power Balance MAE	Battery SOC Variation	Supercapacitor Active Percent
day1	16344.30	30.82	6389.67	3	24.65
day2	15609.76	63.02	4144.01	38	27.08
day3	15528.25	24.64	4990.36	2	32.29
day4	15527.64	31.77	4481.86	36	32.97

5.3.1. Pairwise correlation analysis

Figure 5.2 illustrates a correlation matrix that outlines the interactions among the key components of the hybrid energy system, including load, photovoltaic (PV) generation, grid power, battery, battery state of charge (Bsoc), supercapacitor (SC), supercapacitor SOC (SCsoc), and PHS with its SOC (PHSsoc). These relationships illustrate how energy flows, adapts, and stabilizes under varying conditions. A strong positive correlation exists between load and PV generation ($r = 0.92$, $p < 0.001$), which is expected since both peak during daylight when solar energy is available. Load also positively correlates with battery power ($r = 0.77$, $p < 0.001$), indicating that the battery actively participates in balancing supply when demand increases. Conversely, grid power has a moderate negative correlation with both load ($r = -0.48$, $p < 0.001$) and PV generation ($r = -0.71$, $p < 0.001$), suggesting that the system relies less on external sources when renewables and storage are functioning effectively. The link between PV and battery power ($r = 0.69$, $p < 0.001$) shows a coordinated relationship between solar input and storage output. The correlation between battery SOC and pumped hydro SOC ($r = 0.76$, $p < 0.001$) indicates a synchronized charging and discharging process between these subsystems, akin to a coordinated rhythm in energy management. In contrast, the supercapacitor SOC displays weaker correlations, suggesting a more independent role focused on rapid responses and short-term adjustments rather than long-term storage. Therefore, the FLC plays a crucial role in managing and interpreting these interactions. Rather than relying on fixed thresholds, it uses linguistic rules to make adaptive, real-time decisions about power flow among the PV, battery, supercapacitor, and grid. This adaptability is essential for managing uncertainty and nonlinear behaviours. The FLC particularly enhances the system's ability to mitigate power imbalances and stabilize SOC transitions, facilitating smoother charging and discharging processes. Overall, with the FLC in place, the system exhibits stronger correlations between renewables and storage, reduced reliance on the grid, and improved stability and resilience, even during fluctuations in solar input or demand increases. It represents more than just control; it embodies intelligent orchestration.

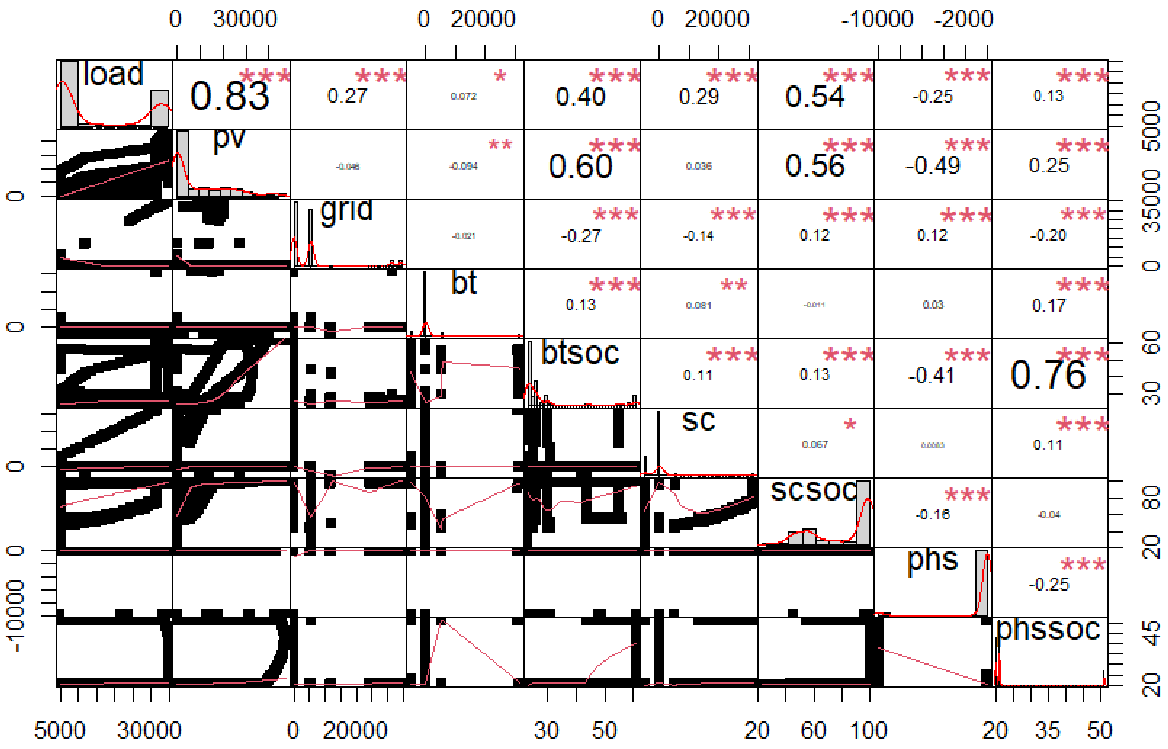

Figure 5.2 Pairwise correlation diagram for energy sources and storage systems

5.3.2. Normality of the data distributions

The normality of the data is assessed to determine the appropriate statistical method for analysis. This is achieved through density plots, Q-Q plots, and the Shapiro Test. Figure 5.3 shows the density and Q-Q plots for key variables in the hybrid energy system, including load demand, PV output, grid output, battery bank, battery SOC, supercapacitor output, supercapacitor SOC, pumped hydro storage output, and its SOC. The density plots clearly indicate that none of these distributions conform to a normal or Gaussian distribution; instead, they exhibit skewed and often multimodal patterns, reflecting the dynamic and nonlinear characteristics of hybrid energy systems. For example, both load demand and PV output display slightly bimodal or right-skewed distributions, highlighting the difference between daytime activity and night-time inactivity. The grid output is also skewed, suggesting an imbalance between import and export events, likely due to intermittent renewable input and changing demand. Battery and supercapacitor outputs show multiple peaks, corresponding to their frequent charge-discharge cycles in response to real-time supply and demand fluctuations. The SOC distributions for the battery, supercapacitor, and pumped hydro storage are broad and spread out, indicating that the system prioritizes adaptability over static charge levels. The Q-Q plots further support these observations, with sample quantiles diverging significantly from the theoretical normal line, especially at the extremes, indicating heavy-tailed and skewed behaviour. This confirms that the data does not satisfy the assumptions for parametric tests, leading to the use of non-parametric methods in Figures 5.4 and 5.7. Overall, the system's variability stemming from solar input, load changes, and storage behaviour results in distributions that are decidedly non-normal. In a hybrid renewable setup characterized by real-time control and fluctuating conditions, this non-normality is not a flaw; rather, it is a fundamental feature.

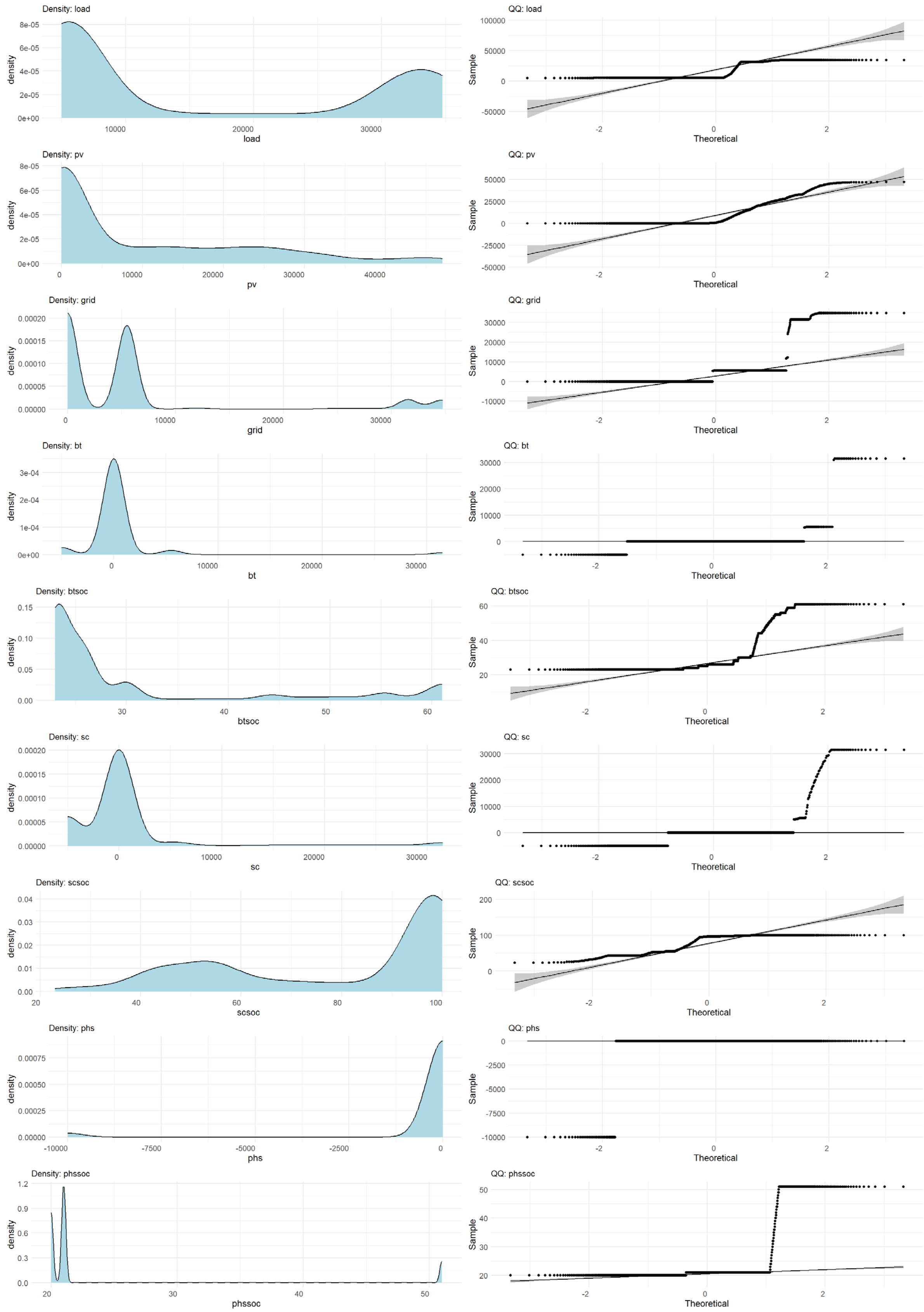

Figure 5.3 Density plots and Q-Q plots of different components of microgrid system

5.3.3. Within-day comparisons of energy sources

Figure 5.4 compares the output power (in kW) from five energy sources battery, grid, PHS, PV, and SC is analysed over four consecutive days. The results of the Friedman test are highly significant for all days ($\chi^2 \approx 295.26$-576.78, $p < 0.001$), indicating that the power distributions are not only different but consistently so. Kendall's W coefficients (0.26-0.50) suggest moderate effect sizes, showing stable yet distinct operational patterns among the sources. The PV output consistently has the highest median values, reaching 2,295.4 kW on Day 1 as shown on Figure 5.5.

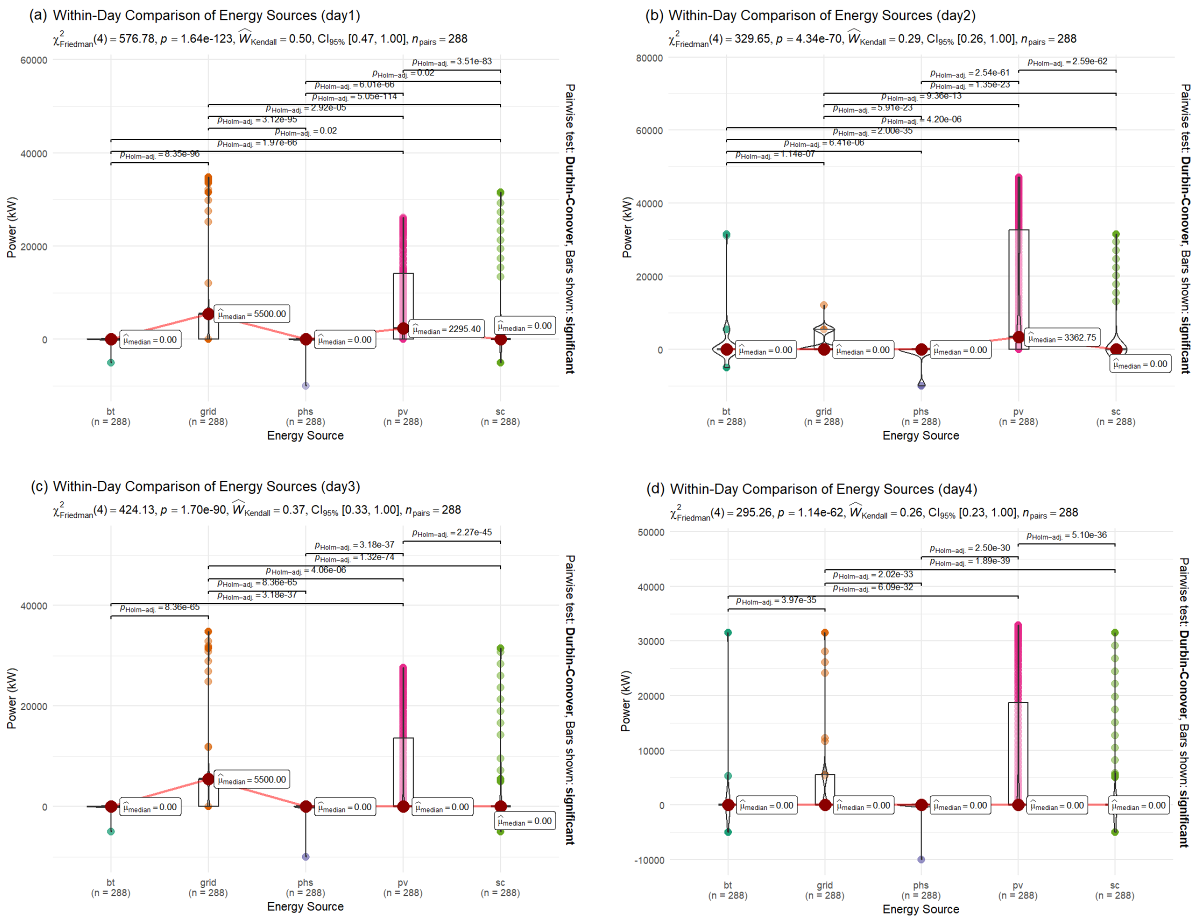

Figure 5.4 Within-Day comparisons of energy sources

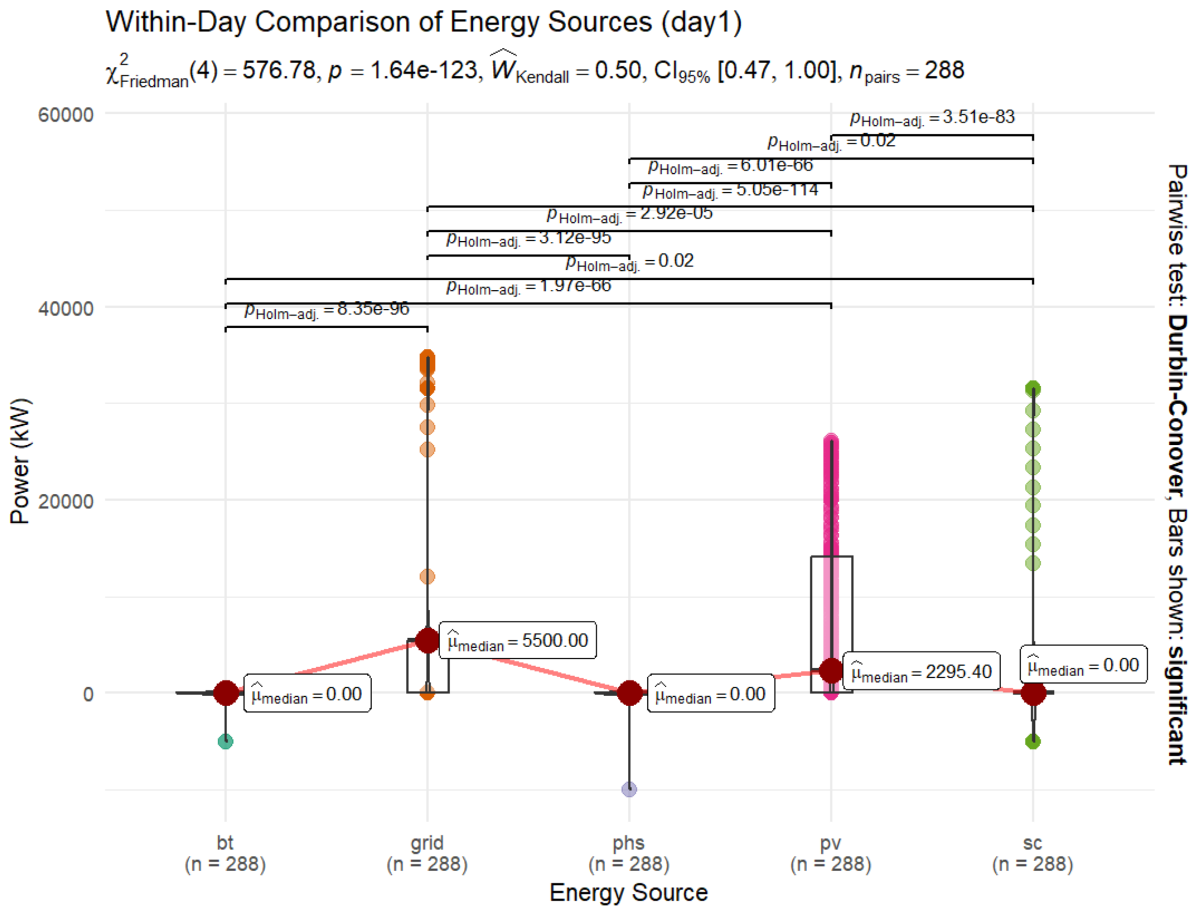

Figure 5.5 Within-Day comparisons of energy sources (day 1)

Figure 5.6 demonstrates the output of 3,362.75 kW on Day 2, reflecting strong solar irradiance during daylight. The grid maintains a steady median output around 5,500 kW, serving as a stabilizing backbone that is always available to compensate when renewable generation decreases. Pumped hydro storage displays both positive and negative median outputs, highlighting its role in both charging and discharging as it adapts to system demands. In contrast, the battery and supercapacitor have median outputs close to zero with minimal variability. This behaviour is not passive; rather, it demonstrates precision, as these components are designed to respond selectively, engaging only when the system needs fine-tuned adjustments. At the core of this coordination is FLC, which manages the transitions between energy generation and storage. Rather than using fixed thresholds, it interprets system conditions with linguistic rules, such as "if load increases and PV output decreases, then activate storage," enabling adaptive, real-time decision-making. The FLC's impact is seen in the smooth transitions of PHS and the controlled outputs of the battery and supercapacitor, reflecting a system that emphasizes renewable energy use while minimizing unnecessary energy dispatch. This control strategy shifts the microgrid from a reactive to a responsive state, where PV generation leads, the grid provides stability, and storage components operate with high precision. The outcome is a system that is not only efficient and resilient but also capable of integrating variable renewable resources without sacrificing reliability, creating a dynamic balance driven by intelligent control.

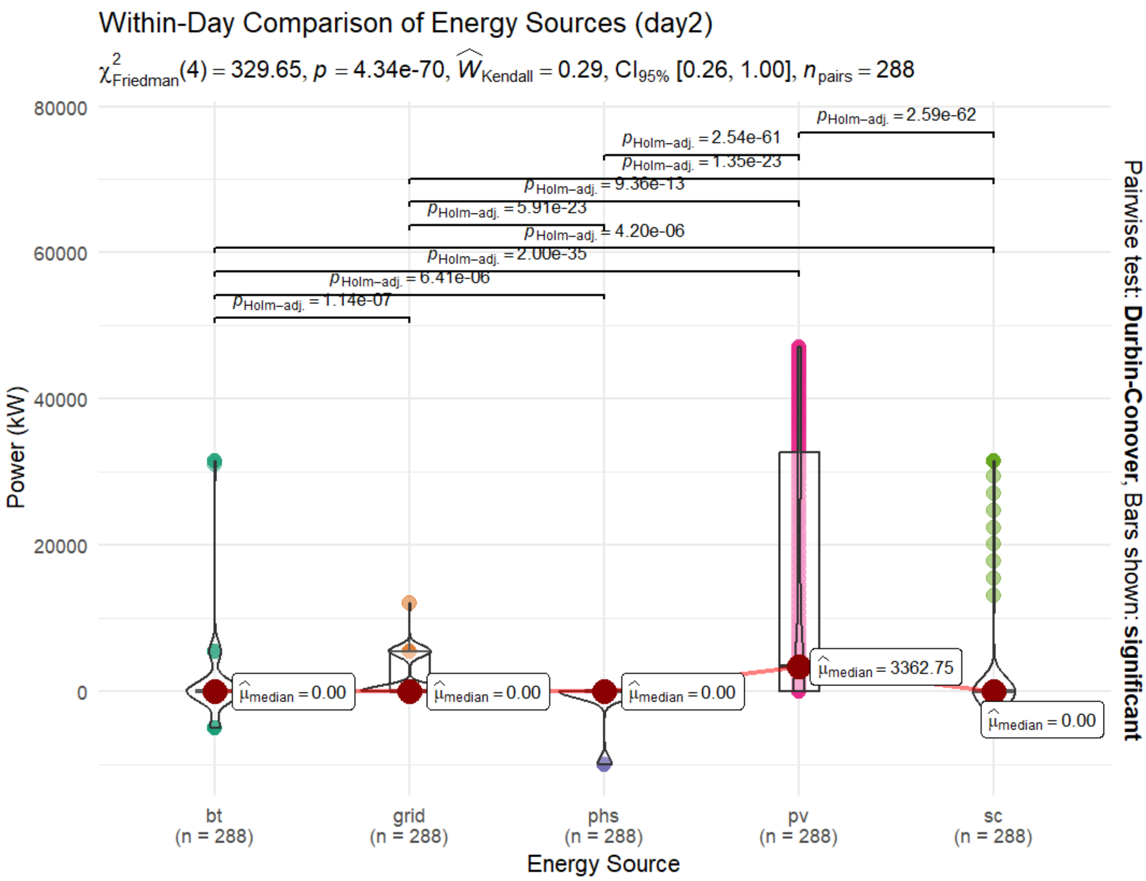

Figure 5.6 Within-Day comparisons of energy sources (day 2)

5.3.4. Between-day comparison of energy sources

Figure5.7 examines the daily power output variations among five energy sources: PV, grid, battery, supercapacitor, and pumped hydro storage. The Kruskal-Wallis's test was conducted to determine whether their median outputs changed significantly over the four days. PV output fluctuates considerably, with Day 2 showing the highest median value of approximately 3,362.75 kW on Figure 5.8, reflecting the natural variations in solar energy due to weather and daylight.

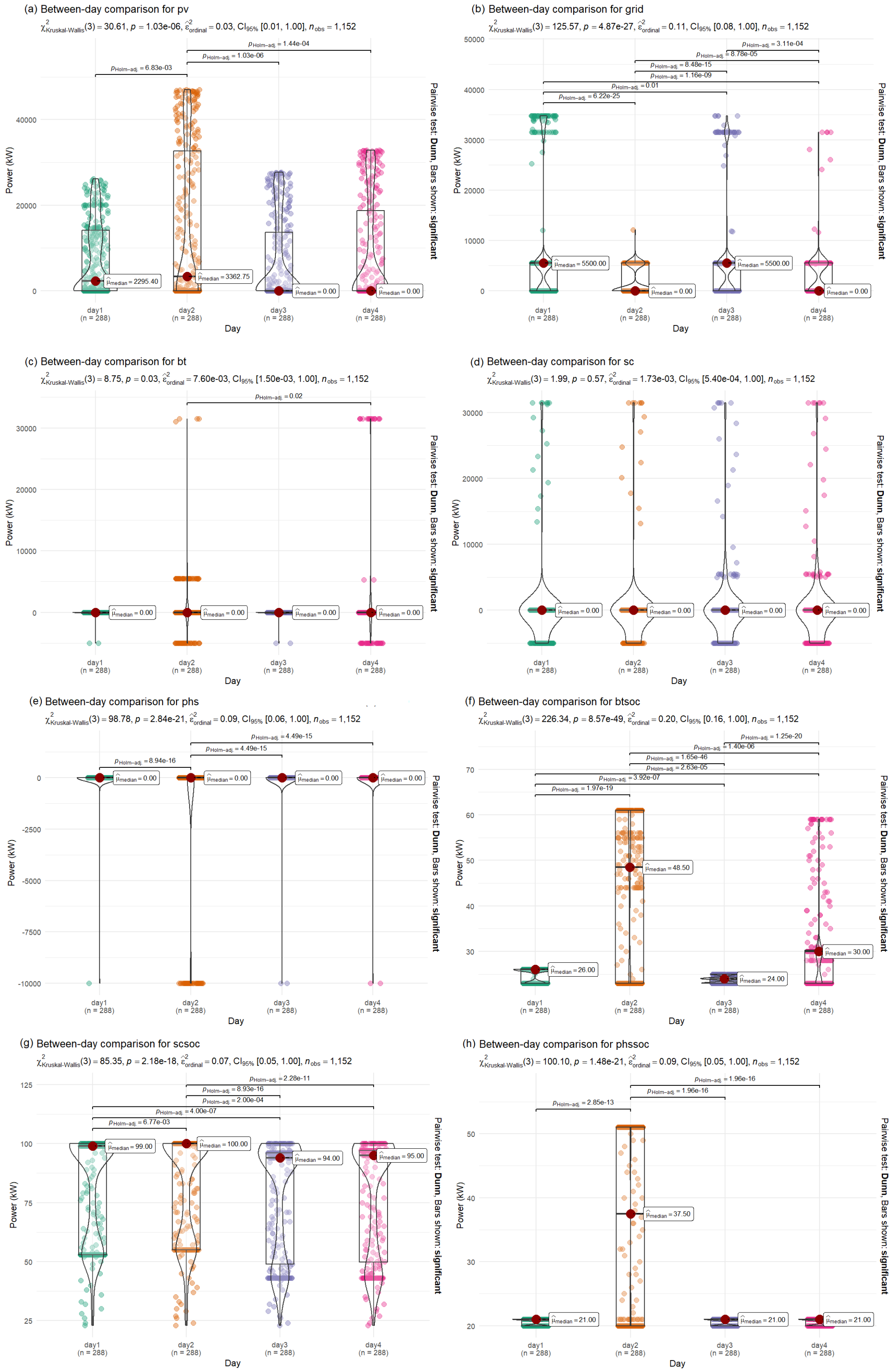

Figure 5.7 Between-Day comparison of energy sources

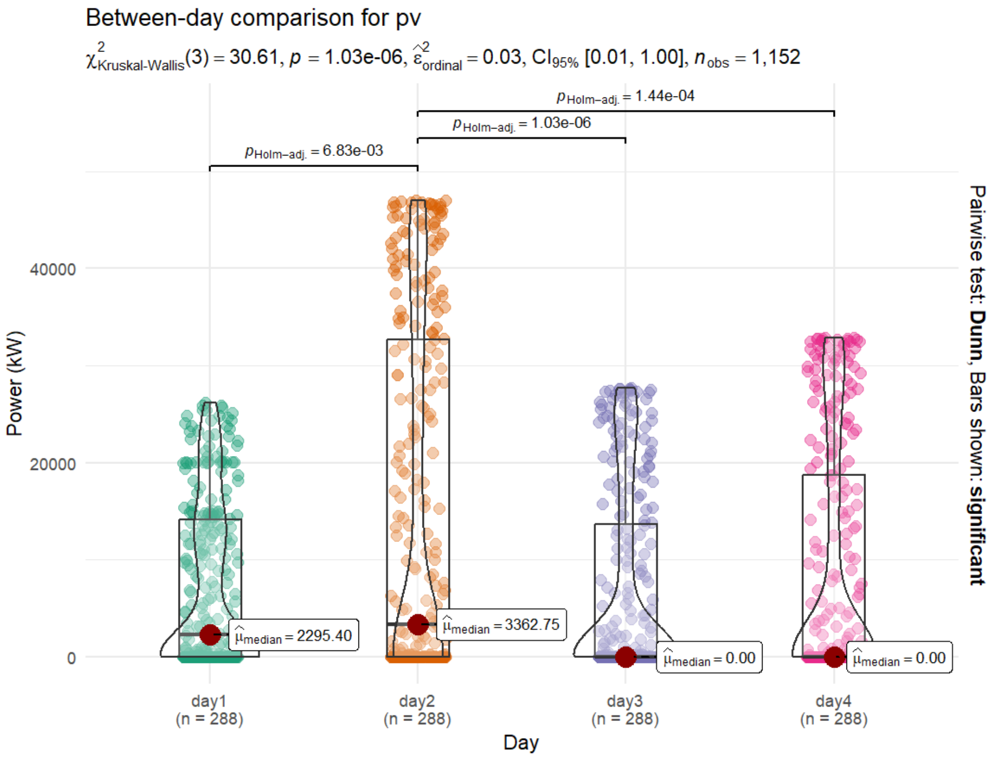

Figure 5.8 Between-Day comparison of PV

Figure 5.9 represents the grid power variation across the four days, adapting to changes in renewable input and overall system demand. Pumped hydro storage exhibits a similar trend, with its charging and discharging cycles adjusting based on energy supply and consumption on Figure 5.10. In contrast, the battery and supercapacitor maintain stable outputs, with the battery showing only minor changes on Figure 5.11 and the supercapacitor remaining almost constant on Figure 5.12. This stability indicates that both components operate in a controlled and predictable manner.

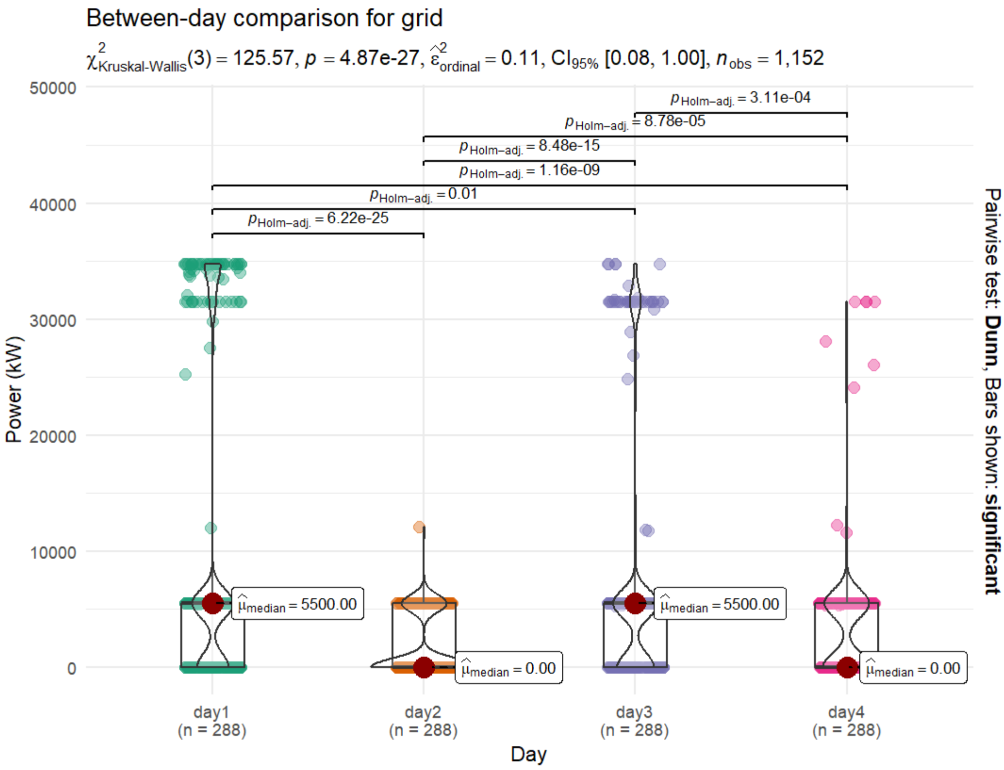

Figure 5.9 Between-Day comparison of grid

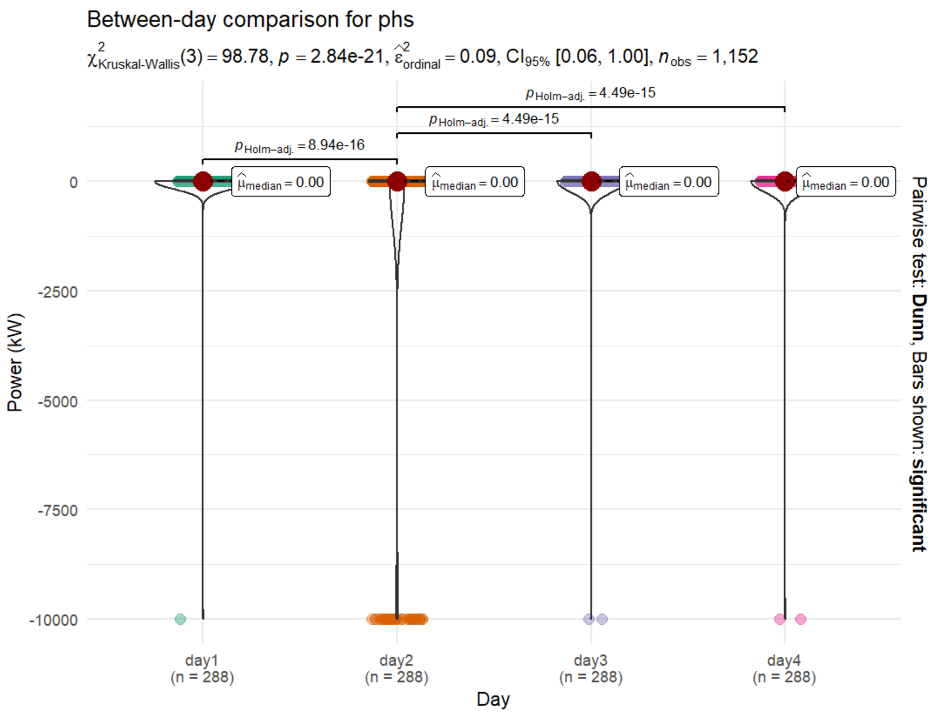

Figure 5.10 Between-Day comparison of PHS

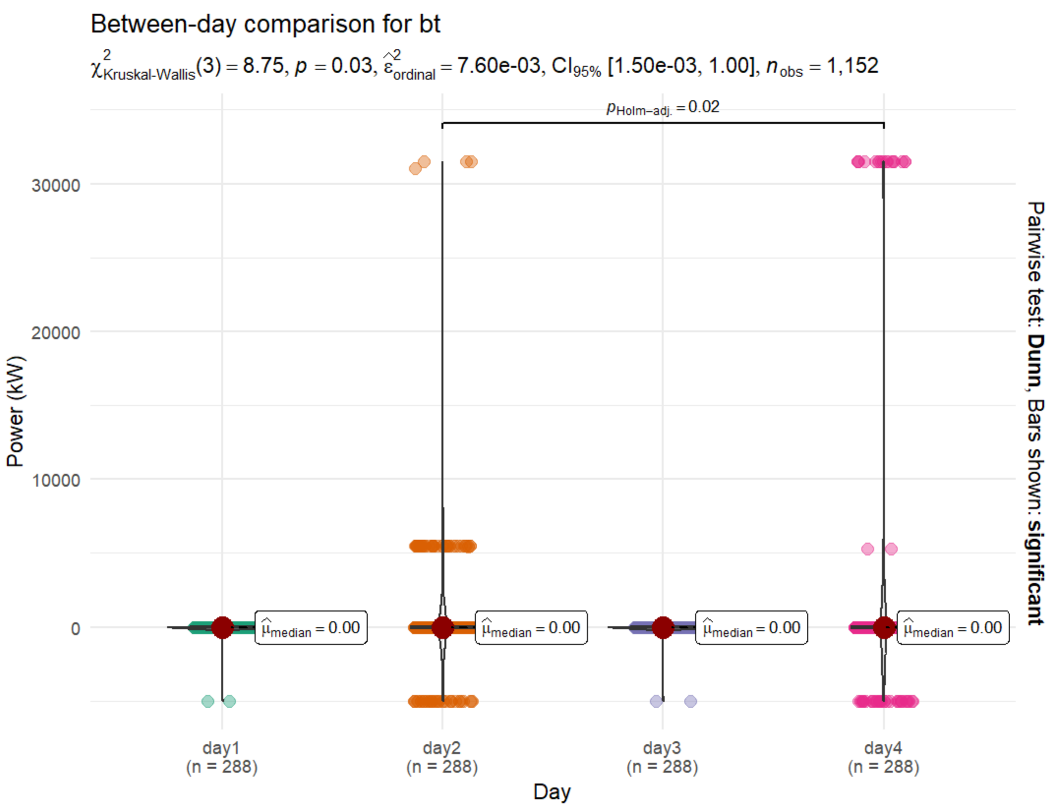

Figure 5.11 Between-Day comparison of Battery

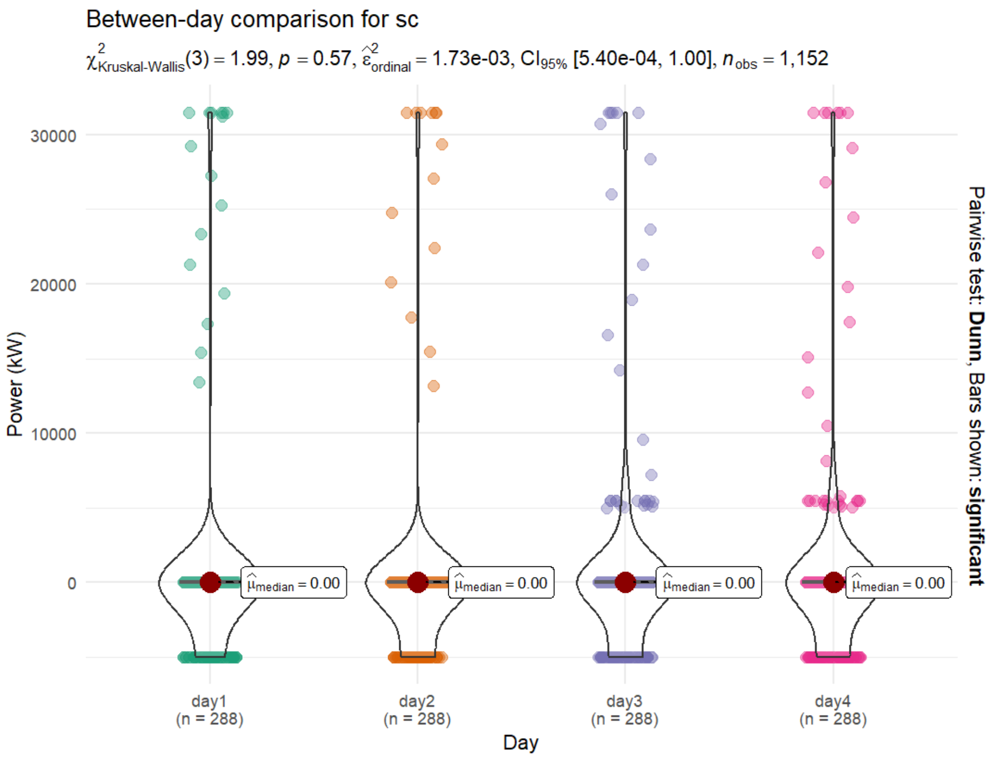

Figure 5.12 Between-Day comparison of SOC

The SOC data reinforces the following trend: battery and pumped hydro SOCs rise significantly, peaking on Day 2 as shown of Figure 5.13 and Figure 5.14, while the supercapacitor SOC remains within a narrow range of about 95 to 100 kW, emphasizing its role in short-term stabilization rather than long-term storage on Figure 5.15.

The FLC is key to these patterns, utilizing rule-based logic to interpret real-time changes in load, solar output, and storage conditions, enabling smooth responses from each system component. The controller maintains steady outputs for the battery and supercapacitor while allowing the PV, grid, and pumped hydro storage to adjust dynamically as conditions evolve. Overall, the FLC enhances coordination within the energy network, reducing unnecessary dependence on the grid, prioritizing renewable energy, and ensuring that short-term fluctuations are managed without disrupting long-term stability. This results in a hybrid energy system that reacts intelligently, maintains balance, and operates with improved stability and reliability.

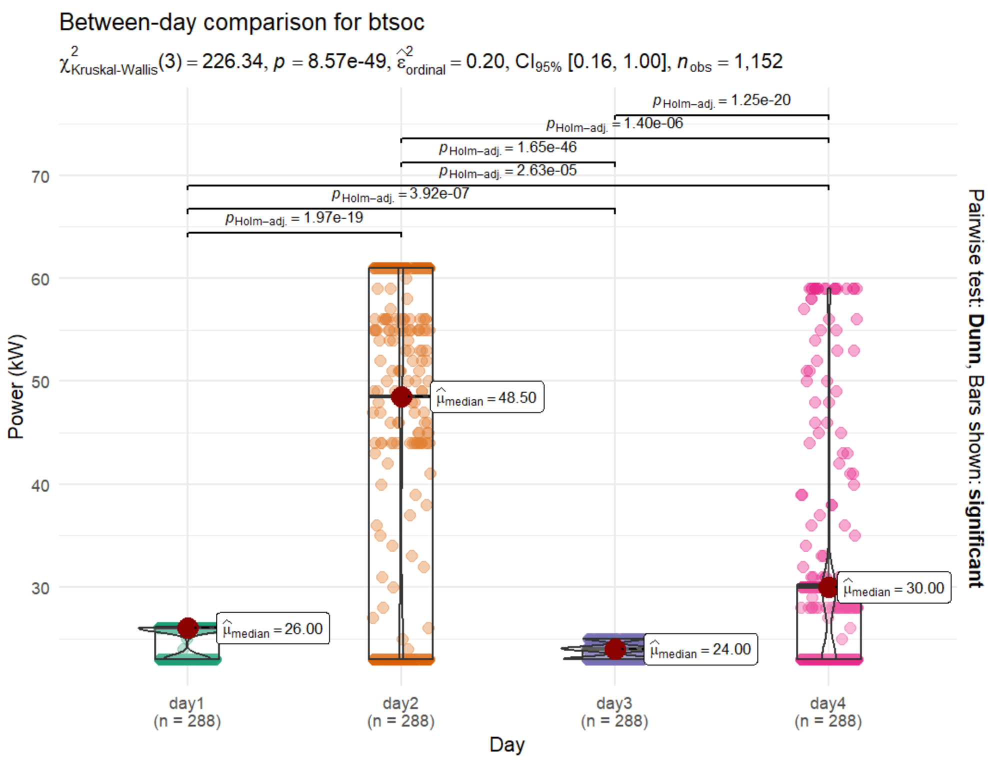

Figure 5.13 Between-Day comparison of BTsoc

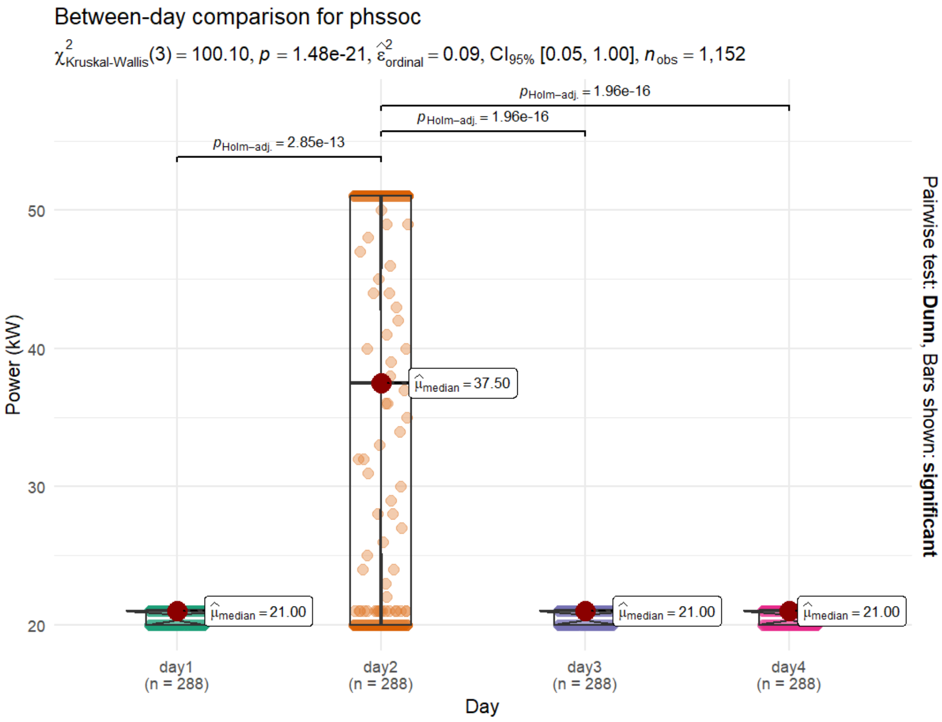

Figure 5.14 Between-Day comparison of PHSsoc

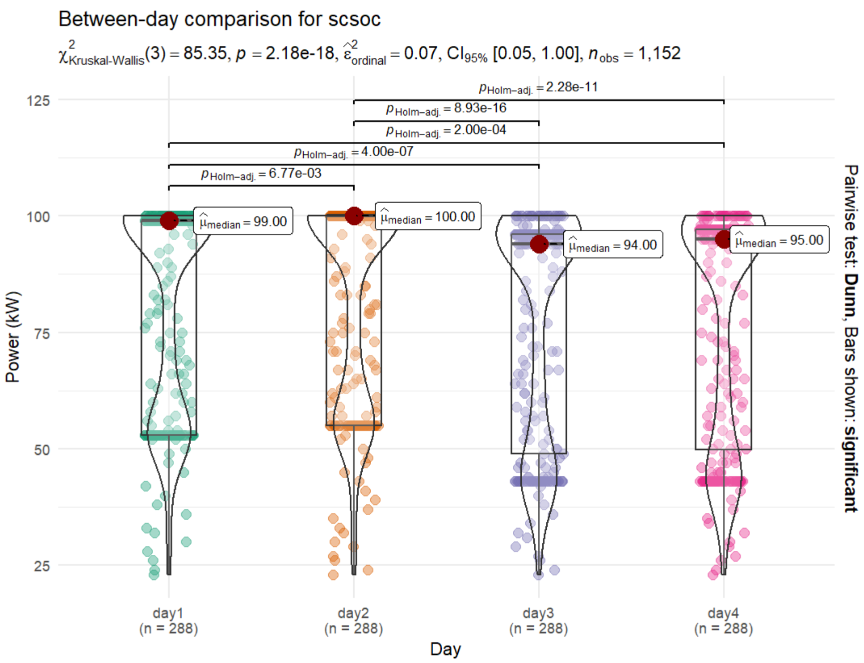

Figure 5.15 Between-Day comparison of SOC

5.4. Machine learning application to microgrid system data

Further analysis of microgrid system is based on the application of machine learning to verify the microgrid behaviour under different weather conditions. Seven machine learning algorithms are used to analyse the reliability and the performance of the FLC to manage the microgrid. To reach the goal, Anomaly Detection, PCA, K-means clustering, Random Forest regression, XGBoost, SVR and ANN are use.

5.4.1. Anomaly detection on load demand

Anomaly detection is employed to identify data points that deviate from the norm. These "outliers" can indicate issues such as faulty equipment, unusual energy consumption, or other system problems. In a microgrid, this process helps detect anything abnormal in energy generation, storage, or usage. Figure 5.16 illustrates the anomaly detection for load over time, with the x-axis representing the timeline and the y-axis showing the load. Most data points are red, indicating normal system operation, while a few blue points highlight instances where the system detected something unusual. These blue points appear near sharp changes in the load curve, indicating that the algorithm identified slight deviations during rapid fluctuations. Anomalies primarily occur at the rising and falling edges of load cycles, where variability is naturally higher. This suggests that the load occasionally strays from the expected pattern or exceeds a predefined threshold. The limited number of anomalies indicates that the system operates smoothly, with only minor irregularities during transitions. Overall, this approach effectively distinguishes between normal and abnormal behaviour, making it valuable for monitoring the microgrid and identifying early signs of unusual load patterns.

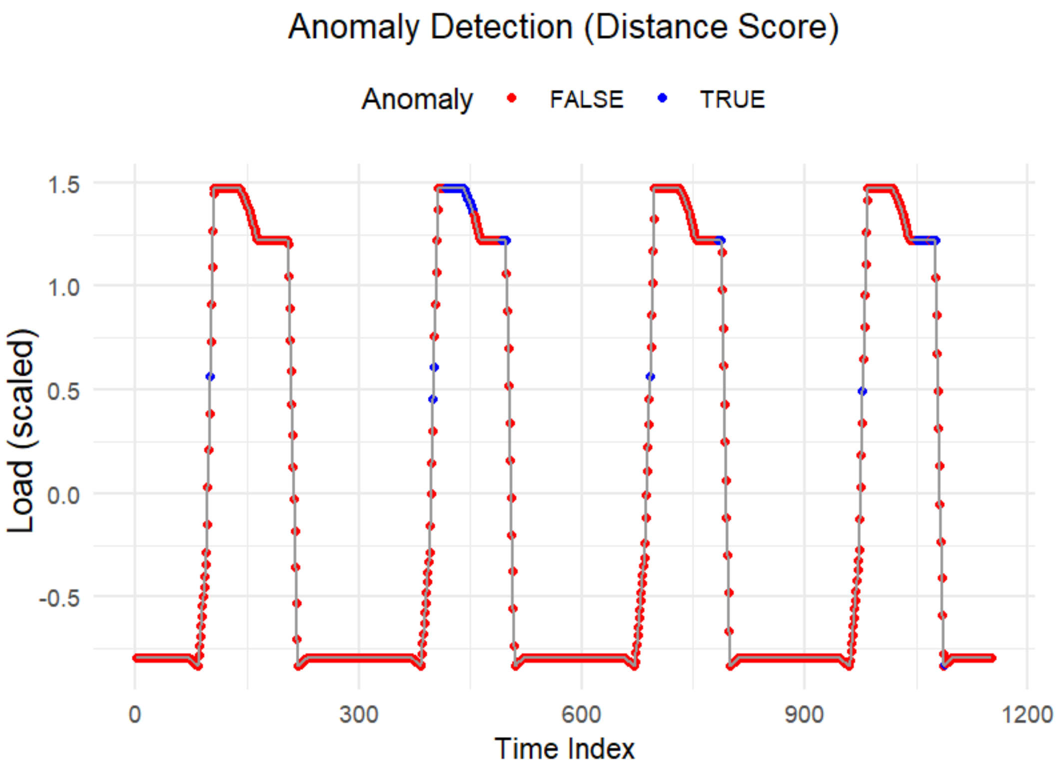

Figure 5.16 Anomaly detection

5.4.2. Principal component analysis

Figure 5.17 presents a scree plot from the PCA, illustrating the proportion of total variance captured by each principal component (PC). The y-axis represents the variance proportion, while the x-axis lists the components from PC1 to PC7. PC1 accounts for about 30% of the variance, reflecting the primary trend in the data, and PC2 explains roughly 20%. Together, PC1 and PC2 explain nearly half of the total variance and capture most of the dataset's variation. The plot exhibits a typical elbow shape, indicating that after the third or fourth component, adding more components provides little additional useful information. This suggests that only the first few components are sufficient for dimensional reduction, data visualization, or further analysis. It also indicates that the dataset has a largely low-dimensional structure, with most significant patterns concentrated in the initial components. This simplifies the data while preserving essential information.

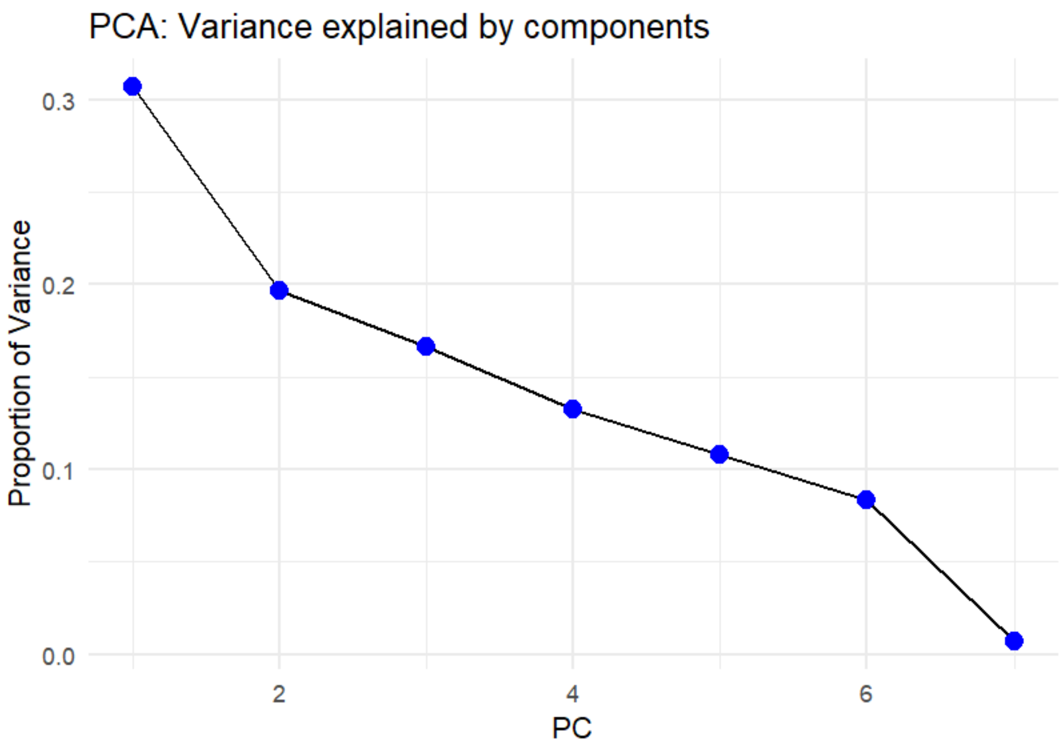

Figure 5.17 PCA: Variance explained by components

5.4.3. K-means clusters

Figure 5.18 displays the results of K-means clustering based on the first two principal components. The points are distributed across PC1 and PC2, which capture the primary patterns in the data. Small histograms at the top and right illustrate the distribution of values for each component. Although three clusters were defined, there is some overlap among them, indicating that the groups are not perfectly distinct and suggesting the presence of mixed or transitional features in the data. The plot also includes a blue regression line along with statistics such as the t-value, p-value, and Pearson correlation. The correlation is nearly zero, and the wide confidence intervals indicate that PC1 and PC2 do not exhibit a linear relationship. This suggests that each component captures different types of variation, making the clusters easier to interpret. Overall, while K-means identified some patterns, the groups are not very clear, indicating that the data is somewhat mixed. This implies that alternative clustering methods may be necessary to achieve more distinct groupings.

Furthermore, the K-means clustering results in Table 5.2 identify three distinct operating patterns based on load and solar PV generation. Cluster 2, which has the largest number of observations at 710, represents periods of low load, with a load mean of -0.7633, and low PV generation, with a mean of -0.6167. This likely corresponds to night-time or early morning hours when solar production is minimal and electricity demand is low. Cluster 1 contains 367 samples and is characterized by high load, with a load mean of 1.2967, and high PV output, with a mean of 1.2334, indicating peak daytime hours when both energy consumption and solar generation are at their highest. Cluster 3, with 75 samples, features moderately high load (mean of 0.8805) and low PV generation (mean of -0.1970), likely reflecting evening hours when demand remains elevated but solar output has decreased. Overall, the clustering effectively distinguishes between low-activity, peak daytime, and evening operational states, offering valuable insights for optimizing energy management strategies.

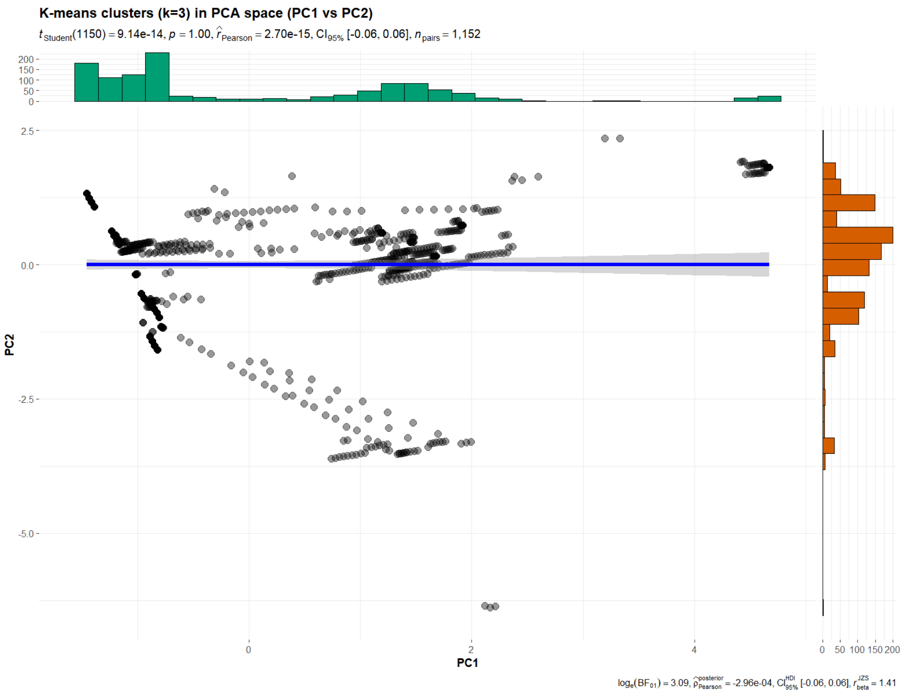

Figure 5.18 PC2 vs PC1 K-means clusters

Table 5.2 Cluster summary

K Means cluster	Count	Load Mean	PV Mean
2	710	-0.7633	-0.6167
1	367	1.2967	1.2334
3	75	0.8805	-0.1970

5.4.4. Supervised learning algorithms

In the area of data-driven modelling and intelligent energy management, machine learning (ML) algorithms are essential for understanding the nonlinear and dynamic relationships that define complex systems like microgrids. Among the most effective methods for predictive analysis and system optimization are Random Forest Regression, XGBoost, SVR, and ANNs. While these models aim to minimize prediction errors and enhance generalization, they differ in their learning mechanisms and computational approaches. Figure 5.19(a) displays the predicted load from the Random Forest model compared to the actual load. The blue line represents the true load, while the red dashed line shows the model's predictions. The close alignment of the two lines indicates that the model effectively captures cyclical load patterns, with minor deviations occurring during sudden changes, which is expected due to the complexity of abrupt transitions and the averaging effect of Random Forest over multiple trees. Overall, the model reliably reflects real data and is suitable for forecasting and pattern recognition in similar scenarios.

Figure 5.19(b) illustrates the predictions made by the XGBoost model, where the blue line indicates actual load, and the red dashed line represents predicted load. The near-total overlap of the two lines demonstrates that XGBoost accurately tracks the load pattern, with minor discrepancies during rapid transitions, which is typical behaviour. This confirms that XGBoost effectively manages nonlinear patterns and produces stable, precise predictions.

Figure 5.19(c) shows the results from the SVR model, where the blue and red lines align closely throughout most of the dataset, indicating strong predictive performance. Slight differences arise during rapid load changes, which is common since SVR often smooths abrupt fluctuations. The model performs exceptionally well in steady-state conditions, accurately capturing the system's behaviour. Additionally, Figure 5.20(d) presents the predictions from the ANN. The blue line represents the actual load, while the red dashed line shows the model's predictions. The ANN closely tracks the actual data, effectively capturing complex nonlinear patterns and managing both high and low load periods. Minor deviations occur during rapid transitions, indicating that the model adapts well to dynamic changes. Overall, the ANN demonstrates excellent predictive accuracy. Although some slight differences are noticeable at points of abrupt load changes, these deviations are minimal, suggesting that the model performs exceptionally well even under dynamic conditions. The ANN accurately reflects the system's behaviour during both high and low load phases, maintaining consistent accuracy across various operating scenarios. This strong alignment between the actual and predicted data indicates that the ANN has successfully learned the relationship between input features and the target variable. In summary, the results highlight the ANN's impressive predictive accuracy and robustness, confirming its effectiveness for modelling and forecasting nonlinear load patterns, where traditional statistical or linear models may not achieve similar precision.

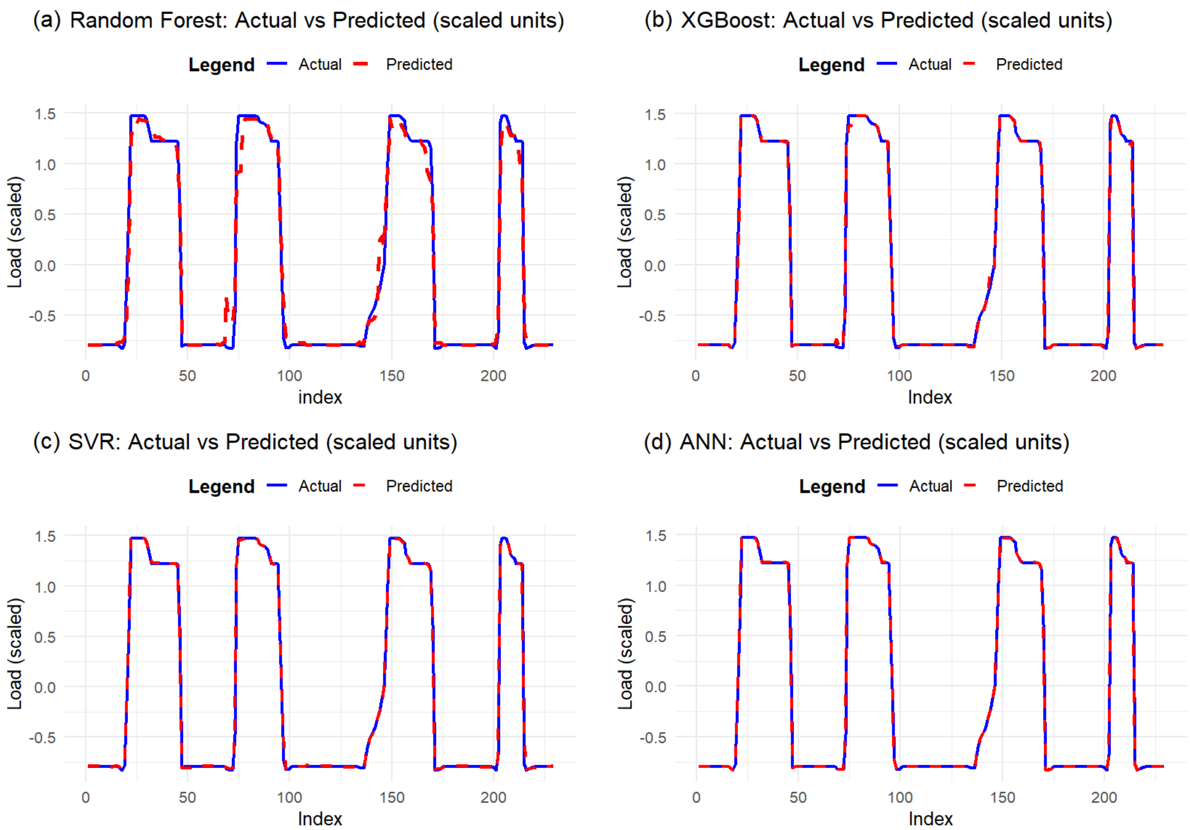

Figure 5.19 Random Forest, XGBoost, SVR and ANN diagrams of the scaled load

The comparative performance analysis of various machine learning algorithms applied to the microgrid system, as shown in Table 5.3, indicates that all models achieved high predictive accuracy, though there are notable differences in their precision and generalization capabilities. The ANN outperformed the others, achieving the lowest root mean square error (RMSE) of 0.00303 and the highest R^2 value of 0.99999, indicating an almost perfect correlation between predicted and actual values. This demonstrates the ANN's exceptional ability to model complex nonlinear dynamics in the microgrid, including fluctuations in load demand, renewable energy generation, and energy storage behaviour. The Support Vector Regression (SVR) model also performed well, with an RMSE of 0.0204 and an R^2 of 0.9996, effectively capturing nonlinearities, though it has slightly less flexibility compared to the ANN due to constraints in kernel and parameter tuning. The XGBoost algorithm showed comparable performance with an RMSE of 0.0265 and an R^2 of 0.9993, reflecting its robustness and efficiency in handling structured datasets with low bias and variance. In contrast, the Random Forest model, while having a strong R^2 of 0.9875, displayed a higher RMSE of 0.1157, indicating some limitations in modelling highly nonlinear or temporal dependencies. Overall, the findings confirm that the ANN and SVR models provide superior predictive performance for dynamic microgrid applications. Additionally, integrating a FLC enhances the system's reliability and adaptability by effectively managing operational uncertainties and nonlinear relationships among generation, storage, and load components. The FLC's ability to maintain stable and balanced operating conditions supports the impressive accuracy achieved by all learning models, highlighting its critical role in ensuring robust, intelligent, and efficient energy management within the microgrid framework.

Table 5.3 Machine learning model performance summary

Model	**RMSE**	**R^2**
Random Forest	0.11569	0.98754
XGBoost	0.02649	0.99931
SVR	0.02038	0.99960
Neural Network	0.00303	0.99999

5.5. Chapter discussion and conclusion

This chapter provided a comprehensive analysis of microgrid data using both statistical and machine learning methods. The analysis revealed patterns among various energy sources, and examining changes within and across days highlighted the impact of weather and demand on the system. Machine learning techniques facilitated predictions of system behaviour: anomaly detection identified unusual load patterns, PCA and K-means clustering simplified the data and organized system states, while regression models (ANN, SVR, XGBoost, Random Forest) effectively predicted load. Combining these approaches with fuzzy logic control enhances the microgrid's stability, reliability, and efficiency, contributing to smarter energy management in future grids.

CHAPTER 6 : CONCLUSIONS AND FUTURE RESEARCH

6.1. Conclusions

This chapter outlines the findings from a study focused on developing an optimal controller for a grid-connected microgrid powered by PV systems, featuring a hybrid energy storage system that includes SC, PHS, and batteries. The data for this study was collected from a commercial farm situated in Mpumalanga. The primary focus was on the control mechanisms necessary for managing the power flow to the farm's energy loads, demonstrating the controller's ability to monitor and regulate the system while maximizing the use of renewable energy compared to grid electricity.

Chapter 2 provides a review of existing hybrid storage systems commonly used in microgrid applications, discussing their advantages and disadvantages. It also explored the control strategies relevant to this research, aiming to identify an optimal controller suitable for real-time applications or hardware platforms. While most existing literature centers on electric vehicles, this work highlights the importance of developing integrated control strategies that consider optimal energy management, sizing, and power flow dynamics in HESS. The literature review revealed that, although PHS has long-lasting benefits and high energy density, its low power density requires careful management to ensure effective performance in hybrid setups.

In Chapter 3, the selected optimal controller was developed using the MATLAB fuzzy logic library to manage the proposed system and supply a variable load from an intermittent energy source. The main system model was then developed in Simulink, incorporating existing and validated resource data to effectively model the PV, PHS, and SC components while integrating the controller into the overall system.

Chapter 4 examined the simulation results from the MATLAB models. The findings demonstrated that the FLC successfully managed the power flow in the proposed system, consistently generating the required output power to meet the demands over a 24-hour period without any shortages.

Chapter 5 presents real-time results validation using Opal-RT. This includes the framework for analyzing and modeling the performance of a hybrid microgrid system using data analytics and machine learning. It begins by examining the operational dataset to identify patterns and relationships among energy sources. Reliability tests are conducted, followed by an analysis of power generation and storage changes over time. The chapter then introduces machine learning techniques, including anomaly detection, PCA, K-means clustering, and four regression models (Random Forest, XGBoost, SVR, and ANN) to improve reliability and predictive performance.

This research has filled a significant gap in the understanding of HESS within renewable energy-based microgrids, particularly in residential, commercial, and industrial settings. The findings reveal important insights that can enhance the efficiency and reliability of the proposed system. The research objectives were achieved systematically, leading to the creation of an optimal energy management model that efficiently distributes energy among the hybrid system's components: batteries, supercapacitors, and PHS. The model, validated through MATLAB Simulink simulations, underscored the critical role of the FLC in effectively managing energy flow, particularly in response to fluctuating load demands. Furthermore, the economic observation highlighted the financial benefits of integrating HESS into microgrids, showing significant potential for cost savings through reduced dependence on grid electricity. Experimental results confirmed that the proposed energy management strategies markedly improved the system's ability to handle load variations, thereby enhancing resilience and reliability. Consequently, this work concludes the following:

- A Fuzzy Logic Controller can be effectively utilized to optimally manage grid-connected renewable energy-based microgrid's components, ensuring that it meets diverse load demands while maximizing efficiency and reliability across various applications.
- The optimal operation of a grid-connected renewable energy based microgrid with a hybrid energy storage system, under ToU pricing, can significantly reduce the costs of electricity purchased from the grid.

6.2. Future work

The study identified limitations in existing research, particularly the lack of comprehensive approaches that integrate both technical and economic considerations in energy management strategies. This thesis advocates for future investigations into joint optimization of sizing and control strategies to further enhance the operational effectiveness of hybrid energy storage systems. In conclusion, the findings of this thesis contribute to the advancement of renewable energy management by providing a robust framework for optimizing the performance of hybrid energy storage systems in diverse applications. Continued research in this area is essential to fully realize the potential of HESS in supporting a sustainable energy future.

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