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PULCHOWK CAMPUS

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**Design and Control of a Multi-Port Energy Router for Grid-
Interactive Local Energy Community**

by
Sandesh Dhungana

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**Design and Control of a Multi-Port Energy Router for Grid-Interactive Local
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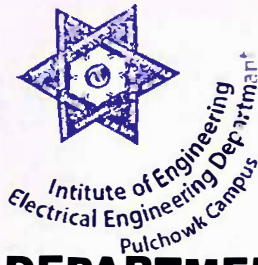
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ABSTRACT

Distributed renewable energy sources (RES) and energy storage systems (ESS) are increasingly being integrated into local power networks through Local Energy Communities (LECs). The design and control of a single-phase Multi-Port Energy Router (MPER) for grid-interactive LEC usage are presented in this paper. To facilitate coordinated power exchange the proposed MPER with LEC-EMS interfaces PV generation, bidirectional ESS and AC/DC loads via a common DC bus.

A straightforward Local Energy Community-Energy Management System (LEC-EMS) is proposed, which coins two main ideas: Dynamic Master Prosumer Selection and Prosumer-Centric Proportional Power sharing strategy. The concept is to dynamically select the most suitable and capable prosumer which could lead the community loads based on real-time surplus capacity (Margin) and State-of-Charge (SoC). Thus, ensuring robust master prosumer for failure events while operating in Islanded mode. Additionally, the power-sharing scheme ensures fairness by dispatching support responsibilities proportionally to each prosumer's available margin.

The MPER with LEC-EMS is configured to work in grid-connected, LEC-PCC (islanded), and standalone modes using hierarchical control scheme to regulate power quality, manage power exchange and perform seamless mode transitions. MATLAB/Simulink simulation studies are used to examine the performance of the system under different operational and test case scenarios. The results indicate that the MPER maintains the DC-bus voltage within $\pm 2\%$ and is able to control and manage successful flow of power as per the proposed novel LEC-EMS strategy. Most importantly, within LEC-PCC mode the control strategy has been able to maintain power quality, where a Total Harmonic Distortion (THD) of the PCC bus current and the individual prosumer's converter current both are well within tolerable ranges. The research highlights that how the coordinated controls schemes can improve prosumer-level flexibility, power sharing reliability, and decentralized and resilient community microgrids.

Keywords—Intelligent Control, Smart Community, Multi-Port Energy Router, Battery Energy Storage System (BESS), Distributed Energy Resources (DER), Bi-directional Converter

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LIST OF ABBREVIATIONS

DER	:	Distributed Energy Resources
DES	:	Distributed Energy Sources
DSO	:	Distributor System Operator
ER	:	Energy Router
EMS	:	Energy Management System
ESS	:	Energy Storage System
EV	:	Electric Vehicle
GC	:	Grid Connected
IBR	:	Inverter Based Resources
IoT	:	Internet of Things
LEC	:	Local Energy Community
MPER	:	Multi-Port Energy Router
PCC	:	Point of Common Coupling
PEI	:	Power Electronic Interfaces
PLL	:	Phase Locked Loop
PQ	:	Power Quality
PV	:	Photo-voltaic
PWM	:	Pulse Width Modulation
RES	:	Renewable Energy Sources
RMS	:	Root Mean Square
SA	:	Stand-Alone
SC	:	Smart Community
LEC-PCC	:	Local Energy Communities Point of Common Coupling
SG	:	Smart-Grid
SST	:	Solid State Transformer
STATCOM	:	Static Synchronous Compensator
UPFC	:	Unified Power Quality Conditioner
VSC	:	Voltage Source Converters

CHAPTER ONE: INTRODUCTION

1.1 Background

The world energy industry is undergoing a significant change, primarily due to the fact that we need more cleaner, dependable and flexible power system. As the energy demand is increasing serious environmental concerns are also rising, there's a urgent need to modernise the traditional electrical infrastructure. One of the major reasons of this upgradation is the transition from conventional centralized grids to smart grids (SGs). These systems implement the most recent digital technologies, automations, and data analysis to optimize the entire energy process, including generation, transmission, distribution, and consumption [1].

1.1.1 Evolution of Grids and Emerging Challenges

Historically, the flow of power was unidirectional. Centralized power plants which generated power were situated in remote location was to be delivered to consumers via hierarchical transmission and distribution lines. These systems were stable over decades; however, it was not designed to adapt high penetration of RES, bi-directional flow of power or increasing variability in load and generation profiles [2].

Increasing large-scale integration of intermittent and unpredictable RES such as solar PV and wind in the present time has introduced significant complexities and unpredictability into the balance of real-time grid operation and the preservation of system stability. Secondly, aging grid infrastructures and limited visibility across the network imply that the faults are not detected on real time, which is detrimental to power quality. Lastly, there are emerging trends such as EV, prosumers behavior (consumers also generate) and local generation have introduced challenges such as voltage fluctuations, harmonic distortions and frequent voltage sags, all of which degrade PQ and compromise transient stability [3]. These evolving demands reveal the urgent need for more flexible and responsive grid infrastructure.

1.1.2 Smart Grid, Distributed Energy System and Energy Router

Smart grids are the essential solution in the future to address the growing challenges in the grid which requires the development of new devices such as energy routers. A smart grid is defined as “an electricity network that can intelligently integrate the

actions of all users connected to it; generators, consumers, and prosumers, to efficiently deliver sustainable, economic, and secure electricity supplies". Smart grids make use of advanced sensors, communication systems and control strategies to monitor in real time and make decentralized decisions enhancing reliability, resilience, and energy efficiency [2], [4].

ERs are the modular and scalable devices designed to automatically control, manage and monitor flow of power from various energy sources, such as PV panels, wind turbines, residential or commercial loads and EV chargers. Smart grids and the ER form a symbiotic relationship: ERs facilitate the integration and control of various energy sources and loads within a local system e.g, energy community or home. Real-time information and past data are used to optimize energy use. The smart grid provides ERs with the necessary information and connectivity to balance energy supply and demand and make the grid more reliable. The combination of these elements creates a more efficient, sustainable and versatile system that will be able to address the present and future energy challenges in effective manner.

Furthering this concept, DES commonly regarded as microgrids or systems of DERs and ESS have become extremely popular. These localized energy ecosystems are self-coordinated often intelligent energy management system. In this context, all the users are active prosumers who are capable of producing and consuming energy. DES are typically operated by advanced Smart Energy Management Systems (SEMS), which facilitate local energy trading or exchange, make optimal utilization of ESS and manage PQ with the help of intelligent load scheduling and generation [5]. This paper is an examination of a dynamic performance and coordinated control of a single-phase MPER within a local community [6].

ER is one of the crucial and transformative enablers of SG and operation of DES rather than conventional power converter only. Next generation power electronic with intelligent control are capable of interfacing diverse DERs, ESSs, utility grid and various local loads. By enabling seamless transitions between GC and SA or islanded operational modes, ERs play a role in maintaining grid stability, controlling active and reactive power exchange and overcoming PQ problems such as voltage sags and harmonic distortion [5], [7]. This grid interactive DES necessitate the ER with its multi-port intelligent design.

1.1.3 Multi-Port Energy Router: Role in Grid-Interactive DES

When the power system becomes more complex and flexible, sophisticated power electronic converters are needed. MPER is a modular and scalable device that enables bidirectional power flow control. It ensures optimal sharing of load, significant PQ improvement, and transient stability support across hybrid AC/DC microgrids to form the backbone of DES[8], [9].

MPERs with the built-in control intelligence make it possible to dynamically and adaptively respond to grid variations such as voltage and frequency fluctuations. During sudden outages MPER can contribute to black-start operations and re-energize local networks. Additionally in coordination with the EMS, they can contribute in real-time load balancing, optimization of DER use and greatly improving grid efficiency [9]. One of the main research areas is the analysis of their performance in dynamic conditions.

Several studies have indicated that the application of MPER into community-scale SG is a way of increasing resilience by mitigating the disturbance, such as harmonics, flickers and in addition dampening fluctuations of voltages with dynamic support and peak-shaving. Another direct benefit of MPER is that they can make direct and substantial contribution to transient stability by regulating voltage and frequency during grid disturbances, thus preventing cascading failures and assist in rapid recovery [8].

Furthermore, the modularity of ER topologies enables them to have unparalleled flexibility to interface with various DERs (e.g., PV systems, wind turbines), multiple ESS units, and medium-voltage networks as well as low-voltage networks. This allows them to be smart connected nodes in a distributed energy environment, bridging between DC and AC systems. Their capacity to support grid resilience extends across multiple scales, from localized microgrid stability to broader systemic reliability [10].

1.1.4 Research Direction and Contribution

ERs and MPERs have been explored in recent studies, however critical gap remains in understanding their comprehensive performance under dynamic operating conditions, such as varying solar irradiance and temperature, grid fluctuations and seamless transitions between GC, LEC-PCC and SA modes of operation. Most of the

existing research focuses on the steady-state evaluations or centralized control architectures of the MPER, with concerns regarding decentralized control layers, prosumer-centric energy management, power sharing, and qualitative power resilience among small consumers and effectiveness of coordinated control largely remains unanswered.

This thesis addresses that gap by designing, modeling and implementing a control strategy and conducting a performance analysis of the MPER in a grid-interactive LEC. The study introduces a straightforward novel LEC-EMS based on two major innovations namely, Dynamic Master Prosumer Selection logic and Prosumer-Centric Proportional Power Sharing strategy. Advanced modeling and simulation of a community with three-prosumer and critical PCC load is done to demonstrate how intelligently controlled MPERs can play a vital role in supporting stable, reliable, and efficient future smart power systems while enhancing system resilience, ensuring fair energy distribution, and maintaining PQ under varying conditions.

1.2 Problem Statement

Growing integration of intermittent RES and diverse DERs into traditional ps has brought new challenges in stability of the system. Unlike traditional feeders which were designed for unidirectional power flow, LEC architectures are required to continuously deal with intermittent PV generation, variable prosumer loads, and diverse ESS operating conditions. These dynamic circumstances often lead to voltage instability, inconsistent and unfair power sharing among prosumers resulting in the reduction of system inertia and poor reliability performance during grid failures. To achieve PQ within acceptable limits and maintain operational resiliency in such environments, intelligent, multi-functional power electronic interfaces are required which can support flexible energy routing, autonomous operation, and stable, decentralized control under a wide range of operating scenarios.

MPER has become a promising solution to address these challenges, as it can integrate PV systems, ESS, DC loads, and AC loads within a single platform and coordinate power exchange across multiple ports. However, current studies focus on conceptual designs or steady-state characteristics of ERs. They have little insights on their dynamic performance being subjected to fluctuating irradiance, variable loads, grid disturbances, or transitions between operating modes. Moreover, there is insufficient

analysis of decentralized control strategies that enable dynamic, margin based prosumer selection within a community and ensure fair, proportional power sharing based on real-time prosumer capacity. Similarly, ability of an MPER to operate in grid-forming mode during islanded operation, selected dynamically based on a prosumer's surplus Margin and SoC, has remained insufficiently explored, especially in the context of single-phase LEC applications.

This research focuses on designing, modeling, and simulation of a single-phase MPER with a decentralized LEC-EMS and synchronized control strategies designed for grid-interactive LEC to fill in the existing research gap. Focus is on developing a control framework that enables dynamic master prosumer selection and prosumer-centric proportional power sharing during islanded operation, while also allowing for economic power trading with the main grid. Additionally, an energy management mechanism is required to facilitate autonomous mode selection and seamless transitions between operating conditions in response to dynamic conditions. Through simulation-based evaluation of a three-prosumer community under dynamic scenarios, this study seeks to test the MPER's capability to maintain stable DC-bus voltage, enable uninterrupted supply of loads, ensure quality of power, and facilitate accurate and fair power sharing. The findings are intended to identify the extent to which the proposed MPER and LEC-EMS framework can provide the reliable and flexible energy interaction within community energy systems.

1.3 Objectives

- To design and simulate a single phase MPER system that integrates PV generation with MPPT, bidirectional ESS, and both AC and DC load interfaces. The system should be able to operate in GC mode, LEC-PCC mode and standalone mode.
- To develop and implement a decentralized LEC-EMS that includes a Dynamic Master Prosumer Selection logic and Prosumer-Centric Proportional Power Sharing strategy ensuring fair and coordinated operation of energy system based on each prosumers real-time Margin and SoC.
- To establish reliable grid-forming and grid-following control strategies that allow seamless transitions between operating modes, while maintaining stable

DC-bus voltage, regulating local voltage and frequency and ensuring continuous supply to critical loads under dynamic conditions.

- To assess the dynamic performance of the proposed MPER and LEC-EMS in a three-prosumer community by analyzing power balance, SoC management, PQ and the uninterrupted supply of loads within the LEC microgrid.

1.4 Scopes

- System Design and Modeling
 - Development of a detailed MATLAB/Simulink model of a single-phase MPER integrating:
 - A PV subsystem with MPPT and DC–DC boost converter.
 - A bidirectional battery ESS using a DC–DC converter.
 - Combined AC and DC load interfaces.
 - A single-phase DC/AC converter for grid and PCC connection.
 - Construction of a representative LEC with three prosumers and a critical facility as test case, with each prosumer having distinct PV capacity, load profiles, and initial battery SoC, connected through a common Point of Common Coupling (LEC-PCC).
- Control Strategy Development
 - Implement coordinated active and reactive power control for grid-connected operation, enabling power trading between prosumers and the utility grid i.e., a hierarchical control structure for the MPER, including inner current control loops and outer voltage/power control loops.
 - Design a grid-forming control method for autonomous voltage and frequency regulation during standalone operation.
 - Design of grid-following control for synchronized operation in grid-connected and LEC-PCC islanded modes.
 - Implementation of a seamless transition mechanism between all operating modes (GC, LEC-PCC, and SA).
- Development and Implementation of LEC-EMS
 - Formulation of the Dynamic Master Prosumer Selection logic based on the real-time calculation of prosumer Margin (surplus capacity) and battery SoC.

- Development of the Prosumer-Centric Proportional Power Sharing strategy for fair dispatch in islanded mode, where support responsibilities are allocated based on individual prosumer Margin.
- Integration of economic decision-making logic for grid-connected mode, incorporating peak hour and off peak hour to govern power injection and absorption.
- Reference setpoints for power sharing among available prosumers.
- Simulation, Performance Evaluation and Analysis
 - Execution of comprehensive simulation case studies for the three-prosumer LEC under dynamic conditions, including
 - Grid-connected operation during peak and off-peak hours.
 - LEC-PCC operation with a critical community load.
 - Conduct simulation-based test cases under dynamic operating conditions for a prosumer in standalone mode of operation in order to evaluate the MPER's operational performance.
 - Quantitative evaluation of the system's performance based on:
 - DC-bus voltage stability and regulation
 - PQ at the PCC and prosumer level, specifically through THD analysis of current waveforms.
 - Accuracy and fairness of proportional power sharing among prosumers.
 - Effectiveness of the dynamic master selection and seamless mode transitions

1.5 Limitations

- The proposed MPER control strategies and LEC-EMS coordination are evaluated solely through simulations. No hardware prototyping or real-time controller implementation is included.
- The power converter and system component models assume ideal conditions. Practical non-idealities such as switching losses, device temperature variations, electromagnetic compatibility constraints, or long-term component aging which may affect real-world performance.
- The study focuses mainly on fundamental performance metrics like voltage stability, power sharing, DC-bus regulation, and continuity of supply; other

disturbances like flicker or electromagnetic interference are not extensively covered.

- The implemented control strategies are developed based on idealized models and examined through simulation. Practical control tuning, robustness testing under hardware uncertainties, and real-time adaptability are not covered.
- The grid model and the implemented LEC are based on a single-phase system. The findings may not be directly applicable to three-phase distribution networks without further study.

1.6 Thesis Organization

This dissertation is structured into five chapters, followed by references and appendices. Below is a brief outline of each chapter and its contents:

- This chapter gives brief introduction of the dissertation. The problem statement, scope, limitation is described and followed by the objectives of the thesis.
- Chapter 2: It presents a concise literature review done for this dissertation.
- Chapter 3: It describes the research methodology of the dissertation including the MATLAB simulation and workflow.
- Chapter 4: Results and discussion present the simulation results
- Chapter 5: Conclusion and Recommendation
- The References section lists all cited works, providing a comprehensive bibliography of standards, journal articles, Books and technical reports relevant to SG, MPER, Power Quality, etc.,
- The Appendices include supplementary data, such as plagiarism test report and paper publication information/certification to support the thesis.

CHAPTER TWO: LITERATURE REVIEW AND RESEARCH GAP

With the shift toward high renewable penetration in the traditional grid, multi-port converters based ERs with intelligent control is emerging as critical node of DERs integration, grid resilience enhancement and PQ improvement.

2.1 Emergence of Smart Grids

The evolution from conventional power grids to smart grids has brought around a significant transformation in energy generation, distribution and consumption process. Traditional power systems were mostly centralized, unidirectional in power flow and most systems depended on fossil fuels leading to inefficiencies and environmental issues. With the increase in the prominence of renewable energy sources like solar and wind, the shortcomings of the traditional systems, including rigidity, poor observability and delays in control responses became increasingly evident [2], [3].

In response SG has emerged as a technologically advanced alternative. They incorporate sensors, communication infrastructure and computational intelligence to enable real-time monitoring and control of grid operations. This facilitates improved reliability, better integration of RES, and enhanced customer participation through demand-side management. Smart communities extend this paradigm to a local or district level, enabling prosumers (entities that both produce and consume electricity) to interact with the grid and among themselves in dynamic energy exchanges [4].

The adoption of these modern grid paradigms has created an environment where decentralized generation, EVs, ESS, and real-time load balancing are becoming the norm. However, these benefits are accompanied by new technical challenges, particularly concerning PQ and grid stability.

2.2 Multi-Port Energy Routers: Concepts, Architectures, Topology and Control Strategies

ERs are central technologies in SG and SC which manages the flow of electricity among multiple sources, loads, and storage units, often in multi directions. It incorporates functions such as voltage regulation, current sharing, harmonic

mitigation, and transitions between GC and SA modes. The broader concept of the Energy Internet builds on this idea, enabling large-scale coordination of distributed generation (DG), storage systems and controllable loads.

Wang et al. [2023] highlighted the importance of DC microgrids in the context of the rural Energy Internet. Their work proposed a scalable structure supported by advanced power electronics and coordinated control. They emphasized bidirectional power flow, intelligent energy management and real-time data communication for achieving energy autonomy and flexibilities in operations of rural electrification. The combination of these characteristics demonstrates the essence of the work MPER, which serve as a bridge between energy resources and end-users in distributed systems [11].

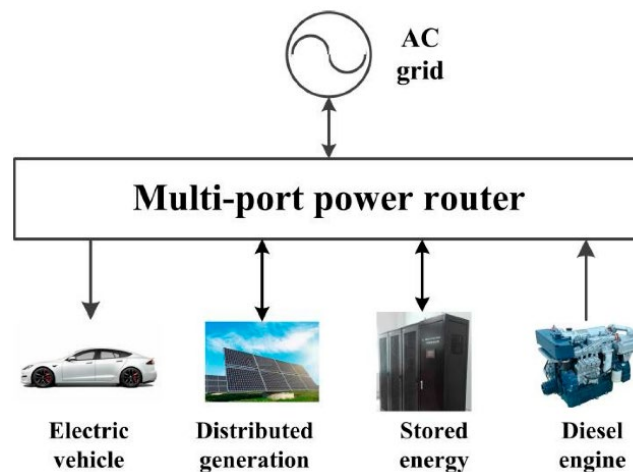


Figure 2-1 Basic architecture of MPER

Similarly, **Cheng et al. [2017]** provided a foundational exploration of the Energy Internet, including a description of its technical and operational structure. They recognized ER as key elements that facilitated information-energy coupling, real-time data exchange and efficient cascade utilization of energy across different voltage levels and energy forms. However, their work focused mainly on the conceptual level. It did not evaluate ER performance during transient grid events or address PQ improvement-critical aspects that this thesis investigates within the context of distributed grids and microgrids [12].

MPERs are now being equipped to be able to be plug and play to easily incorporate DG units, ESS, and other developing smart loads. This flexibility enables the multi-

directional energy flow which is essential for handling the complexity and variability present in modern distribution networks.

Kabalci et al. (2019) discussed the convergence of the Energy Internet and IoT, where advanced communication and control platforms allow the real-time coordination of the distributed energy assets. They emphasized that MPERs are the smart nodes within this ecosystem, which dynamically control the exchange of power and local energy balance [13].

Sun et al. (2019) presented a control framework for integrated EMS systems operating within the Energy Internet. Their work showed how MPER can optimize energy distribution by matching demand profiles as well as availability of the resource, which shows that they are critical to increasing the adaptability and responsiveness of the grid. Nevertheless, the two studies primarily concentrate on the aspects of conceptual and control integration but do not investigate into the qualitative impact of MPERs on grid resilience and PQ leaving an important gap that this thesis addresses [14].

One topology that is very popular with MPERs is the common DC bus topology that incorporates multiple, independent AC/DC and DC/DC converters that are linked together by a common DC link. This configuration allows effective power transfer between high and low voltage side in both directions and the exchange of power between diverse sources of energy, storage and loads through modular exchange of energy. This structure is found to be highly flexible and scalable, and thus is applicable in dynamic energy systems because converters can be customized according to the physical properties of the connected devices, including pv panels, batteries or loads local to them. This modular design is well suited to the need of DESs, where heterogeneous sources and sinks have to be synchronized with each other. Additionally, the common DC bus structure minimizes conversion losses by reducing the number of power conversion stages, which directly contributes to improved PQ and operational efficiency.

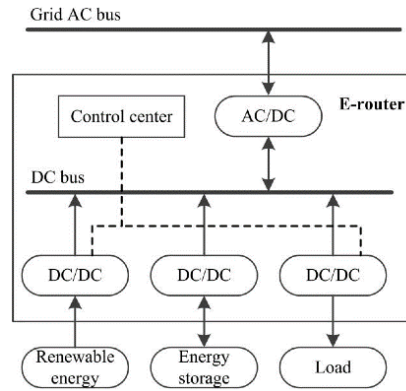


Figure 2-2 Block diagram of basic topology of MPER

Xu et al. (2019) proposed a single-bus MPER topology consisting of multiple DC/AC and DC/DC converters interfaced through a common DC bus. This architecture integrates diverse ports such as PV, wind energy and ESS, and provides simple and scalable structure suited for distributed generation systems. The design permits energy transfer between ports via the common DC link which encourages compactness and modularity of the system. However, a major weakness of this configuration is that there is no electrical isolation between ports which makes them dangerous and unreliable in case of fault conditions or asynchronous operations. Furthermore, the system faces operational challenges related to multi-working condition management, as renewable sources and storage units often operate intermittently. Notably, the study identified issues such as difficulty in switching during operating mode transitions, which can lead to sudden changes in voltage fluctuations in the DC bus that may adversely affect PQ and put pressure on system components. Despite its structural simplicity, the design lacks provisions for smooth working condition transitions, which limits its applicability in high-reliability environments. This gap underscores the need for advanced control strategies and dynamic reconfiguration mechanisms, which this thesis seeks to address through an in-depth evaluation of MPER architectures under various operational conditions [10].

Vilhena et al. (2020) introduced a modular ER that can be used in three different operating modes such as GC, SA, and seamless transition modes. Their DC bus voltage-based MPPT and ESS control ensured seamless transitions, but it lacked fault resilience capabilities since transition events were pre-scheduled rather than triggered by real-time grid faults [5].

Kamagaté and Shah (2024) can be regarded as a significant contribution to the issue of energy balance in microgrids because it suggests an adaptive management algorithm used in a grid-interactive DC system. Their strategy is the combination of a rule-based algorithm and a frequency separation strategy in order to dynamically split the power. This design ensures that the battery deals with steady-state demands while the supercapacitor deals with transient surges and the grid should offer specific support. One of the key innovations is a straightforward battery SoC that optimizes power flow between the battery and grid, enhancing PQ while implementing safety measures to extend the lifespan of the energy storage units [15].

Roncero-Clemente et al. (2020) came up with a three-phase local ER scheme to be implemented in SC. The study emphasized decoupled voltage and power control throughout DERs and local loads, which proves to be effective in changing renewable output. He implemented a three-phase ER prototype in a prosumer community. Their rule-based controller managed active/reactive power flows and voltage support, achieving smooth transitions between GC and islanded modes. It is worth noting that the ER processed the compensation of voltage imbalance and provided ancillary services. However, the implementation was limited to static or scheduled transitions, without addressing dynamic grid disturbances like voltage sags [16].

Zhou & Wang (2024) conducted a comprehensive survey on multi-port ERs, categorizing architectures such as common DC-bus, transformer-based modular designs, and hybrid converter cascades. They emphasize trade-offs in flexibility, efficiency, and modularity, while highlighting the importance of hierarchical control to coordinate PV, ESS, and grid interfaces. However, their review does not provide insight on real-time response in case of fault [17].

Zhu et al. (2025) presented a 710 V DC bus modular multi-port ER with hybrid AC (690 V, 380 V) and DC (220 V, 24 V) ports. Their system successfully maintained stable operation across loads as well as participated in DERs via a centralized controller. Although they were thorough in topology, no information on fault detection or ride-through behavior during grid disturbances was reported [8].

Romero-Cadaval et al. (2022) proposed an enhanced operational strategy for the high-voltage input stage of a multi-port smart transformer, which operates in a similar way as a multi-port ER. The ER in their work serves as a central location, which

interfaces the utility grid, DG units, ESS, and other loads together using a mixture of high-efficiency AC and DC power electronic interfaces. Such topology allows the management of power flow in both directions and provides easy integration and use of renewable sources of energy. The authors focus on the coordination of the control of DG and the new forms of dynamic loads in order to obtain the optimized power dispatch and enhance the efficiency of energy conversion. Through intelligent switching and modulation schemes, the proposed system will improve the total energy management capacity and ensure the distribution of energy system enjoys maximum economic and technical advantages. However, while the paper excels in optimizing the high-voltage stage and introduces the clear methodology of control, but it does not pay much attention to dynamic response under real-time grid disturbances such as voltage sags, harmonic distortion, or fault ride-through performance areas that are in the focus of this thesis [18].

Wang (2023) explored the control strategy of a power router within a distribution network, and noted the increasing need of MPER in the conditions of the change of energy structures and economic transformation. The study emphasizes that developing such ERs aligns not only with technical requirements posed by increased renewable energy penetration but also with national objectives regarding energy efficiency and economic development. The MPER described in this study is designed to operate on low-voltage distribution systems and medium or small-scale systems unlike the much more complicated and expensive SST-based solutions, which makes it especially applicable to localized grids or microgrids, or in regional energy centers. The system is able to handle distributed generation units, ESS and other AC/DC loads through adaptive control strategies and with high flexibility and reliability. It prioritizes power conversion efficiency, real-time switching, and localized energy optimization. However, this study concentrates more on the steady and non-variable mode of operation of the power router and offers limited discussion on its behavior during grid anomalies such as faults, voltage sags, or mode transitioning modes which are core to the resilience objectives addressed in this thesis [19].

Alsaif and Faheem (2023) demonstrated that incorporating IC-based duty cycle control within a two-stage PV converter topology resulted in enhanced MPPT efficiency and faster response times over traditional IC or P&O algorithm.

Most ER architectures typically comprise two or more VSCs that are usually localized with some intelligence to perform energy management and coordination. The control strategies include droop-based control, hierarchical control and multi-agent control, each offering different advantages depending on the grid configuration, communication latency and required response time.

Despite substantial developments, research gaps persist in understanding how MPERs interact under complex system dynamics and how the different control layers work. Most studies so far have been limited to simulation-based validations, indicating the need for more robust field-deployable implementations for small scale consumers in a local community and with decentralized controls.

2.3 Solar PV System

Solar cells are special devices that turn sunlight directly into electricity in a solar power system. Solar power is a clean, renewable energy source that helps the environment by reducing pollution and supports sustainable energy goals.

A typical solar system has four main parts: solar panels, devices called inverters, sometimes batteries for storage, and a connection to the electricity grid. Because they can provide continuous power, these systems are also increasingly used with battery storage or in combination with other energy sources (hybrid systems).

The way a solar panel works is called the photovoltaic effect. Simply put, when sunlight hits the solar cell, tiny particles of light (photons) energize electrons in the material, which creates an electric current.

The performance of a PV cell is described by its respective parameters, namely:

- Open-circuit voltage (V_{oc}): This is the voltage the cell produces when no load is connected.
- Short-circuit current (I_{sc}): This is the maximum current produced when the cell's terminals shorted.
- Maximum power point (MPP): This is the specific point where the solar cell operates most efficiently, giving its highest power output by combining the best voltage and current.

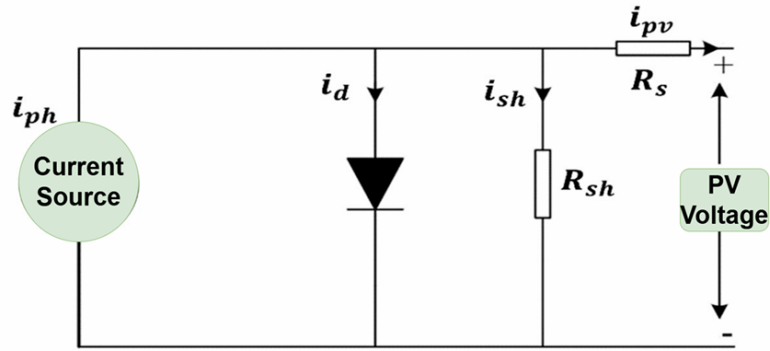


Figure 2-3 Network diagram of PV Single Module

The amount of electrical power a solar panel produces depends on how strong the sunlight is, the size of the panel, and the specific design of its cells.

MPPT is critically important in PV systems to ensure maximum power extraction and achieve high efficiency, thereby mitigating power losses and reducing overall system cost. Among various MPPT techniques, the Incremental Conductance algorithm has gained prominence for its ability to track the MPP by analyzing the slope of the PV panel's power characteristics. A study modeled an MPP tracker using the IC algorithm, rigorously investigating its performance under rapidly changing environmental conditions of temperature and irradiation levels. Utilizing a simulation model in MATLAB/Simulink, which included a PV panel, a DC-DC boost converter, and a 3-phase inverter connected to the grid, the research demonstrated the algorithm's effectiveness in tracking the MPP with a quick settling time of 2 seconds, even under highly dynamic operational scenarios [21].

2.4 Energy Storage System

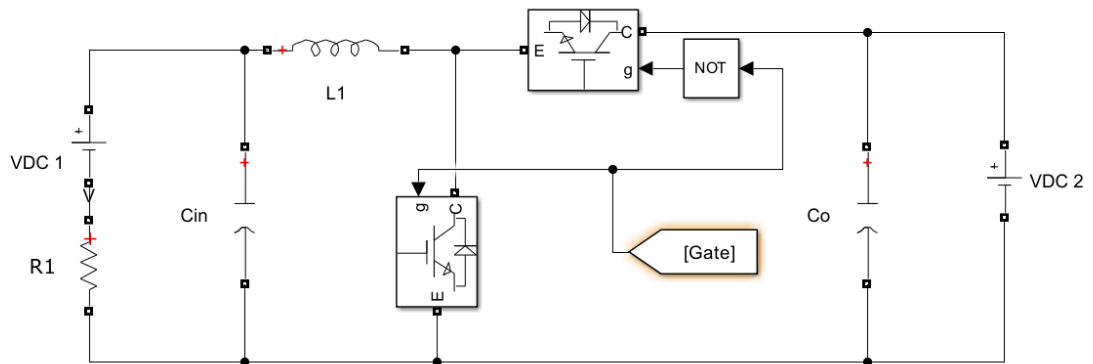


Figure 2-4 Topological structure of the bidirectional buck-boost DC/DC converter developed in Simulink

ESS are important technologies which store energy that can be when there is power deficit. They are particularly essential in combining intermittent RESs like solar and wind so that excess energy can be captured during peak hours of consumption and discharged during peak demand or during low RES production. In addition to maintaining supply and demand balance, ESS also contribute to grid stability by offering frequency and voltage regulation, peak shaving, as well as making overall systems more reliable and resilient by offering a source of power during outages.

Bidirectional DC-DC Converters are essential power electronic devices found within these ESS which help to support the flow of electrical power in both directions between varying DC voltage levels. Bi-directional converters operate as critical interface between an energy storage system e.g. batteries and the common DC bus of a microgrid or power system. Bi-directional Converters manage both the charging and discharging of the battery. They buck the DC bus voltage while charging the battery and control the charging current; buck mode. On the other hand, they step-up the battery's voltage to inject power back into the DC bus when DC bus voltage falls; boost mode. This bi-directional capability often controlled by PI controllers, makes BDCs fundamental for seamlessly integrating and optimizing energy storage in complex power systems [22].

2.5 Power Quality: Issues, Metrics, and Mitigation

Power quality is a fundamental metrics which is used to determine the level of how well the electrical power delivered to users complies with specified standards in terms of voltage, frequency and waveform. Ineffective PQ results in malfunctioning of the equipment, poor performance and blackouts in extreme cases. Voltage sags/swells, harmonics, flickers, transients and interruptions are the primary disturbances. Voltage sags are among the most common and harmful PQ issues, especially affecting sensitive electronic equipment. Harmonic distortion, often introduced by nonlinear loads and inverter-based generators causes overheating, increased losses and malfunctioning of protection systems [24].

Deployment of passive filters, active power filters, dynamic voltage restorers and the use of advanced power electronic devices like VSCs and Smart Inverters can help in mitigating the disturbances.

In that regard, MPER being VSC-based architecture and with real-time control capabilities, have demonstrated opportunity to resolve or reduce PQ issues more adaptively. They are able to dynamically compensate for voltage sags and harmonics on a local level as well as wider network needs. Unlike traditional mitigation devices, MPER are capable of coordination with distributed generation and energy storage elements seamlessly thus enabling proactive rather than reactive PQ management [8]. However, there is no single framework which measures the degree of PQ improvement following the integration of MPER, in the available literature.

2.6 Grid Stability: Phenomena, Analysis Methods, and Influencing Factors

The increasing penetration of IBRs, characterized by intermittency and low inertia, has changed the conventional inertia based behavior of the grid making it more vulnerable to rapid dynamic disturbances. Advanced control strategies and power electronic interfaces such as STATCOMs and SSTs, have been developed to enhance stability by providing dynamic reactive power support and voltage regulation.

However, such devices often function independently and lacks the integrated approach necessary for comprehensive stability management. ERs are the potential solution to integrated stability enhancement with their capability to manage multiple energy flow and various operating modes. [7], [23].

2.7 Impact of Power Electronic Interfaces on Power Quality and Grid Stability

Power electronic interfaces (PEIs) including VSCs, Smart inverters and SSTs are very important in the modern power systems as they facilitate efficient energy conversion, control and DERs integration. These devices are beneficial in PQ improvement and grid stability with functions such as harmonic compensation, voltage regulation and frequency support. Such devices rely on fast-switching capabilities and digital control to inject or absorb reactive power, mitigate harmonics and maintain voltage profiles.

Although these interfaces have advantages, their implementation is not very coordinated thus leading to suboptimal performance and potential interactions which may compromise system stability. The concept of ER covers the functionality of such devices by providing a unified platform for energy management, PQ enhancement and stability control within SG and DES. What distinctly sets MPERs apart is their ability to integrate multiple PEI functionalities in one unit and coordinate them with local

generation, energy storage and loads. Despite this, existing literature often treats MPERs as a variant of VSCs or as basic microgrid controllers, without adequately recognizing their unique multifunctional characteristics and their potential for integrated controls [23], [24].

2.8 Research Gap

The existing literature consistently highlights the substantial potential of MPER in supporting energy management and enabling effective integration of RES within the SG and DES. Its capability to integrate RES, ESS and a wide range of AC and DC loads makes it a key technology for next-generation LECs. However, despite continuous progress in this field, several important research gaps still limit the practical deployment of MPERs in real grid-interactive community environments.

- **Lack of Prosumer-Centric and Decentralized Supervisory Control:** There is a significant gap in decentralized, prosumer-centric control strategies. Recent frameworks do not dynamically assign leadership or ensure fair power distribution based on the real-time capacity and operating state of individual prosumers. These aspects are essential for fairness, resilience, and reliable operation in community-level systems.
- **Insufficient Focus on Dynamic Energy Sharing in Islanded Mode:** Most existing research on MPERs often focuses on their behavior either while connected to the grid or when operating alone. There is a notable lack of studies examining their performance in a LEC-PCC mode, where multiple prosumers must collectively maintain an islanded microgrid. In such cases, they need to share power using a transparent, fair, and capacity-aware method that does not rely on a central dispatcher.
- **Limited Integration of Simple, Straightforward EMS with Power Electronic Control:** There is a noticeable gap between complex optimization-based EMS and simpler, easy-to-implement control approaches. strategies that operate using straightforward and robust rules, such as those based on SoC and instantaneous power margin, to make fast and reliable decisions for economical operation.
- **While prior works have explored GC and SA ER operations separately, the transient behavior during seamless mode transitions (GC to islanded and vice**

versa) remains underexplored. The ability of the MPER to sustain stable voltage, maintain uninterrupted critical load supply and ensure coordinated reconnection to the grid has not been comprehensively analyzed, especially in the context of single-phase.

- There is a notable absence of comprehensive frameworks that simultaneously evaluate the internal dynamics of MPERs and their collective contribution to grid-interactive stability, autonomously selecting operating modes, managing power flow among multiple prosumers, and prioritizing critical community loads during grid contingencies, thus enhancing sustainable energy delivery and reducing carbon emissions.

This thesis directly addresses these gaps by proposing a single-phase MPER controlled by a novel LEC-EMS. The core contributions include a Dynamic Master Prosumer Selection algorithm and a Prosumer-Centric Proportional Power Sharing strategy. These are tested and examined through simulations of a three-prosumer community with critical community load operating under varying GC and islanded conditions.

CHAPTER THREE: MODELING AND METHODOLOGY

3.1 Introduction to the Research Methodology

This chapter describes the methodology used in this research, detailing the process from the initial design of the MPER system to the final evaluation of its performance under different scenarios. It explains the overall architecture of the MPER and its components, development of the coordinated control strategy and LEC-EMS, implementation of the simulation models, and evaluation of the results under various operational and test case scenarios.

The primary objective of this study was to evaluate the foundational performance and effectiveness of an intelligently controlled MPER operating within a grid-interactive LEC under dynamic conditions. A simulation-based approach was implemented using Simulink, as it provides a safe, flexible and cost-effective platform for designing complex power electronic systems, conducting parametric studies, and collecting performance data before prior to implementation in hardware.

The chapter is organized as follows: First, the overall architecture and design of MPER are presented. Second, the mathematical modeling of the key components are explained. The next section describes the development of the hierarchical control strategy and the proposed LEC-EMS logic. This is followed by an outline of the simulations and the modeling of the integrated system. Finally, the test scenarios and the key performance indicators used for evaluation are defined.

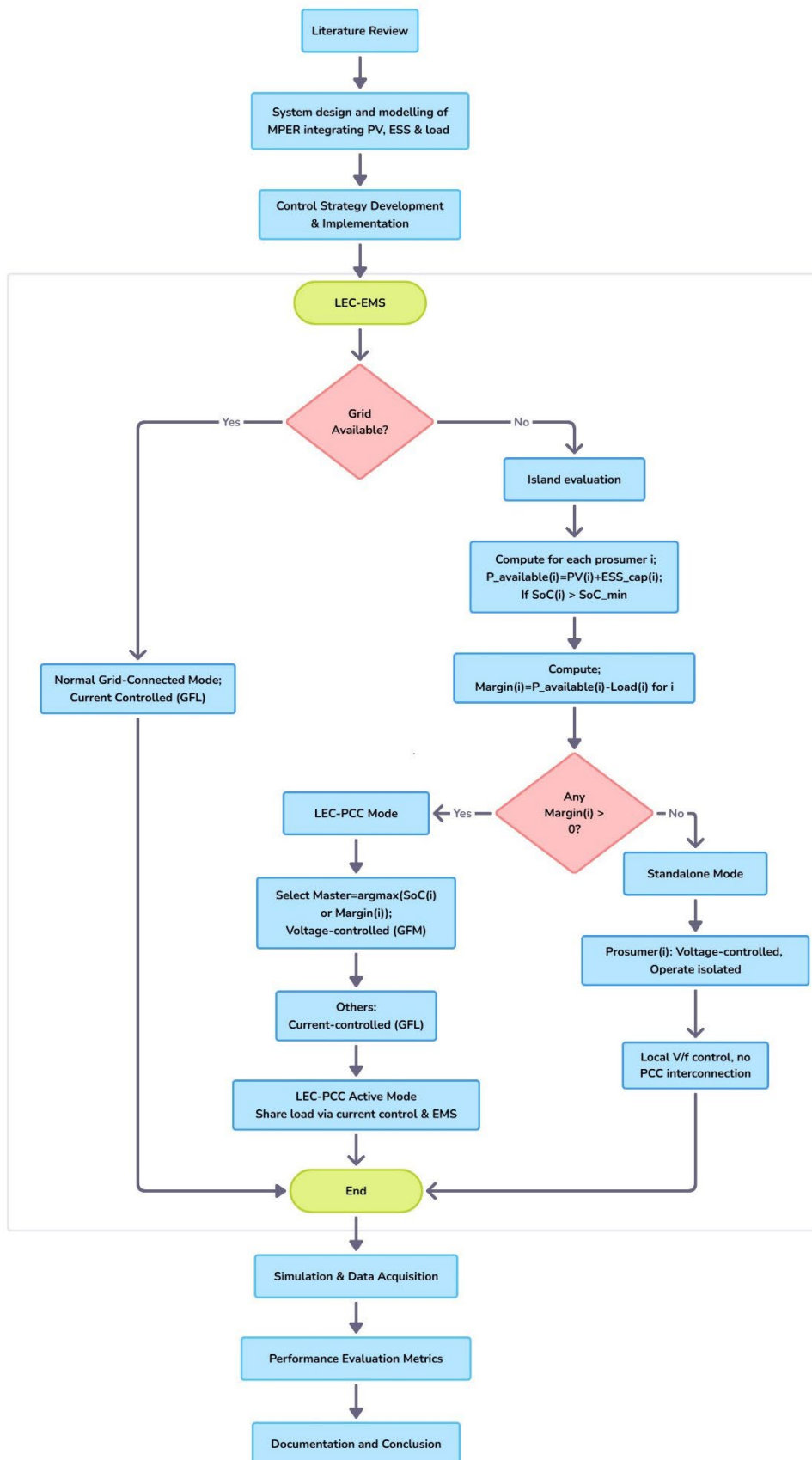


Figure 3-1 The preliminary procedure of the research methodology for MPER design and dynamic evaluation using LEC-EMS

3.2 System Design and Architecture of the Multi-Port Energy Router

Modern DES rely heavily on flexible and intelligent energy management. The MPER plays a crucial role by acting as a central unit that connects various energy sources, energy storage systems and the loads, facilitating efficient and bidirectional flow of power.

The fundamental idea behind the MPER developed in this research is to serve as a single, intelligent energy management for a household or a small group of loads which incorporates RES. Instead of connecting each energy source or devices connecting directly to the utility, everything is routed via MPER. This approach offers several benefits:

- a) Flexibility: New energy sources or devices can be plugged easily in to the MPER without major separate conversion and re-wiring of the entire property or separate coordination with the utility.
- b) Optimized Resource Use: MPER can intelligently evaluate available energy and select the most efficient energy. For eg., When solar PV generation is abundant, it prioritizes powering the house, then charging the battery and finally selling excess power back to the grid. If the solar power is low, it can absorb power from the energy storage system or grid to meet demand.
- c) Enhanced Reliability: By managing local energy resources, the MPER can potentially keep critical loads powered even if the main grid experiences an outage.
- d) Grid Support: The MPER can offer support services to the utility, such as injecting reactive power to help stabilize grid voltage during disturbances. Because it has a direct, controlled connection to the main grid and LEC-PCC.

The chosen architecture for this research utilizes a common DC bus as the central nervous system of the MPER, carrying power in DC form. All the different energy sources and storage systems naturally produce or store power in DC.

3.2.1 Detailed MPER Topology

The specific design of the MPER for this study, built around a common DC bus, is composed of several critical subsystems, each connected to this central DC common Bus. The arrangement of these components, depicted conceptually in Figure 3.1, is

exactly chosen to ful-fill the objectives of intelligent energy management and grid interaction.

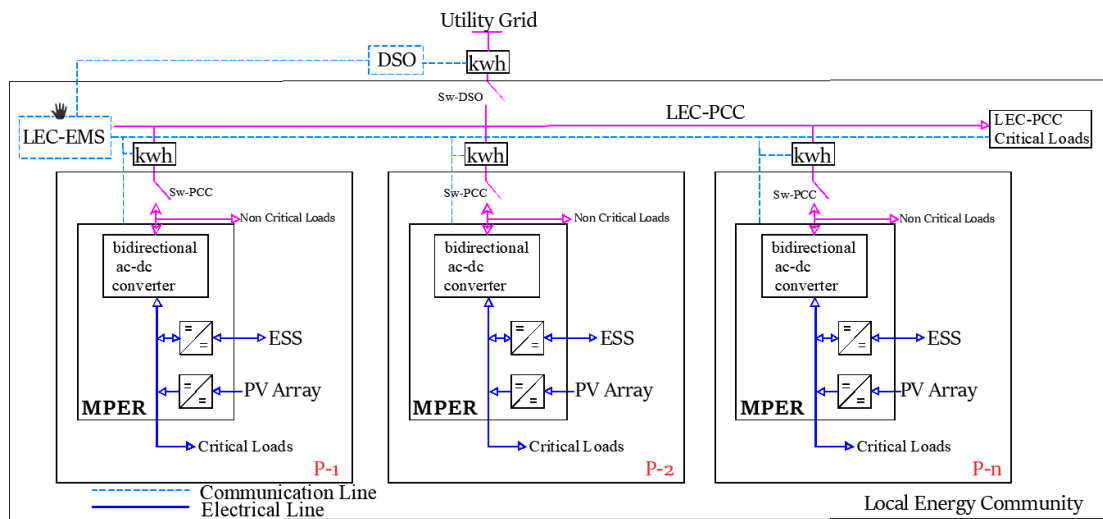


Figure 3-2 Representative architecture of the MPER at LEC with LEC-EMS

- a) Photovoltaic (PV) System: It represents the renewable energy generation source. Solar panels convert sunlight into DC electricity. Since the output voltage of solar panels can vary significantly with the intensity and temperature of the sunlight, it is not directly connected to the DC bus to ensure maximum power is always harvested.
- b) MPPT and Boost Converter:
 - MPPT: Solar panels have a unique operating point where they produce the most power. The MPPT algorithm continuously adjusts the operating point of the solar panels to extract the maximum possible power, regardless of weather conditions.
 - Boost Converter: This electronic circuit takes the variable DC voltage from the PV panels and efficiently boosts it up to the stable, higher

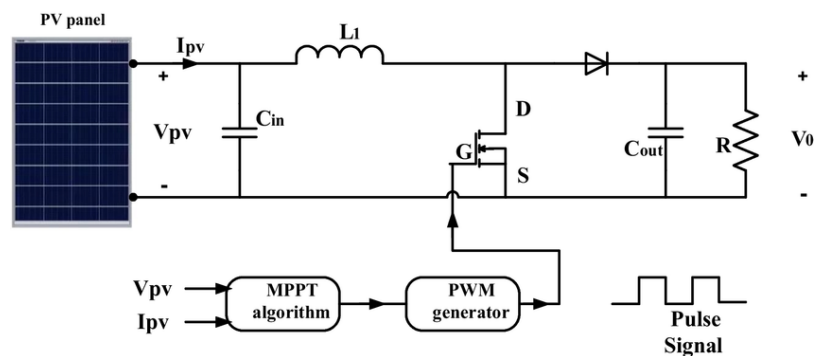


Figure 3-3 Network diagram of PV panel's MPPT control with boost converter

voltage level required by the common DC bus, which also acts as the interface for the MPPT algorithm to control the PV's operating point.

- c) Battery Energy Storage System (ESS): This component provides the flexibility to store excess energy when available (e.g., from PV) and release it when needed (e.g., during high demand or grid outages).
 - Bidirectional DC/DC Converter (for ESS):
 - Charge the battery: Taking power from the DC bus and stepping down the voltage to charge the battery.
 - Discharge the battery: Taking power from the battery and boosting the voltage up to the DC bus level when the system needs energy. Its bidirectional capability is crucial for flexible energy management, allowing easy operation of DC critical loads.
- d) Common DC Bus: The common DC bus serves as the main electrical backbone of the MPER. It maintains a stable and regulated DC voltage of 400 V, and all system components draw from or supply power to this bus. Keeping the bus voltage stable is essential, as it directly affects the reliability and performance of the system.
- e) DC Load: Any electrical devices that operate on Direct Current (e.g., LED lighting, consumer electronics, specialized industrial equipment) are DC loads. It's directly connected to the DC bus, making easier power delivery without additional conversion.
- f) Bidirectional DC/AC Converter (VSC): This is the complex and critical gateway of the MPER. It acts as a two-way bridge between the DC bus and the AC side of the system, which includes both local AC loads and the main grid.
 - DC to AC (Inversion): It converts the stable DC voltage from the bus into the required AC voltage and frequency (e.g., 230V, 50Hz) for local AC loads or for exporting power to the grid in grid-connected mode or to PCC in islanded mode.
 - AC to DC (Rectification): It can also draw power from the AC grid (when battery SoC is low, and when energy is cheap) and convert it to

DC to supply the DC bus, charge the battery, or support critical DC loads.

- Power Quality Filter (LCL/RL/L Filter): To ensure the AC power exchanged with the grid and supplied to local AC loads is clean and free from distortions introduced by the switching of the VSC, an electrical filter is always integrated at the output of the VSC. This filter smoothens the fluctuating output of the ac-dc converter into a clean sinusoidal waveform.
- g) AC Load: This represents typical household or commercial electrical devices that operate on Alternating Current (e.g., washing machines, water pump, conventional lighting etc.). AC loads are connected to the AC side, after the VSC and its filter via switches.
- h) Single-Phase Grid Interface: As per the research scope and limitations, the MPER connects to a simplified single-phase representation of the main utility grid. The connection is made on the output side of VSC and its AC filter.

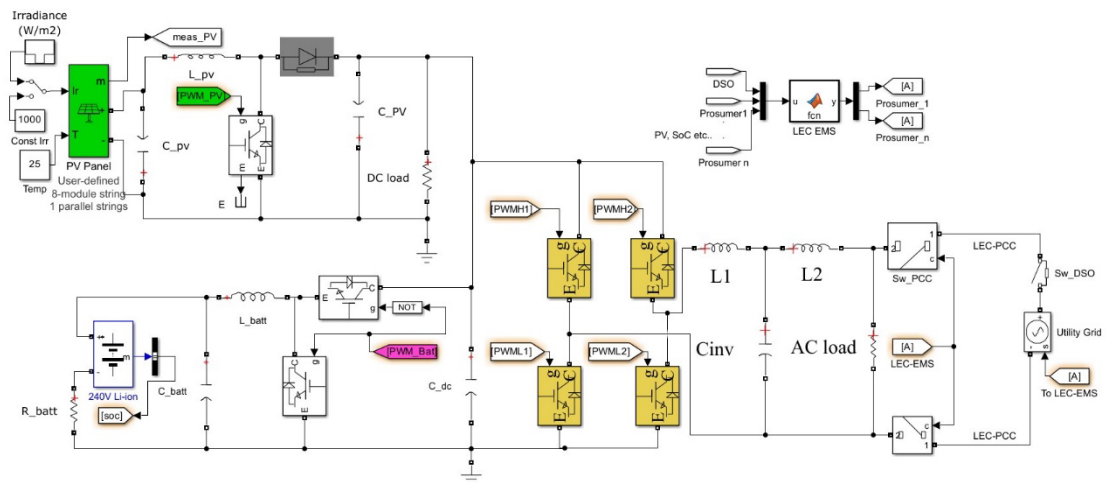


Figure 3-4 Block diagram of overall system MATLAB model with power topology

3.2.2 Rationale for Design Choices

The selection of this architecture over alternative configurations such as AC-coupled microgrids or hybrid AC/DC structures with multiple separate AC/DC interfaces is driven by several compelling advantages appropriate to the research objectives:

- Direct integration of DC sources/loads, eliminating unnecessary conversion for efficiency.

- Simplified control for DC-connected DERs, i.e. Single and straightforward parameter to control.
- High Power Density and Modularity: DC-coupled architectures often allow for more compact converter designs and easier modular expansion. New DC sources or loads can be added by simply connecting them to the common DC bus via appropriate DC-DC converters.
- Single-phase grid for focused MPER control examination.
- Enhanced Reliability and Islanding/Isolation Capability: The DC bus acts as a natural buffer, decoupling dynamic variations on the AC grid side from the DC sources and loads.
- Enables renewable-first operation, reducing dependency on backup generators.

3.3 Mathematical Modeling of Subsystems

In order to accurately simulate the behavior of MPER and assess how it performs under various conditions, mathematical model is used to represent each physical component of the system. This step is essential because it enables the analysis of complex electrical phenomenon, testing of control strategies and identify early detection of potential issues before implementation.

In this research, simplified yet accurate models suitable for power system simulations were selected to run in MATLAB/Simulink.

3.3.1 PV System Model

The PV system converts solar irradiance into electrical energy. Its output characteristic, voltage and current it produces are non-linear and highly dependent on both irradiance and temperature.

- A PV module can be conceptualized as a current source, where the amount of current it produces is directly proportional to the sunrays on it. The goal is to operate the PV system at its MPP, where it delivers the most power for a given set of conditions.
- The fundamental behavior of a PV cell or module is often described by a single-diode model, which considers the photocurrent, diode saturation current, series resistance, and shunt resistance.

The current (I) output from a PV module can be approximated by:

$$I = I_{ph} - I_0 \left[\exp \left(\frac{V + IR_s}{\eta V_t} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

Where:

- I_{ph} is the photocurrent, directly proportional to solar irradiance.
- I_0 is the diode saturation current.
- V is the output voltage of the PV module.
- R_s is the series resistance, accounting for internal resistive losses.
- R_{sh} is the shunt resistance, representing leakage current paths.
- η is the diode ideality factor.
- $V_t = \frac{kT}{q}$ is the thermal voltage, with k as Boltzmann's constant, T as absolute temperature, and q as the electron charge.

During simulation, pre-built PV array blocks are used, which encapsulate these complex characteristics based on manufacturer datasheets. The inputs to this model are typically irradiance (W/m²) and temperature (°C), and the output is the current and voltage produced by the array.

3.3.2 Boost Converter (PV Integration)

The Boost converter is a DC-DC power converter that steps up a DC voltage from a lower level to a higher level. In this MPER, it takes the variable voltage from the PV array and boosts it to the common DC bus voltage level, while also serving as the actuator for the MPPT algorithm.

- The inductor stores energy. The semiconductor switch, typically an IGBT or MOSFET, repeatedly closes and opens, allowing the inductor to store and release its energy at a higher voltage. A diode ensures the current flows only towards the higher voltage side, and capacitor smooths out the output. By controlling the duty cycle we can control the output voltage.
- Basic Operation:
 - Switch ON: Inductor stores energy (current builds up).
 - Switch OFF: Inductor releases stored energy, adding it to the input voltage, pushing current through the diode to the output capacitor and load.
- Key Mathematical Relationship:

The theoretical output voltage V_{out} is related to the input voltage (V_{in}) and the duty cycle (D) of the switch:

$$V_{out} = \frac{V_{in}}{1 - D}$$

Where D is between 0 and 1. By varying D, the converter effectively varies the voltage seen by the PV array to track its MPP.

- Components: Inductor (L), Capacitor (C), Diode (D), Semiconductor Switch (IGBT/MOSFET).
- Control Input: The duty cycle of the switch is adjusted by the MPPT controller.

The Incremental Conductance (Inc-Cond) MPPT algorithm method is used in solar photovoltaic (PV) systems to track the maximum power point (MPP) by comparing the instantaneous conductance (I/V) with the incremental conductance ($\Delta I/\Delta V$ or dI/dV). By analyzing the P-V curve's slope, it determines if the PV module is operating to the left of the MPP (slope > 0), at the MPP (slope = 0), or to the right of the MPP (slope < 0), adjusting the operating point to find the peak power. Especially under rapidly changing solar irradiation, this algorithm is more efficient than the P&O algorithm, as it provides better steady-state accuracy and faster tracking.

3.3.3 Energy Storage System (ESS) Model

The ESS is crucial for energy balancing, allowing the MPER to store when energy is surplus and inject power when it is deficit.

- The battery is modeled as a controllable voltage source with an internal resistance. Its voltage changes slightly with its SoC and the current flowing through it. The SOC indicates how much energy is left in the battery.
- Mathematical Representation:
 - Open Circuit Voltage (V_{OC}): Voltage across the battery terminals when no current is flowing. It's primarily a function of the battery's SOC.
 - Terminal Voltage (V_{batt}): When current (I_{batt}) flows, the actual terminal voltage is affected by the internal resistance (R_{int}):

$$V_{batt} = V_{OC}(SoC) - I_{batt}R_{int}(\text{during discharge})$$

$$V_{batt} = V_{OC}(SoC) + I_{batt}R_{int}(\text{during charge})$$

- State of Charge: The amount of current drawn from or supplied to the battery over time determines the SOC. It's calculated by integrating the current. $SoC(t) = SoC(t_0) - \frac{1}{C_{rated}} \int_{t_0}^t I_{batt}(\tau) d\tau$

where C_{rated} is the nominal battery capacity in Ampere-hours (Ah).

- Implementation: Battery models that can simulate various battery chemistries (e.g., Lithium-ion) and their voltage-SoC characteristics, internal resistance variation, etc., in the Simulink library are considered.

3.3.4 Voltage Controller for Bidirectional DC/DC Converter

This converter facilitates the two-way power flow between the battery and the common DC bus, enabling both charging and discharging.

- A bidirectional DC/DC converter can operate in two modes:
 - Buck Mode (Charging): Steps down the DC bus voltage during battery charging, i.e., when PV generation is sufficient, and load is non-significant.
 - Boost Mode (Discharging): Steps up the battery voltage to the DC bus level when the battery supplies power. This is achieved by using two controllable switches (e.g., IGBTs/Diodes) in place of the single switch and diode of a simple boost converter, allowing current to flow in both directions through the inductor.
- Key Mathematical Relationships: The relationships depend on the mode of operation (buck or boost).

$$\text{Buck Mode: } V_{out} = D \cdot V_{in}$$

$$\text{Boost Mode: } V_{out} = \frac{V_{in}}{1-D}$$

Where D is the duty cycle of the appropriate switch.

- Components: Inductor (L), two Bidirectional Switches (e.g., MOSFETs with antiparallel diodes), Capacitors (C).
- Control Input: The duty cycle of the switches, determined by the ESS control strategy, with the PI and PWM generator controls the bidirectional converter.

3.3.5 Common DC Bus Model

The common DC bus serves as an energy buffer and a voltage reference point for all DC-connected components. Maintaining a stable voltage on this bus is essential for the reliable operation of the entire MPER. In this model DC bus is primarily

represented by a large capacitor, which stores energy and helps to smooth out voltage fluctuations caused by sudden changes in power flow from connected sources and loads.

- The dynamics of the DC bus voltage (V_{dc}) are governed by the balance of power (or current) flowing in and out of the bus.
- Maintaining a stable V_{dc} within a narrow tolerance is a primary control objective for the MPER.

3.3.6 Bidirectional DC/AC Converter (VSC) Model

The VSC in the MPER, acts as the main interface between the DC common bus and the AC loads/PCC/grid. It converts DC power to AC power and vice versa, and can control both active and reactive power flow.

- A VSC consists of a set of controllable semiconductor switches arranged in an H-bridge configuration for single-phase systems. By rapidly switching these devices on and off in a precise sequence (PWM), the VSC can synthesize a sinusoidal AC voltage from the DC bus voltage. Conversely, it can rectify AC power from the grid into DC power for the bus.
- Key Mathematical Relationships:
 - The instantaneous output voltage of the converter depends on the DC bus voltage and the switching states.
 - Active Power (P) and Reactive Power (Q) Control: In grid-connected applications, power exchange with the grid is controlled by manipulating the amplitude and phase angle of the VSC's output voltage relative to the grid voltage. This is often done using a dq-reference frame transformation (Park transformation), where active power is proportional to the d-axis current component (I_d) and reactive power is proportional to the q-axis current component (I_q).

$$P = \frac{3}{2}(V_d I_d + V_q I_q)$$

$$Q = \frac{3}{2}(V_q I_d - V_d I_q)$$

- For a single-phase system, a modified dq-transformation or instantaneous power theory (p-q theory) can be used. Simply, controlling the current in

phase with the voltage controls real power, and controlling the current 90 degrees out of phase with the voltage controls reactive power.

- To apply the dq transformation in single-phase systems, virtual orthogonal signal from your real signal is created. The original signal is delayed by 90° i.e., Phase-shifting method. This shifted signal serves as the β component, while the original is used as the α component. Filters or PLL-based generators are used to produce an orthogonal version of the input using Orthogonal Signal Generator. This method is common in grid-connected inverter control. After obtaining both α and β , use the Clarke transformation (often trivial in single-phase with synthetic β) followed by the Park (dq) transformation.
- Components: Semiconductor Switches (IGBTs/MOSFETs with antiparallel diodes), AC Filter (LCL or L type), Capacitors.
- Control Inputs: Reference active power (P_{ref}), reference reactive power (Q_{ref}), or reference d-axis current ($I_{d,ref}$), and reference q-axis current ($I_{q,ref}$).

3.3.7 AC Filter (LCL/L Filter) Model

An AC filter is an essential part of the VSC interface, particularly when connected to an AC grid.

- The VSC generates its AC voltage by rapidly switching the DC bus voltage on and off, which creates a square-wave-like voltage that contains undesirable high-frequency components known as harmonics. The AC filter effectively blocks these high-frequency components while allowing the desired sinusoidal 50 Hz component to pass through to the grid and AC loads. This is crucial for maintaining PQ.
- An LCL filter commonly preferred over a simple L (inductor) filter due to its superior harmonic attenuation capabilities, particularly at the switching frequency, with a smaller overall inductance value. However, an LCL filter is more complex to design and can introduce resonance issues if not properly damped. For this study, a well-damped LCL filter, which is more effective than L filter, was modeled.

- **Mathematical Representation:** The filter's behavior is described by the impedance characteristics of its inductors (L) and capacitors (C). The transfer function of the filter dictates its ability to attenuate harmonics.

$$Z_L = j\omega L \text{ (Inductive Impedance)}$$

$$Z_C = j\omega C \text{ (Capacitive Impedance)}$$

- The design involves selecting L and C values to achieve desired attenuation while avoiding resonance with the grid or the converter's switching frequency.

3.3.8 DC and AC Load Models

Loads represent the consumption of electricity within the system.

- For simulation purposes, load was modeled in various ways depending on their behavior.
 - **Constant Power Loads:** Consume a fixed amount of active power regardless of voltage fluctuations.
- **Mathematical Representation:**
 - **DC Load:** Modeled as a simple resistor or a constant power sink.

$$P_{DC_Load} = V_{dc} \cdot I_{dc_Load}$$

- **AC Load:** Modeled as simply resistive (R) for heating/lighting. Can also be modeled as constant power.

$$P_{AC_Load} = V_{ac} \cdot I_{ac_Load} \cdot \cos(\phi) \text{ (Active Power)}$$

$$Q_{AC_Load} = V_{ac} \cdot I_{ac_Load} \cdot \sin(\phi) \text{ (Reactive Power)}$$

3.3.9 Single-Phase Grid Model

The utility grid represents the power source or sinks for the MPER.

- The grid is simplified to a stable AC voltage source with a small internal series impedance (resistance and inductance) representing the grid's strength and short-circuit capability.
- **Mathematical Representation:**
 - The grid is modeled as a sinusoidal voltage source:

$$V_g(t) = V_{peak} \sin(2\pi ft)$$

- As outlined in the limitations, modeling a full three-phase grid (like the IEEE 9-bus system) in detail would significantly increase simulation complexity and computational time, diverting focus from the core MPER control and performance analysis thus single phase system was chosen.

3.4 Development of Control Strategy

In this section, the multi-layered control strategy of the MPER is designed to achieve flexible, autonomous, and resilient operation within a LEC. It ensures optimal use of DER, effective management of ESS and seamless prosumer-centric fair power exchange between prosumers. The control architecture is based on a hierarchical design, which consist of two major layers:

- a) Local layer control (Primary Control) is the independent control responsible for real-time regulation of power converter of MPER
- b) Supervisory LEC-EMS is responsible for community-level coordination, decision-making and mode supervision.

3.4.1 Local Control Layer

This layer comprises fast-acting control loops dedicated to each power electronic converter within the MPER. Their primary role is to ensure the specific component operates correctly, tracks its given reference signals, and responds rapidly to local disturbances.

3.4.1.1 PV Converter Control

- It continuously forces the PV array to operate at its Maximum Power Point (MPP) regardless of changes in solar irradiance or temperature. This ensures that the maximum possible energy is harvested from the sun at all times.
- Working (Incremental Conductance - IncCond Algorithm): The Incremental Conductance algorithm is a widely used and robust MPPT technique that aims to directly find the MPP without continuous oscillation around it, particularly under rapidly changing atmospheric conditions. The fundamental principle behind this algorithm is that at the Maximum Power Point, the slope of the power-voltage (P-V) curve is zero, meaning the change in power with respect to voltage is zero ($\frac{dP}{dV} = 0$).
 - The controller continuously measures the instantaneous voltage (V) and current (I) from the PV array.
 - It then calculates:

- a) The incremental conductance ($\frac{\Delta I}{\Delta V}$), which is the change in current divided by the change in voltage from the previous measurement.
 - b) The instantaneous conductance ($\frac{I}{V}$).
- It then decide and adjust:
 - a) If $\frac{dV}{dI} = -\frac{I}{V}$ (or very close to it): This indicates that the operating point is at or very near the MPP. The controller holds the current operating voltage (or duty cycle).
 - b) If $\frac{dV}{dI} > -\frac{I}{V}$: This means the operating point is to the left of the MPP on the P-V curve. To reach the MPP, the controller increases the PV array voltage (by decreasing the boost converter's duty cycle).
 - c) If $\frac{dV}{dI} < -\frac{I}{V}$: This means the operating point is to the right of the MPP on the P-V curve. To reach the MPP, the controller decreases the PV array voltage (by increasing the boost converter's duty cycle).
- This process is continuously repeated, causing the operating point to oscillate slightly around the MPP thus tracking it effectively.
- IncCond offers faster tracking and less oscillation around the MPP compared to simpler methods like Perturb and Observe (P&O), especially under rapidly changing irradiance conditions (e.g., passing clouds). This makes it well-suited for dynamic simulation environments where quick and precise power extraction is necessary.

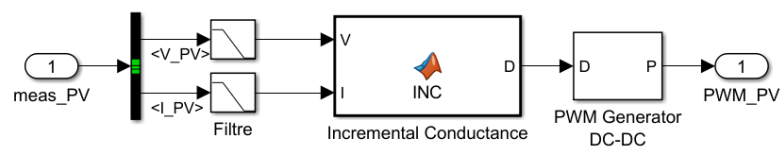


Figure 3-5 Block diagram of Incremental Conductance Algorithm

- Control Output: The IncCond algorithm generates a reference duty cycle for the Boost converter's switch, which is then applied via Pulse width Modulation (PWM_PV) to control the PV array's operating voltage.

3.4.1.2 ESS Converter Control

- It regulates the common DC bus voltage to its nominal setpoint. By controlling the power flow to and from the battery, this converter ensures the DC bus remains stable, thereby enabling the reliable operation of all connected DC and AC components. The battery's charging or discharging is a direct consequence of its role in maintaining this stable DC link voltage.

- Control Strategy (Direct DC Bus Voltage Control):

The ESS bidirectional DC-DC converter has a fully autonomous, local cascaded control system to hold the 400 V DC bus. Its major purpose is to maintain the DC bus voltage at its reference of 400 V. This is provided by two special control loops.

The outer voltage loop continuously measures the actual DC bus voltage, compares it to the 400V setpoint reference and via a PI controller, compares the actual current necessary to correct any voltage error. A current reference signal is produced in this calculation. This calculation outputs a current reference signal.

The inner current loop acts as the fast executive that quickly adjusts the PWM duty cycle to make the inductor current follow this reference precisely. This two-layer structure ensures the DC bus remains stable against load/generation changes (voltage loop) while fast-acting current protection for the battery and power switches. Importantly, all this is decentralized process and operates independently at the local controller level which does not need the commands of the supervisory LEC-EMS to achieve basic stability.

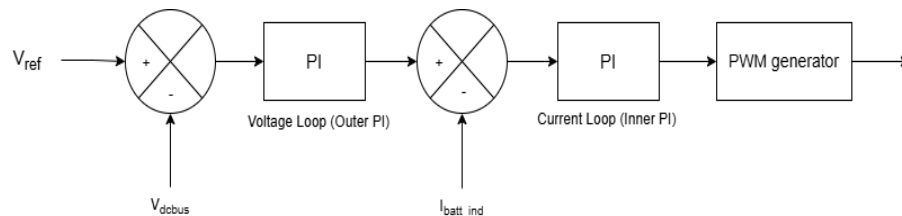


Figure 3-6 Block diagram of voltage controller for bidirectional DC-DC converter of ESS

- Bidirectional Operation: The inherent design of this converter and its control allow for seamless two-way power flow. When the DC bus voltage tends to drop

(e.g., due to increased load or reduced PV input), the controller will command the battery to discharge and inject power, boosting the voltage. Conversely, if the DC bus voltage tends to rise, the controller will enable the battery to charge and absorb power, thereby reducing the voltage. The flowchart below depicts the operating modes of PV and ESS during different scenarios.

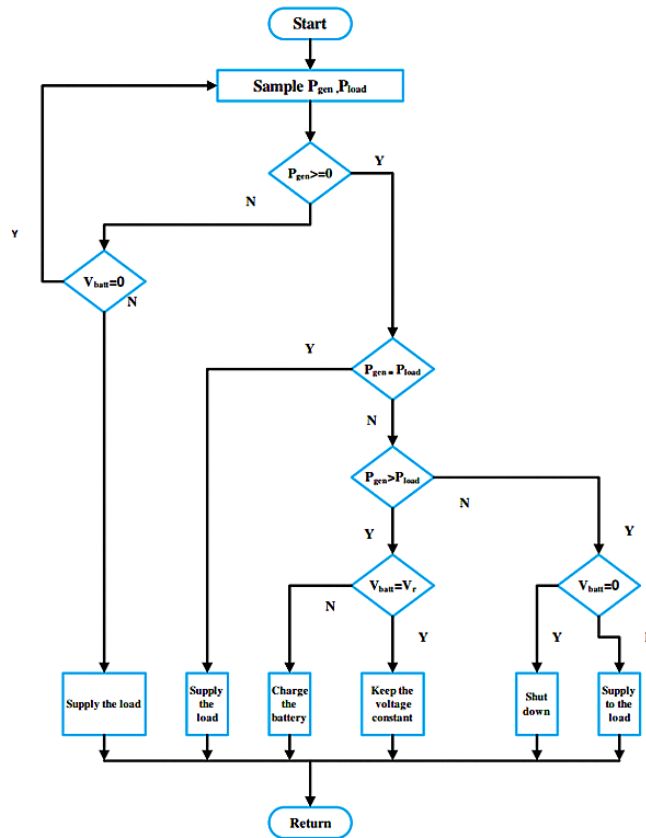


Figure 3-7 Flowchart of different operating modes of PV and ESS

3.4.1.3 Bidirectional DC/AC VSC Control: This is responsible for managing active and reactive power exchange with grid, supplying local AC loads, and maintaining local AC voltage and frequency when islanded.

- Control Strategy (Cascaded Voltage/Current Control in dq-frame):
 - Grid Synchronization (PLL): Accurate synchronization with the utility grid's voltage phase and frequency is paramount for stable grid-connected operation. A custom-implemented PLL is utilized for this purpose. The PLL's primary function is to extract the instantaneous grid phase angle and frequency, which are essential for the transformations between the

stationary alpha-beta ($\alpha\beta$) reference frame and the synchronous rotating d-q reference frame (Park and inverse Park transformations). The PLL synchronizes the controller with the grid voltage (V_{grid}). Its primary outputs are the grid voltage angle (θ) and the fundamental frequency (ω), which are essential for the accurate transformation of variables between the stationary (ab) and rotating (dq) reference frames.

- Reference Current Generation: In GC mode or as slave, the outer loop DC voltage PI controller is omitted. Instead, the active and reactive power commands (P_{ref} and Q_{ref}) from the LEC-EMS are directly converted into current references for the inner loop. During GC mode using the measured grid voltage or during PCC (islanded) mode operation using the measured PCC voltage, P_{ref} is transformed into the d-axis current reference ($I_{d\text{ref}}$), and Q_{ref} is transformed into the q-axis current reference ($I_{q\text{ref}}$). This establishes the VSC as a controlled current source, with its output dictated by the EMS.
- For a MPER with a LEC-EMS, Current Reference from EMS is superior over Voltage ref of V_{dc} with outer loop. It provides the EMS with direct, fast-acting control over the power flow, which is essential for executing advanced functions like peak shaving, frequency regulation, or optimal power sharing. The DC bus voltage is then a consequence of the power balance dictated by the EMS, which can be managed by other elements in the system.

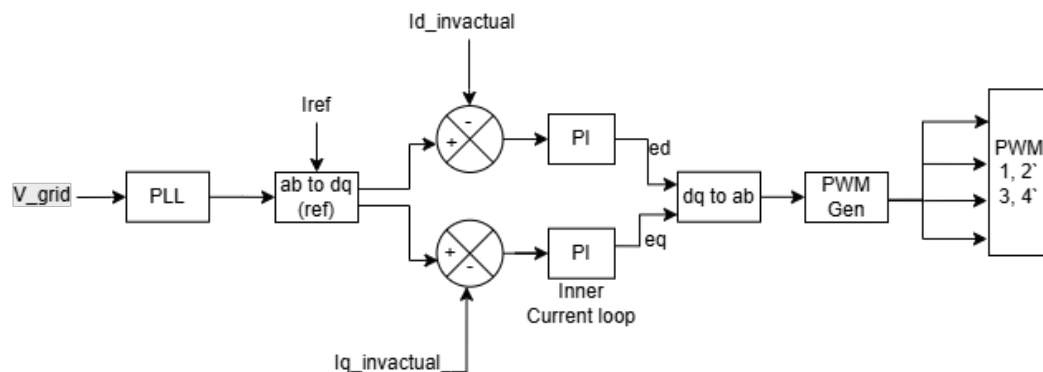


Figure 3-8 Block diagram of GC subsystem, internal control loops to generate PWM signal

- In LEC-PCC mode operation, one of the prosumers (VSC) acts as Grid forming inverter. In a master-slave configuration, the Master VSC operates in Grid-Forming (GFM) mode to establish the voltage and frequency of the islanded microgrid. The Slave VSCs operate in Grid-Following (GFL) mode, synchronizing to the voltage created by the Master and injecting current/power as commanded. The EMS acts as the supreme commander, sending setpoints to both. Here, The EMS sends the fundamental setpoints directly to the Master inverter:
 - Voltage Reference (V_{ref}): The desired RMS voltage (e.g., 230 V).
 - Frequency Reference (ω_{ref}): The desired system frequency (e.g., 50 Hz / 2π rad/s).

These references are used to generate the voltage waveform templates. The angle (θ) for the Park transformation is generated by integrating ω_{ref} . There is no PLL.

- Inner Voltage Control Loop (The Core of GFM): The measured output voltages at the inverter terminals (V_{inv}) are transformed into the dq-frame using the internally generated angle (θ), yielding V_{d_meas} or V_{d_inv} and V_{q_meas} . These are compared to their references (V_{d_ref} , $V_{q_ref} = 0$). The errors are fed into PI Voltage Controllers. The outputs of these controllers are the voltage commands/modulating signals (V_{d_cmd} and V_{q_cmd}). Crucially, there is no outer power control loop here. The Master's output power is not fed back to adjust voltage or frequency. It simply maintains V_{ref} and ω_{ref} regardless of the load. Voltage PI outputs go directly to PWM. Current measurements $I_{invactual}$ used in the Figure 3-9 below is only for overcurrent protection/hard limiting, which makes current limited voltage source. This is what makes it a true voltage source. It cannot properly support the grid during faults or load steps. Thus, we omit the current PI part during PCC mode master VSC. The master prosumer shares power passively - as a consequence of maintaining voltage, the proportion is controlled indirectly via EMS dispatch to slaves. It provides residual power for whatever slaves don't supply. EMS plays the main role in controlled power sharing among

master slave VSC, which would have been totally uncontrolled proportional without EMS intervention.

- Standalone Mode: When the grid or PCC both are disconnected, the VSC transitions from being a current source (following the grid) to a voltage source for the local AC loads. The VSC operates as a voltage-controlled inverter (grid-forming). The outer loop maintains AC voltage amplitude and frequency references, thus forming current-limited voltage source and supplying local loads autonomously as shown in figure below.

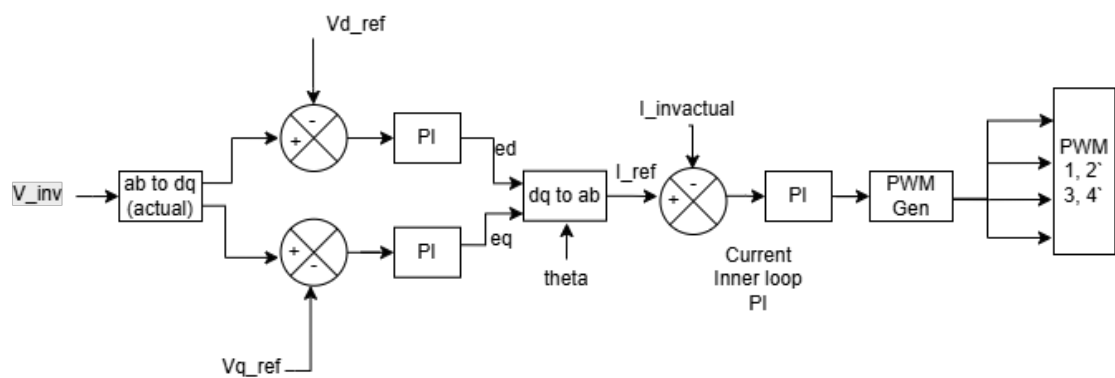


Figure 3-9 Block diagram of SA subsystem, internal control loops to generate PWM signal

- Seamless Mode Transition Logic: A critical part of the VSC control is the ability to smoothly switch between grid-connected/PCC-connected (voltage-controlled-master, current controlled-slave) and SA (voltage control) modes. To ensure an uninterrupted power supply, the MPER supports seamless transition between different operation modes. During grid faults or disconnection, the PLL detects loss of synchronization, prompting the EMS to switch the inverter to voltage control mode. The ESS immediately assumes DC-bus regulation duties, maintaining power to critical loads. Upon grid restoration, a synchronization process (voltage, frequency, and phase matching) is executed before reconnection. This transition occurs smoothly without noticeable transients or load disturbances.

3.4.2 Local Energy Community Energy Management System (LEC-EMS)

The LEC-EMS is the supervisory intelligence of the LEC, which manages all the prosumers, including their MPER units. It collects real-time data and implements decision algorithms and sends dispatch instructions to local controller and switches so that it can coordinate its operation, stability across the entire system, optimal use of renewable energy, and provide grid support.

3.4.2.1 Inputs to the LEC-EMS

The LEC-EMS continuously collects the following parameters from each prosumer:

- PV power output (P_{PV})
- Battery SoC
- Load demand (P_{Load})
- Grid Voltage/PCC voltage and grid frequency (V_{grid} , f_{grid})
- Operational mode indicators (GC or SA)
- DSO signals such as ToU etc.,

3.4.2.2 Supervisory Decision Logic

(a) Dynamic Master Prosumer Selection

This study proposes a dynamic method of choosing a Master Prosumer that leads the LEC. Unlike traditional microgrids with a fixed master controller, this approach dynamically identifies the most suitable prosumer to act as the grid-forming unit based on real-time conditions. The selection is based on the calculation of a Margin of each prosumer which is the instantaneous surplus power capacity of the prosumer. The margin is calculated as the sum of available PV generation (P_{PV}) and maximum dischargeable power of the battery, minus the prosumer's own critical load. The Battery maximum energy available is not a constant value but is smartly weighted by a SoC dependent derating factor, which provides battery health by ensuring that the discharge is limited when the SoC is close to its lower limit. The threshold of 20%-50% was considered to ensure the battery health. It is assumed that the battery with SoC greater than upper threshold is capable of supplying maximum capacity. The prosumer with the maximum Margin is selected as the Master Prosumer. This

dynamic selection ensures that the community is continuously driven by the member with the highest ability to support the grid to improve overall system reliability and efficiency, especially during mode transitions like entering islanded operation.

$$P_{battery_max} = Battery_Capacity \times C - rate \times f(SoC)$$

where, Battery_Capacity = Nominal Battery Capacity (kWh)

C-rate = Maximum Safe Discharge Rate (Typically 0.5C-1C); Li-ion

Battery=1

$f(SoC) = SoC \text{ dependent derating factor}$

$$= \frac{SoC (Current) - SoC(Lower \text{ threshold})}{SoC(Upper \text{ threshold}) - SoC (Lower \text{ threshold})}$$

$$Margin(i) = P_{pv(i)} + P_{battery_{max}(i)} - P_{CriticalLoad(i)}$$

where, $i = 1,2,3..n$, Prosumer number

$$Master \text{ Prosumer} = \max(Margin(i))$$

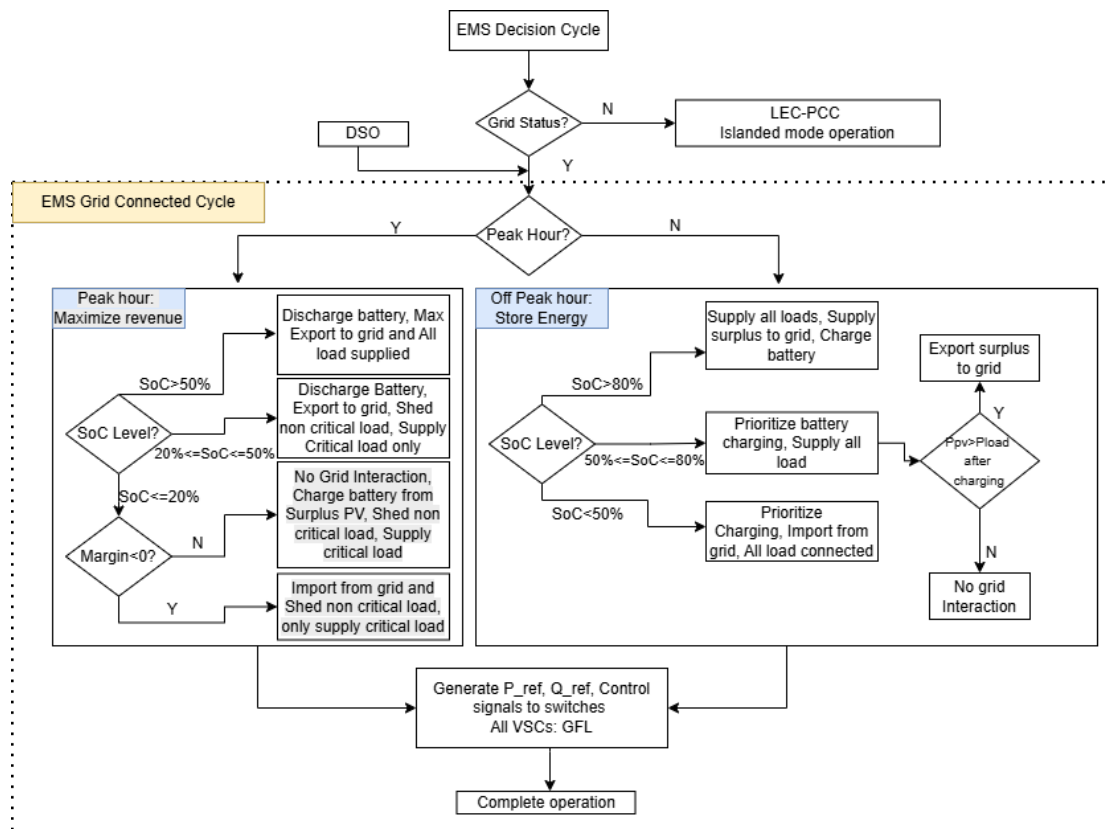


Figure 3-10 Flowchart of the LEC EMS Decision cycle in GC mode for Economic Optimization

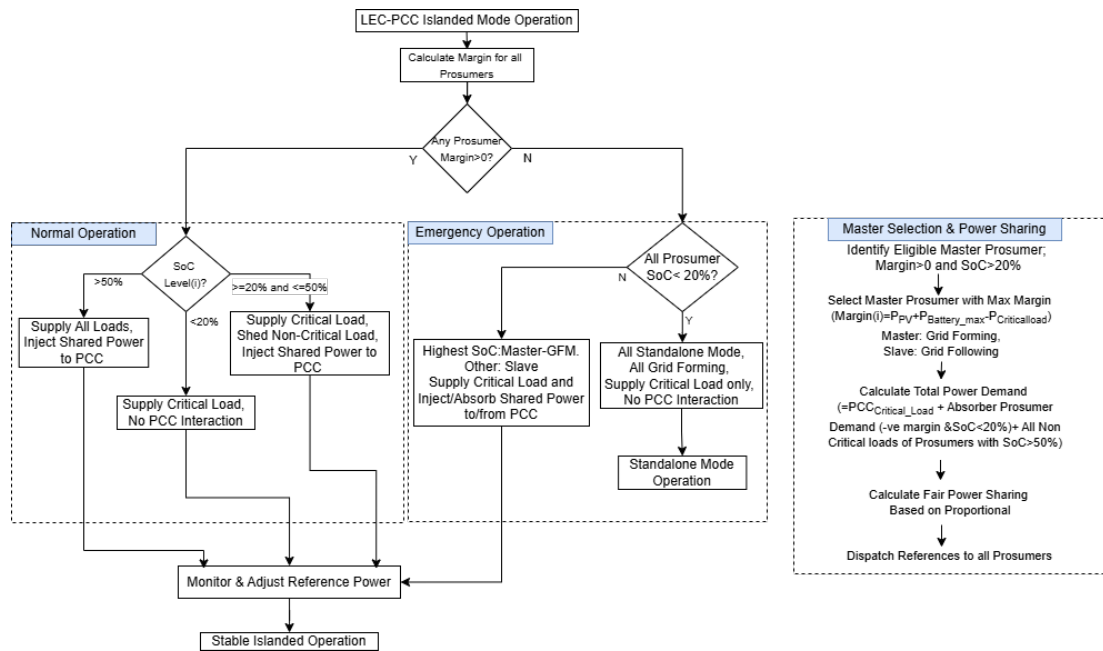


Figure 3-11 Flowchart of LEC EMS decision in LEC-PCC mode operation

(b) Prosumer Centric Proportional Power Sharing / Newness in Dispatching the Power

A Prosumer-Centric Proportional Power Sharing strategy is proposed in order to guarantee fair and efficient power distribution in the islanded LEC. This method represents a significant transition from conventional, inflexible dispatch plans. The process starts with the classification of prosumers into groups with surplus and deficit power with special consideration to those with a critically low SoC (Critical SoC). The amount of power needed to stabilize the community, the PCC critical load and the deficits of the struggling prosumers are calculated first. The novelty is in the way this aggregate power demand is distributed among the prosumers that have a surplus. Each surplus prosumer is allotted a proportional share to its respective Margin as opposed to an equal split. Each prosumer is then allowed to set its share of the total requirement as reference power. This is to make sure that the prosumers who contribute more resources to the community are given a proportionately larger portion of the burden of maintaining it.

- For LEC-PCC Islanded Mode Operation

Step 1: Classification of Prosumers based on Margin and SoC

Positive_Margin = Prosumers with Margin > 0 and SoC>20%

Negative_Margin= Prosumers with Margin < 0 or SoC<20%

Critical_SoC = Prosumers with SoC < 20% and margin<0

Step 2: Calculation of Total Power Requirement

Total Power Requirement

$$\begin{aligned} &= PCC_{Critical_Load} \\ &+ Sum(abs(Margin) \text{ for } Negative_{Margin} \text{ prosumers}) \\ &+ (Non - Critical - Load \text{ of those prosumers whose SoC} \\ &> 50\%) \end{aligned}$$

Step 3: Power Share Calculation

Total_Positive_Margin

$$= \sum_{i=0}^n Margin(i) \text{ of } Positive_Margin \text{ Prosumer}$$

$$Share_{Ratio}(i) = \frac{Prosumer \ Margin(i)}{Total_Positive_Margin}$$

$$P_{ref}(i) = Share_{Ratio}(i) \times Total \ Power \ Requirement$$

Step 4: Power Dispatch

Master Prosumer: Grid-Forming

P_{ref}: Calculated proportional share

Slave Prosumers (Positive Margin):

VSC Mode: Current-Controlled (Grid-Following)

P_{ref}: Calculated fair share

Deficit Prosumer (Negative Margin and SoC<20%):

VSC Mode: Current-Controlled (Grid-Following)

P_{ref}: Negative (Absorb from PCC)

- For GC Mode Operation both in peak hour and off peak hour.

In GC mode, the dispatch logic is adapted to consider economic factors, with P_{ref} being constrained by both the Margin and the inverter capacity, allowing prosumers to make decisions based on energy prices and their own storage levels.

$$P_{ref}(i) = \min(\text{Margin}(i), \text{Inveter Capacity})$$

3.4.2.3 EMS Outputs

The EMS transmits the following reference signals to local controllers:

- To VSC: ($P_{grid,ref}$, $Q_{grid,ref}$) or d-axis/q-axis current references ($I_{d,ref}$, $I_{q,ref}$), and mode selection commands (Grid-Connected/Islanded).
- To Load Switches: ON/OFF commands for critical and non-critical loads during islanded operation.

3.4.2.4 Performance Indicators

The performance of the proposed LEC-EMS and MPER control framework is evaluated through the following key indicators:

- DC-Bus Voltage Stability: The ability to maintain the DC-link voltage within a deviation of $\pm 2\%$ of its nominal value (400V) across all operating modes and during transitions.
- Power Sharing Accuracy and Fairness: The effectiveness of the Prosumer-Centric Proportional Power Sharing strategy, measured by the accuracy with which each prosumer's power injection/absorption matches its calculated reference power (P_{ref}) during LEC-PCC islanded operation.
- Power Quality: The quality of the AC power, quantified by measuring the THD of the current at the PCC bus and at the output of individual prosumer's converters.
- Dynamic Mode Transition: The system's ability to perform seamless and stable transitions between grid-connected, LEC-PCC islanded, and standalone modes without disconnecting critical loads.
- Energy Management Efficacy: The performance of the Dynamic Master Prosumer Selection algorithm and battery management, evaluated through:

- The correct and timely selection of the Master Prosumer based on the highest Margin.
- The SoC trajectory of each prosumer's battery, ensuring safe operation and demonstrating effective energy arbitrage during grid-connected operation.

3.5 Simulation Environment and Implementation

3.5.1 Software Selection

The selection of MATLAB/Simulink as the simulation platform was deliberate and based on several compelling advantages relevant to power system and power electronics research:

- a) Comprehensive Libraries
- b) Graphical Programming (Block-Diagram Interface)
- c) Integrated Control Design Capabilities
- d) Versatile Solvers
- e) Robust Analysis and Visualization Tools
- f) Industry Standard and Community Support

3.5.2 Model Building Process

The construction of the MPER system model in Simulink was a systematic process, adhering to the designed architecture and mathematical models:

- a) Component Selection from Simscape Electrical Libraries.
- b) Subsystem Construction: This modular approach significantly improves readability, manageability, and debugging. For instance, the PV array, its boost converter, and the MPPT controller were grouped into a single "PV_MPPT_System" subsystem.
 - PV System and Boost Converter: The Simscape Electrical PV array block was configured with appropriate parameters (e.g., peak power, open-circuit voltage, short-circuit current). This was then connected to the modeled boost converter circuit (comprising IGBT, diode, inductor, capacitor) using individual component blocks.

- Battery and Bidirectional DC/DC Converter: A Simscape Electrical battery block (e.g., a Lithium-Ion model with adjustable capacity and initial SoC) was used. This was interfaced with the bidirectional DC/DC converter, built from two IGBTs, two diodes, an inductor, and input/output capacitors, connected to the common DC bus.
 - Common DC Bus: The DC bus itself was modeled primarily as a large capacitor, representing its energy storage capability and voltage smoothing function, with parallel resistive loads representing leakage.
 - DC/AC VSC and AC Filter: A single-phase H-bridge VSC was constructed using IGBT blocks. This was followed by the LCL filter, built from discrete inductor and capacitor blocks, connecting to the PCC.
 - Loads: Both DC and AC loads were modeled using a combination of constant power blocks and resistive.
- c) Grid Interface:
- As per the scope, a single-phase AC voltage source was configured to represent the utility grid. This source was given a series R-L impedance to simulate the grid's strength and allow for realistic voltage drops during load changes or faults.
 - The grid was connected to the AC side of the MPER via the VSC's LCL filter at the PCC.
- d) Control Algorithm Implementation:
- Each local controller was implemented as a separate Simulink subsystem.
 - PI Controllers: Custom PI controller blocks from the Simulink "PID Controller" library were extensively used for voltage and current regulation loops. The proportional (P) and integral (I) gains of these controllers were carefully tuned using trial-and-error and PID Auto Tuner.
 - dq-Transformation: For the VSC's grid-connected control, custom MATLAB Function blocks or specialized Simscape Electrical blocks

were used to implement the Park and Inverse Park transformations for converting AC quantities to the dq-reference frame and back.

- PLL (Phase-Locked Loop): A custom PLL block was used to synchronize the VSC control with the grid voltage, providing the necessary phase angle.
- Energy Management System (EMS): The intelligent decision-making logic for the EMS was primarily implemented using a MATLAB Function blocks with conditional logic and Stateflow chart. Stateflow is particularly powerful for modeling finite-state machines and the transitions between them based on sensor inputs and predefined rules.
- Measurement and Feedback: Voltage and current measurement blocks were strategically placed throughout the model to provide real-time feedback signals to the control algorithms.

e) Signal Routing and Connections

f) Data Logging and Visualization

3.5.3 Representative Distributed Energy System (Grid Model)

While the overall objective is to interact with a distributed energy system, the grid connection in this study, as per the defined limitations, focuses on a single-phase interface. This simplified representation is modeled in Simulink as:

- A controlled voltage source block was configured to operate in a single-phase mode. Nominal voltage (e.g., 230 V RMS) and frequency (e.g., 50 Hz).

Why a Single-Phase Grid?

- Focus on Core Functionality: The primary objective of this research is to analyze the performance and control of the MPER itself, particularly its operation in LEC, its internal energy management, PQ enhancement and seamless mode transitions. These fundamental principles and control algorithms (e.g., current/voltage control, MPPT, battery management) are largely similar whether applied to a single-phase or three-phase system, albeit with scaled power levels and additional complexities for three-phase balancing.

- Reduced complexity for initial examination.
- Foundation for future work: A successful single-phase model serves as a robust foundation. The control strategies and insights gained can then be extended and adapted to more complex three-phase systems in future research.

This meticulous approach to model building and parameterization ensures that the simulations are not just theoretical exercises but accurately reflect the behavior of the proposed MPER system under realistic and challenging operational conditions, providing a solid basis for performance analysis.

3.6 Operational Scenarios and Test Cases

Simulation-based test cases under various operating conditions and modes were designed and developed to evaluate the effectiveness of the coordinated control strategy and fundamental operation of the MPER. These scenarios examined the functionality, stability, and adaptability of the proposed control architecture in maintaining power balance, voltage regulation, and renewable power usage.

Among these, a key scenario focuses on the SA operation of the LEC, representing the community-level autonomy during grid outages or intentional islanded operation (LEC–PCC mode). This mode demonstrates the MPER’s capacity to coordinate distributed prosumers to maintain critical load supply without external grid support.

3.6.1 Fundamental Operation of the single-phase MPER in Dynamic Operating Conditions

In the context of this research, dynamic operating conditions refer to any situation where the system's state is not static. This includes:

- Varying Renewable Energy Generation: Solar power changes with clouds, time of day, and season.
- Fluctuating Loads: Appliances turn on and off, demand changes throughout the day.
- Grid Disturbances: Voltage sags (momentary dips in voltage) or complete power outages.
- Mode Transitions: The act of seamlessly switching between being connected to the main grid and operating independently (islanded).
- The different operational scenarios considered and simulated are:

- Scenarios 1 & 2: GC / LEC-PCC Mode
 - Objective: Examine power exchange and DC bus stability
 - Test Conditions: Variable PV irradiance
- Scenarios 3 & 4: SA Mode
 - Objective: Ensure autonomous voltage/frequency regulation
 - Test Conditions: ESS-only operation and variable generation
- Scenarios 5 & 6: Mode Transition
 - Objective: Ensure seamless islanding and re-synchronization
 - Test Conditions: Grid disconnection and restoration events

Summary of MPER Operational Scenarios:

- The fundamental operation of the single-phase MPER was examined first through a series of core scenarios designed to test its stability and autonomy. These scenarios establish the MPER's capability to:
 - Maintain a stable DC-bus voltage across all conditions.
 - Regulate local AC voltage and frequency in SA mode under variable PV generation and load.
 - Execute seamless transitions between GC/LEC-PCC and SA mode, and ensure an uninterrupted power supply to critical loads.
 - These foundational tests confirms the MPER's as an individual unit, providing the necessary platform for the subsequent evaluation of the multi-prosumer LEC.

3.6.2 LEC–EMS Test Case Configuration and Evaluation

Building upon the examined MPER performance, this research introduces and tests a LEC-EMS. LEC with the following details are considered to test the proposed decision cycle for Power Sharing and Master Prosumer Selection in the GC mode, the LEC-PCC mode and the SA mode of operation in CHAPTER Four:. The test case involves a community of three distinct prosumers with varying PV capacities, load profiles, and initial battery SoC, connected via a common PCC that supplies a critical community load.

- **Objective:** Assess coordinated control of multiple MPER units and EMS decision logic during autonomous community operation as well as in GC mode of operation.

- **Critical Load:** PCC community critical load: Health post facility (~2.0 kW) powering essential medical equipment such as a 1.5 kW portable X-ray machine and a 500 VA hematology analyzer.
- **Prosumer Setup:**
 - Prosumer 1: PV = 2.0 kW, Non-critical Load = 1.0 kW, Critical Load= 0.5 kW, Initial SoC = 65%.
 - Prosumer 2: PV = 1.5 kW, Non-critical Load = 1.0 kW, Critical Load= 0.2 kW, Initial SoC = 35%.
 - Prosumer 3: PV = 0.5 kW, Non-critical Load = 0.8 kW, Critical Load= 0.2 kW, Initial SoC = 15%.

Evaluation Focus:

- Master–slave selection logic based on SoC and available power margin.: The EMS has been tested on its ability to dynamically identify and designate the Master Prosumer; the unit responsible for grid-forming control during islanded operation. Selection is based on the real-time calculation of each prosumer's Margin (instantaneous surplus power capacity) and SoC, which is a function of PV generation, battery SoC, and local load.
- Load prioritization and supply continuity for critical community services: In the LEC-PCC mode, the EMS was evaluated on its ability to fairly allocate the total community power requirement (PCC critical load and struggling prosumers absorbing power) among the surplus prosumers. The expected outcome is that each supporting prosumer contribute a share of power proportional to its individual Margin, thus ensuring an efficient and fair distribution.

The performance has been assessed in both grid-connected and LEC-PCC modes, analyzing economic dispatch during peak/off-peak hours and resilient, fair operation during grid outages. The corresponding simulation outcomes, power flow behavior, and performance evaluation of this scenario are presented in CHAPTER Four:

By systematically subjecting the MPER model to these diverse operational and test case scenarios, the research aims to provide a comprehensive and quantitative assessment of its performance, control strategy effectiveness, and overall contribution to qualitative grid resilience and PQ in DES.

3.7 Performance Evaluation Metrics

After designing, modeling and simulating the MPER with LEC-EMS operating under various dynamic conditions, the crucial next step was to quantitatively and qualitatively assess its performance. This involves defining specific metrics measurable indicators that allow us to determine how well the MPER achieved its design objectives and addressed the identified problems.

The performance metrics were directly derived from the research objectives and are categorized to cover the overall key aspects of the MPER's functionality such as PQ, Energy Management and Utilization and grid support. All these metrics have been extracted from simulation results from Simulink.

3.7.1 Power Quality Metrics

PQ is defined as the degree to which power systems components such as voltage, current, and frequency deviate from their ideal sinusoidal waveforms. Equipment malfunctions, lifespan reductions, and increment in the energy losses occurs due to poor PQ. The MPER aims to improve this.

3.7.1.1 DC Bus Voltage Regulation:

- It measured how stable the common DC bus voltage (V_{dc}) remained. Ideally, it should stay very close to its nominal setpoint (e.g., 400V).
- V_{dc} waveform over time using Simulink Scope blocks was monitored.

Quantitatively:

- Maximum Deviation: The largest percentage difference between the actual V_{dc} and its nominal value during dynamic events.
- Root Mean Square (RMS) Error or Standard Deviation: A statistical measure of overall voltage fluctuation over a period.

3.7.1.2 AC Side Total Harmonic Distortion (THD):

- It measured the level of distortion in the AC voltage and current waveforms at the PCC and the local AC loads. Harmonics are unwanted frequencies that are multiples of the fundamental frequency (e.g., 150 Hz, 250 Hz for a 50 Hz system). High THD can cause overheating and malfunctions in sensitive electronic equipment.

- Simulink's THD measurement blocks or FFT analysis tools was used to analyze the frequency components of the voltage and current waveforms and calculate the THD value as a percentage. IEEE standards (e.g., IEEE 519) provide limits for acceptable THD levels.

3.7.2 Energy Management and Utilization Metrics

These metrics evaluated how efficiently the MPER manages the energy flow among its various components and utilizes renewable resources.

3.7.2.1 Battery SOC Trajectory:

- It measured the battery's charge level over time period. It indicates whether the battery is being charged and discharged according to the LEC-EMS's strategy, avoids overcharging/over-discharging, and adequately supports the system.
- The SOC value is a direct output of the battery model block in Simulink and is plotted over the simulation duration. Observing its limits (e.g., keeping it between 20% and 95%) and its response to PV changes and load demands are noted.

3.7.2.2 PV Power Utilization:

- It measured how much of the generated PV power was actually used by the system (for loads, charging ESS, or exporting to grid), rather than being curtailed due to insufficient demand or storage.
- By comparing the total PV power generated (from the MPPT controller) with the power consumed by loads, absorbed by the energy storage systems, and exported to the grid it was measured. This has been visualized as power flow plots.

3.7.2.3 Grid Power Exchange Profile:

- It measured the active and reactive power exchanged between the prosumer and the utility grid or vice versa. This indicated whether the MPER is importing power when needed, exporting surplus PV power.

- By using instantaneous power measurement blocks at the PCC in Simulink. Plots of active (P) and reactive (Q) power over time shows clearly show import/export patterns.

3.7.3 Grid Support and Resilience Metrics

These metrics quantify the MPER's contribution to the overall robustness and stability of the interconnected grid and its ability to withstand and recover from disturbances.

3.7.3.1 Power Contribution to PCC

- It was measured by simulating the test case as described above in LEC–EMS Test Case Configuration and Evaluation
- It measured how quickly and smoothly the system recovers to a stable operating state after load or margin changes. This includes observing the power shared by each prosumer to the community critical load based on the available margin.

3.7.3.2 Seamlessness of Mode Transitions (LEC-PCC to SA and vice-versa):

- It measured the smoothness between different operating modes, and vice-versa. A truly seamless transition should ideally involve no perceptible interruption to local loads.
- It was measured by closely examining the voltage and frequency waveforms at the local AC bus and the DC bus during the transition points. Key indicators of seamlessness include:
 - Absence of Voltage/Frequency Spikes/Dips: Minimal deviation
 - No Interruption to Load Power: Continuous supply to critical loads.
 - Smooth Current Transfer: Absence of large current and reduction of inverter current.

3.8 Data Analysis and Interpretation

The final stage of the methodology involves extracting the raw data generated by the simulations and transforming it into meaningful results that support the initial hypotheses and help answer the research objectives.

3.8.1 Data Extraction from Simulink:

- Simulink scope data was logged to the workspace for visual inspection of waveforms.

3.8.2 Post-Processing and Visualization:

- Quantitative Calculations
 - Calculating THD using built-in MATLAB functions or custom FFT algorithms.
 - Calculating average power flows over specific periods.
- Graphical Representation: MATLAB's powerful plotting functionalities was used to generate clear and insightful graphs and charts. These include:
 - Time-domain waveforms (e.g., voltage and current plots during faults).
 - Power flow charts (e.g., showing PV generation, load consumption, battery charge/discharge, and grid power exchange over time).

3.8.3 Interpretation of Results and Hypothesis Testing:

- Analyzed data and generated plots have been meticulously interpreted against the specific hypotheses.
- The results for each of the scenarios were discussed in details, explaining how the MPER behaved and whether its control strategies achieved the desired outcomes or not.
- Qualitative comparisons have demonstrated the benefits of the MPER, such as the improvement in PQ, and the enhancement in the reliability and resilience during grid outages.
 - Any deviations from expected behavior or limitations observed in the simulation have been discussed, providing insights into potential areas for future research or practical considerations.
 - Finally, the interpretation explicitly linked the findings back to the overarching objectives of the thesis, concluding each objective have been met and to what extent.

CHAPTER FOUR: RESULTS AND DISCUSSION

This section presents the results from the simulation examining the performance of the proposed MPER and the LEC-EMS. It is divided into two main parts: first, the foundational operational stability of the individual MPER is confirmed, and second, the core contributions of the LEC-EMS, the dynamic master selection and proportional power sharing evaluation in a multi-prosumer community. The main parameters are summarized in the Table 1. ER passive values are calculated according to the guidelines previously described in Section 3.

Table 1 MPER System and Simulation Parameters

Parameters	Values	Notes
PV Power	250 W/module (8s × 1p) = 2000 W	Test Irradiance: 250-1000 W/m ²
Energy Storage (ESS)	Li-ion, 24 V, 100 Ah (2.4 kWh)	SoC Operating Range: 20-95%
DC-Link Voltage	400V	Ensures V _{ac} = 230 V Compatibility
DC-DC Switching Frequency	F _s =10 kHz	For PV and ESS Converters
VSC Switching Frequency	F _{sw} = 20 kHz	For LCL filter design
PWM Carrier Frequency	S = 20 kHz	Two-arm bridge, Sets the VSC switching frequency (S = F _{sw})
LCL Filter	Custom Design	Designed for F _{sw} = 20 kHz to ensure THD < 5%
Loads	AC & DC constant resistive	Models critical and non-critical prosumer demands; Variable for different prosumers
Grid Voltage and Frequency	230 V, 50 Hz	Standard single-phase utility connection

The Simulink model incorporates all subsystem components and controls using Simulink. A MATLAB function and Stateflow-based EMS governs operational transitions. The different operational scenarios and test cases considered and simulated as per section 3.6.1.

Dynamic operating conditions refer to situations in which the system's operating state is continuously changing rather than remaining steady. These variations arise from fluctuations in renewable energy generation caused by weather conditions, changes in load demand and external grid disturbances such as outages.

4.1 Foundational MPER Performance and Stability

To establish a baseline performance and core functionality, MPER's was tested under varying conditions. Based on the simulation and system parameters in Table 1, the system was subjected to varying irradiance and load changes.

One second simulation was conducted to evaluate the proposed MPER's foundational performance under these conditions. A stair-step irradiance profile was applied to emulate the variability of solar generation, with irradiance levels set to [1000, 500, 200, 500, 1000] W/m² at time instants [0, 0.3, 0.6, 0.9, 1.2] seconds, respectively at 25 degrees Celsius. These test scenarios focus on a representative prosumer (Prosumer 1) within the LEC in islanded mode operation, with varying operating conditions and a power share of 1500W.

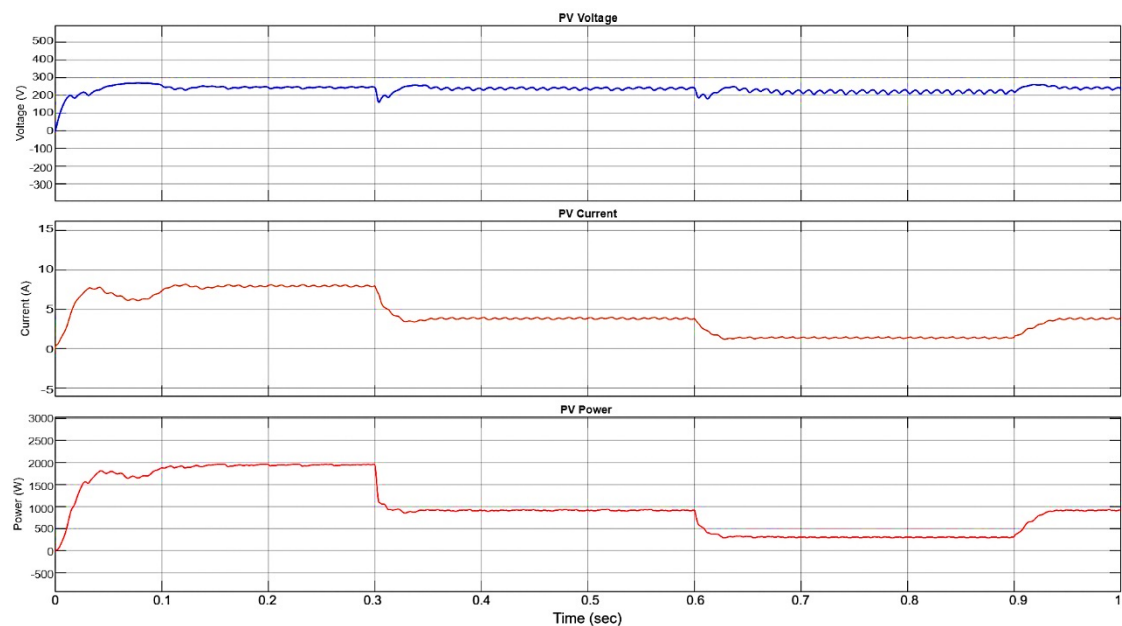


Figure 4-1 Simulated MPER Waveforms of PV voltage=250V, PV Current and PV power at varying irradiance from t=0 to 1 sec

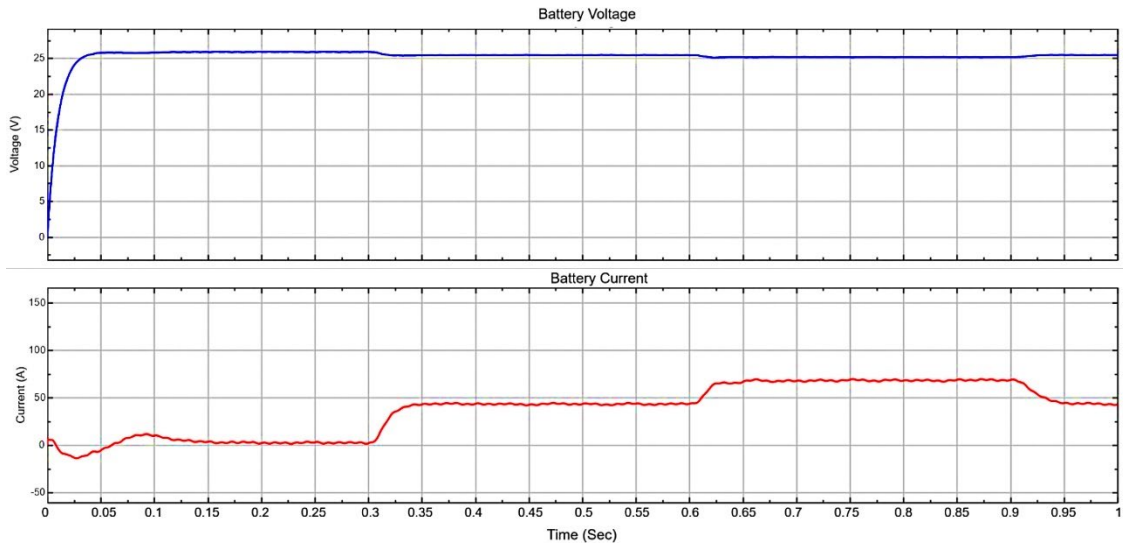


Figure 4-2 Simulated MPER waveforms of the magnitude of ESS voltage and ESS current corresponding to variable PV irradiance

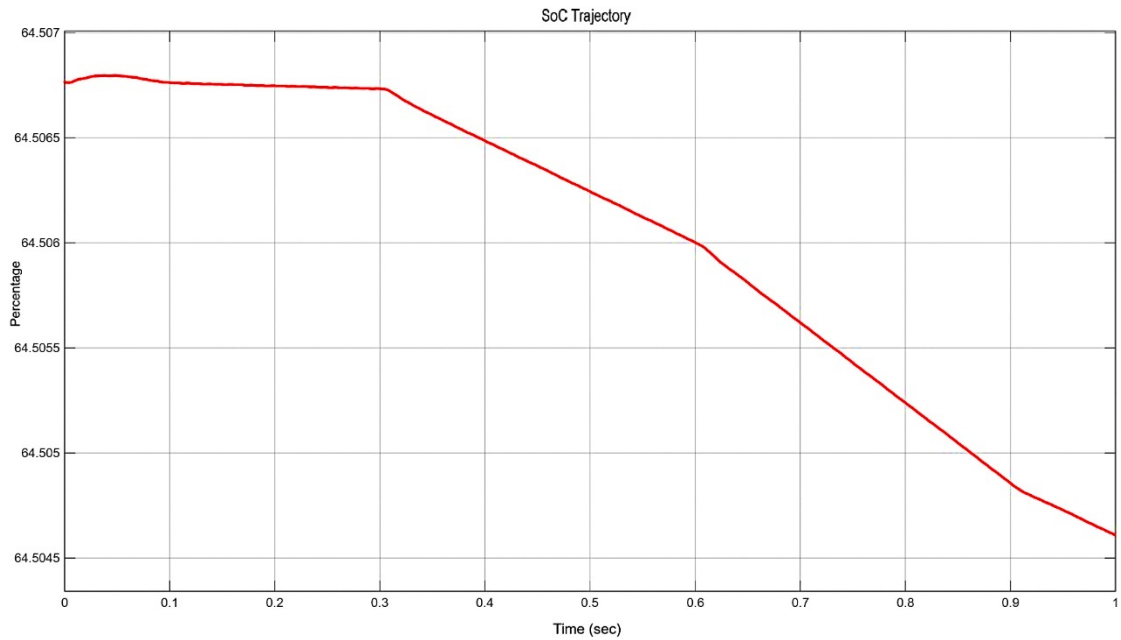


Figure 4-3 Waveform of Battery SoC Trajectory; shows the discharging of the ESS corresponding to the available varying $P_{available}$ supplying 500 W critical load, 1000 W non-critical load and 450W surplus to grid/PCC

The main waveforms corresponding to the PV output *Figure 4-1*, ESS parameters (*Figure 4-2*), and battery SoC at an initial 65% level (*Figure 4-3*) illustrate two dynamic operating scenarios: Scenario 1 ($t = 0-0.3$ s) and Scenario 2 ($t = 0-0.5$ s), both simulated in Islanded mode operation . During these intervals, the PV array generates sufficient power to meet the internal demand (i.e., critical dc loads and AC loads) of the prosumer, while the surplus energy charges the ESS. As shown in *Figure*

4-1, around $t = 0.3$ s, the battery SoC begins to decrease in response to a drop in PV generation and a slight increase in DC load from 500W. Although the PV continues to provide adequate power to local loads, the battery SoC gradually declines since the MPER maintains constant active power injection into the grid. The MPER sustains grid support until both the PV power and battery SoC reach their minimum thresholds. The LEC-EMS dynamically tracks reference inputs from each prosumer to determine whether power should be injected into or absorbed from the grid, ensuring coordinated operation across the community.

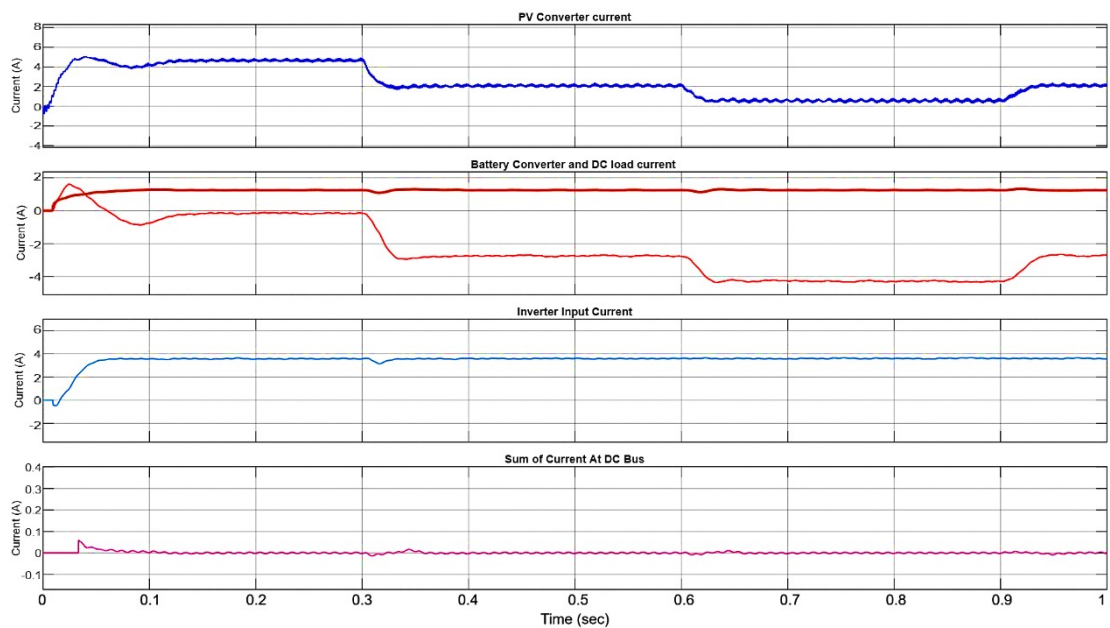


Figure 4-4 Waveform of simulated MPER DC bus link current; the sum of current at DC bus at display 4 is nearly equal to zero showing no or very minute deviation despite varying condition

The DC-link current behavior is presented in *Figure 4-4*, showing that the sum of the PV converter current (I_{pvbus}), battery current ($I_{battbus}$), inverter input current (I_{invbus}), and DC load current (I_{dload}) remains balanced ($\Sigma I = 0$), confirming optimal utilization of available power. During the brief grid interruption between approximately $t = 0.35$ s and 0.5 s *Figure 4-5*, the critical DC load continues to receive uninterrupted power supply, examining the MPER's ability to maintain load continuity. Meanwhile, the inverter injects nearly 2A of current into the grid when system conditions remain within permissible thresholds. *Figure 4-5* also illustrates the seamless and stable transition between GC and SA modes, demonstrating the effectiveness of the proposed coordinated control strategy in maintaining smooth operation during mode switching.

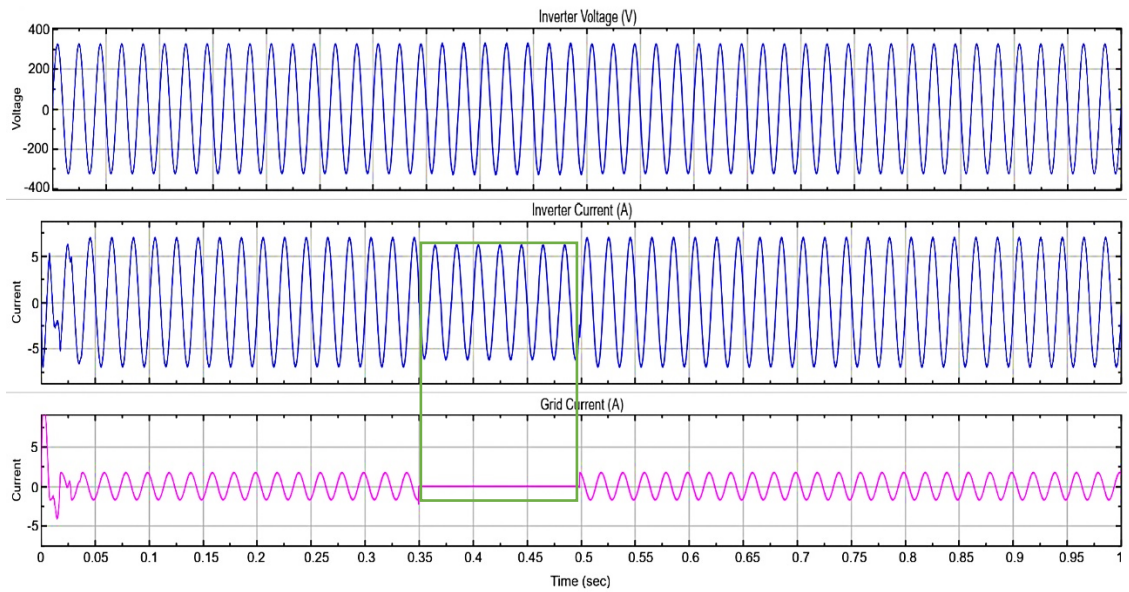


Figure 4-5 Waveforms of stable inverter voltage, inverter current and LEC-PCC/grid current during seamless transitions. During grid failure from $t=0.35$ to 0.5 sec there is decrease in inverter current proportional to LEC-PCC/grid current.

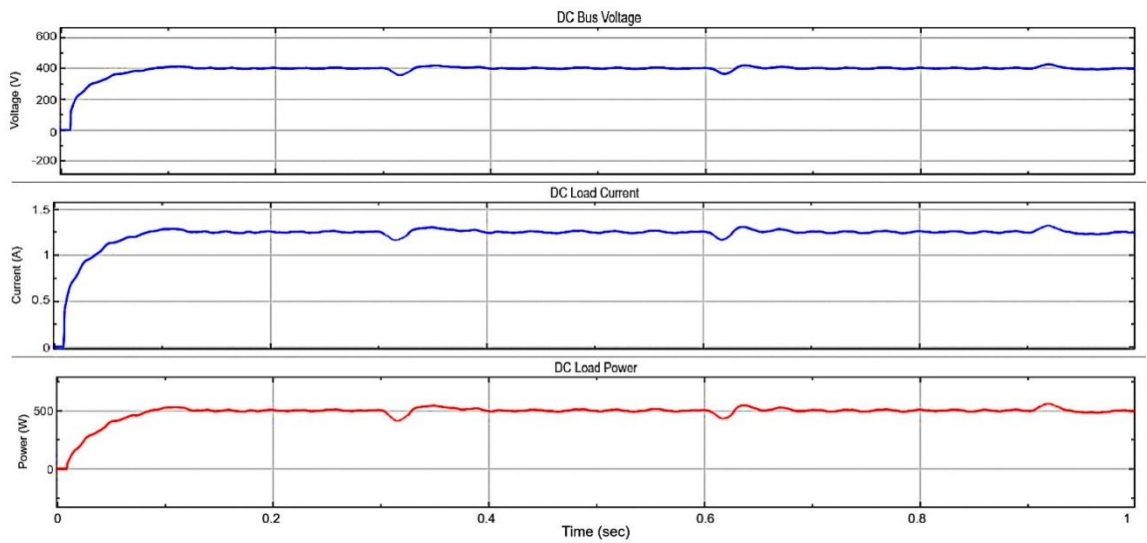


Figure 4-6 Stable DC bus voltage at 400V, DC load current and DC load power at constant critical load of 500W

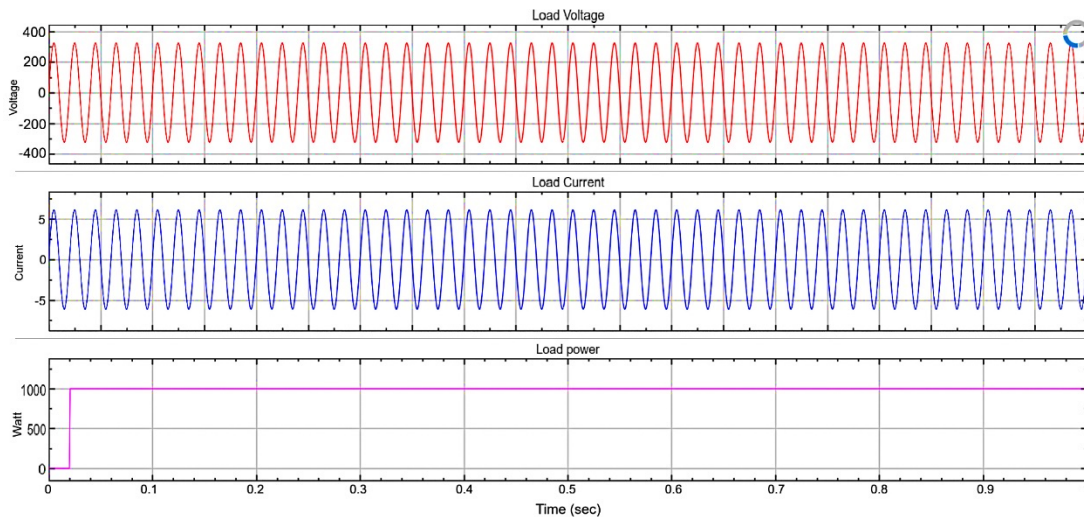


Figure 4-7 Waveform of the simulated MPER AC load voltage, AC load current and AC power; at non-critical load of 1000W

From Figure 4-6 depicts that the voltage of MPER DC-bus is within $\pm 2\%$ and ensuring uninterrupted supply to critical loads and classical ac loads. No undesired transients are presented in this action. The simulation results confirm the theoretical predictions and the implemented flexible strategy in the considered scenarios.

Figure 4-6 shows that the MPER DC-bus voltage remains within $\pm 2\%$ of its nominal value, ensuring reliable supply to both critical loads and non-critical loads without any noticeable transient distortion. With the obtained results it confirms that the proposed control strategy effectively regulates internal DC-bus voltage, manages prosumer-level energy exchange, and supports continuous operation even under varying operating conditions. The simulation outcomes thus examine the theoretical design and confirm the MPER's potential as a robust and flexible interface for enhancing PQ, reliability, and resilience in grid-interactive LEC.

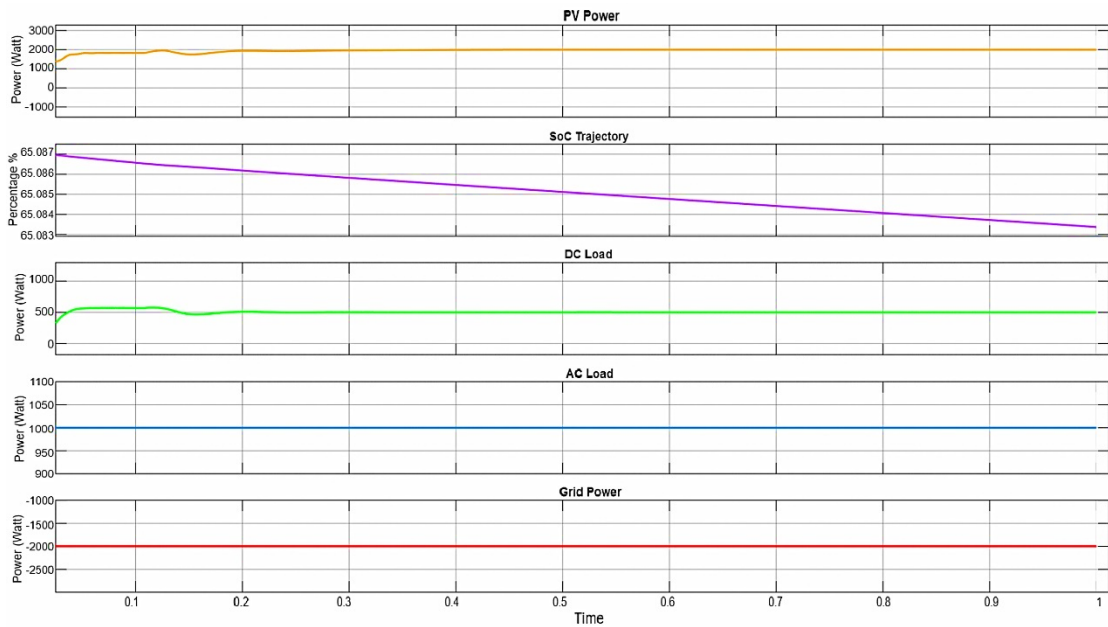
4.2 LEC-EMS Performance in a Multi-Prosumer Community

The performance of the novel LEC-EMS is evaluated using the three-prosumer test case detailed in the Methodology. A simulation test case scenario as per section 3.6.2 where the LEC operates autonomously in LEC-PCC mode, disconnected from the main grid. The objective was to power a critical health facility with a demand of approximately 2 kW, using three prosumers with varying generation and storage profiles. The objective was to analyze the coordinated performance of the MPER units and LEC-EMS in maintaining system stability and critical load supply.

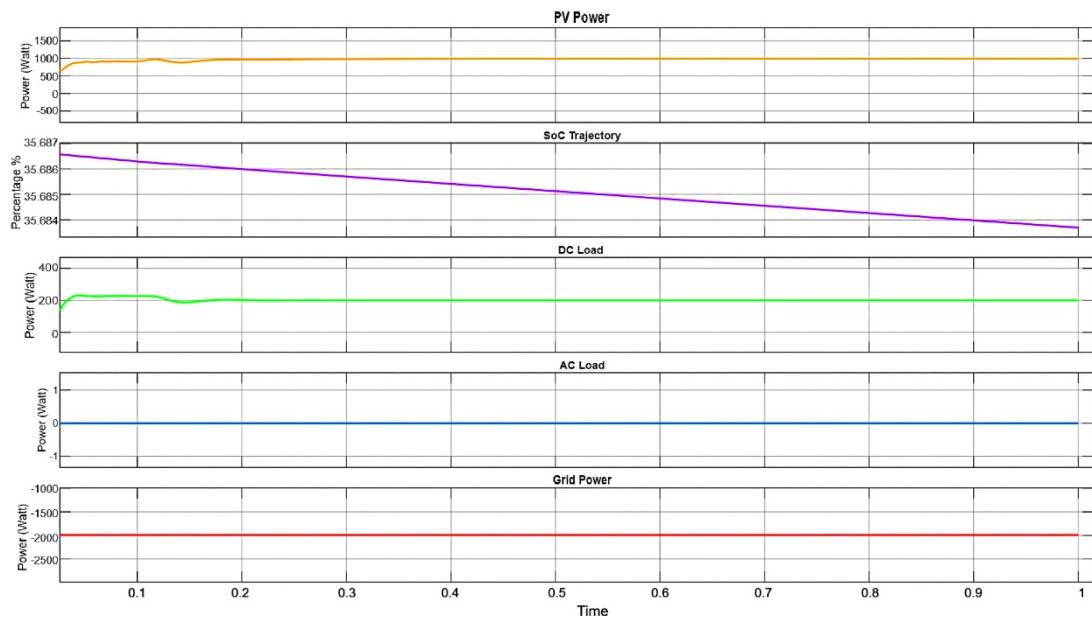
4.2.1 Grid-Connected Mode: Economic Operation

The EMS successfully showed economically-driven behavior during both peak and off-peak hours, as shown in Figures 4 and 5.

- **Peak Hours (High Export Tariff):**



(a)



(b)

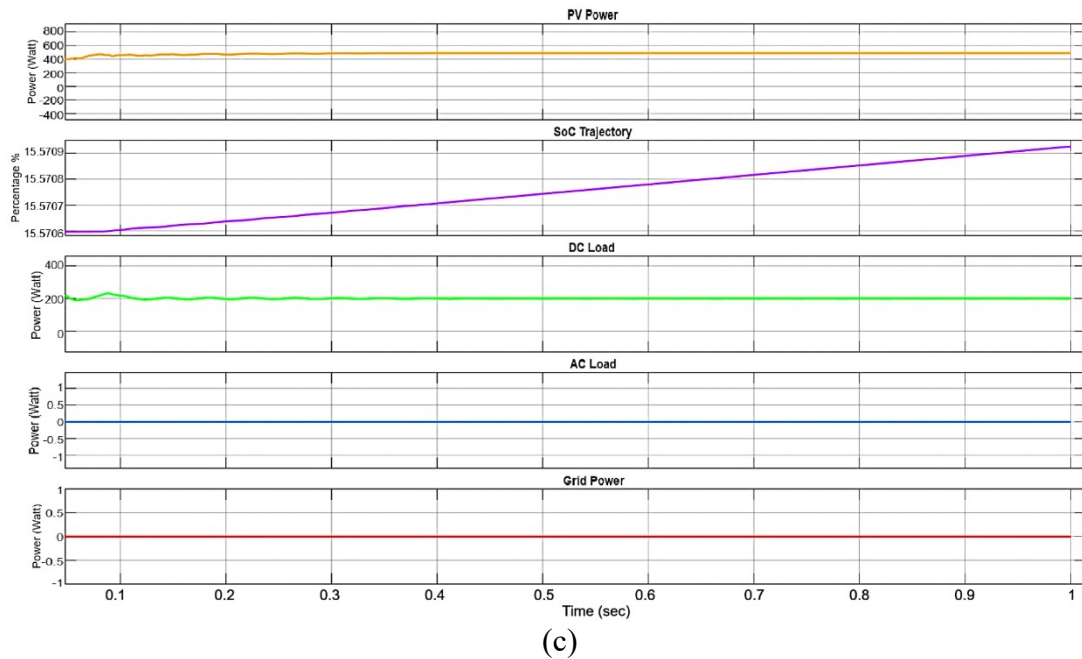
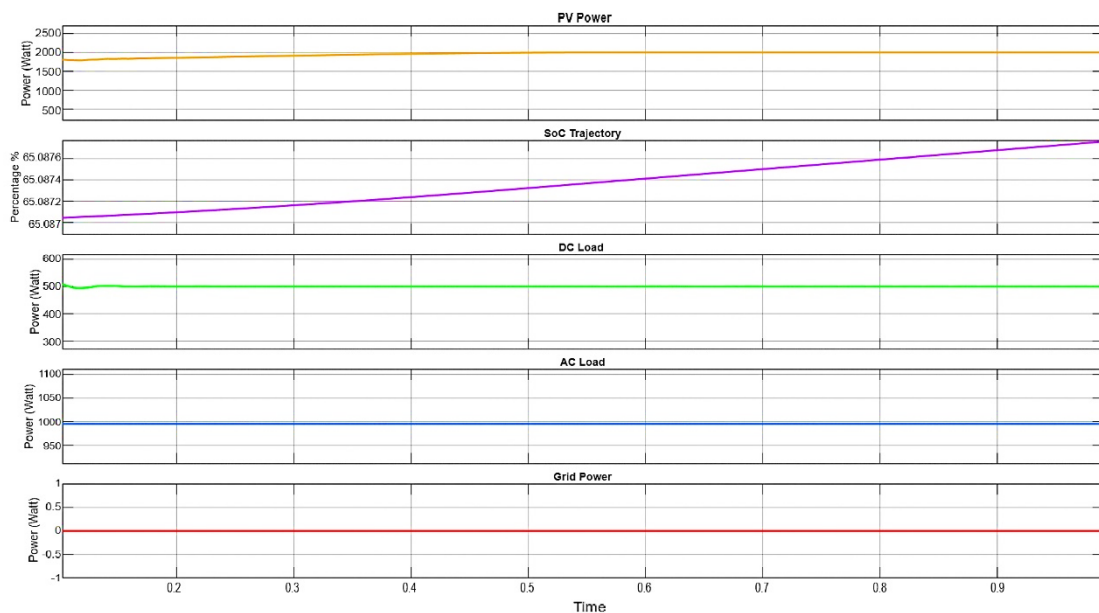


Figure 4-8 Simulated MPER waveforms of (a) Prosumer 1, (b) Prosumer 2 and (c) Prosumer 3 in GC mode operation during peak hour; From top to bottom: Generated PV power, SoC_{ESS}, Prosumer’s critical load, Prosumer’s noncritical load, and Grid power (-ve power means injection)

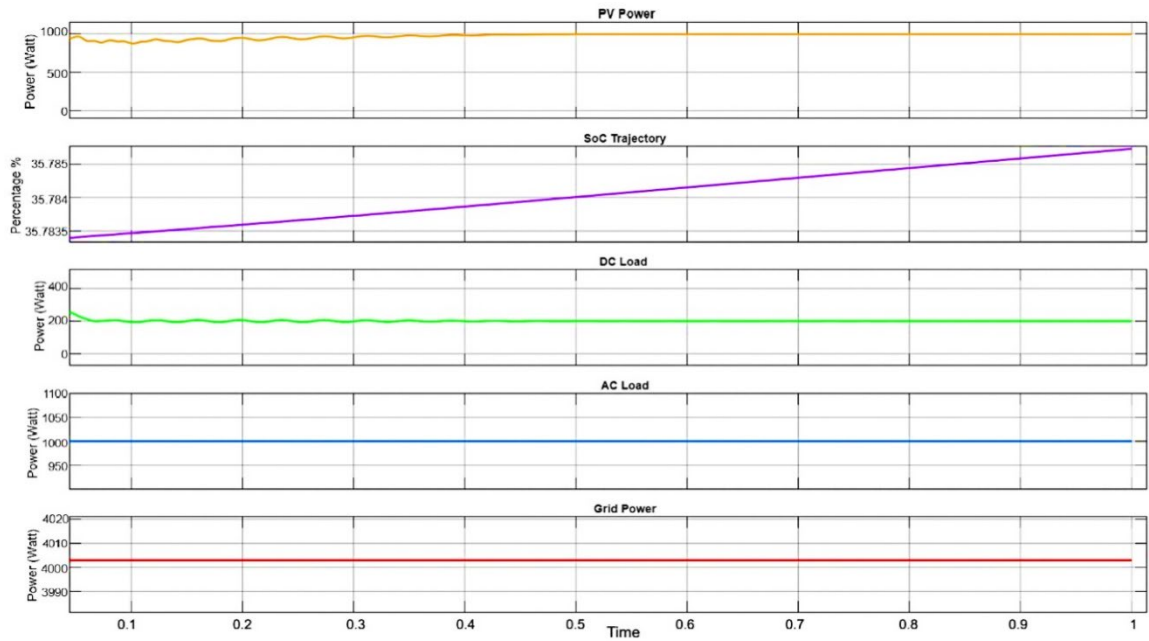
The simulation results for peak hours Figure 4-8(a) demonstrate that Prosumer 1 operates with a significant power surplus. It serves its entire local load (1.5 kW critical and non-critical) using a combination of PV generation (2000W) and battery discharge. The substantial amount of power is injected into the main grid (maximize revenue), as indicated by the negative 'Grid Power' at display 5. It is important to note that the export is capped at 2 kW, as the inverter's maximum capacity (3 kW) is reached after supplying the local non-critical load of 1000W, despite having a higher theoretical power margin i.e., $\text{Margin (1)} = 3900\text{W}$. This behavior demonstrates optimal prosumer economics by generating maximum revenue through grid export during high-tariff periods. Similarly, in Figure 4-8(b) Prosumer 2 exhibits a balanced but constrained operation. Its PV generation and battery discharge are sufficient to supply its own critical and non-critical loads. However, the surplus power available { $\text{Margin (2)} = 2000\text{W}$ after supplying its critical load of 200W} for grid injection is minimal. This indicates that Prosumer 2 is operating near its self-sufficiency limit during peak hours, with its lower initial SoC = 35% likely limiting its ability to discharge aggressively and contribute significantly to grid export by shedding its local non-critical load.

Prosumer 3 Figure 4-8 (c) operates with an energy deficit. Its low PV generation and critically low initial SoC (15%) prevent it from fully supporting its own non-critical load. As a result, the prosumer breaks its interaction with grid and shedding the non-critical load. It doesn't absorb from grid though $SoC < 20\%$, it's because margin is still positive which is used to charge battery after supplying its critical load. This behavior aligns with the EMS strategy, which prioritizes self-preservation for prosumers with low resources, preventing further battery degradation. Since the margin is positive, the surplus power from the PV is used for charging ESS after supplying local critical load.

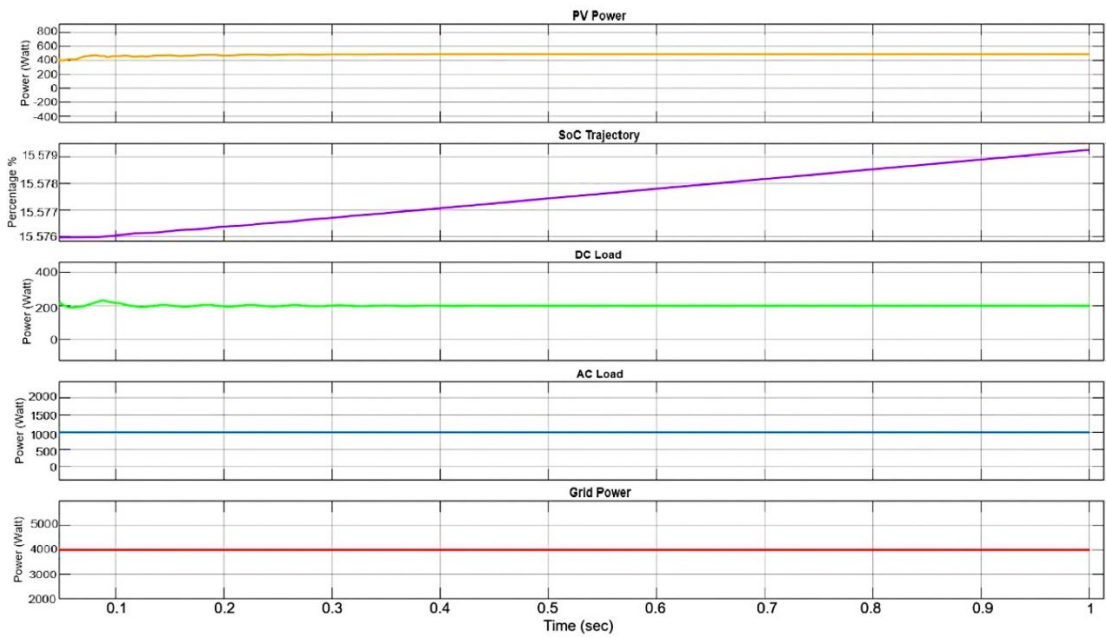
- **Off-Peak Hours (Low Import Tariff):**



(a)



(b)



(c)

Figure 4-9 Simulated MPER waveforms of (a) Prosumer 1, (b) Prosumer 2 and (c) Prosumer 3 in GC mode operation during off peak hour; From top to bottom: Generated PV power, SoC_{ESS}, Prosumer’s critical load, Prosumer’s Noncritical load, and Grid power

Prosumer 1 Figure 4-9(a) off-peak hours, the behavior of Prosumer 1 shifts strategically. While it still uses PV power to serve local loads, it breaks interaction with grid and instead uses the surplus energy to charge its battery (rising SoC). This reflects

an intelligent economic strategy: storing energy when grid prices are low for later use or sale during high-price peak hours.

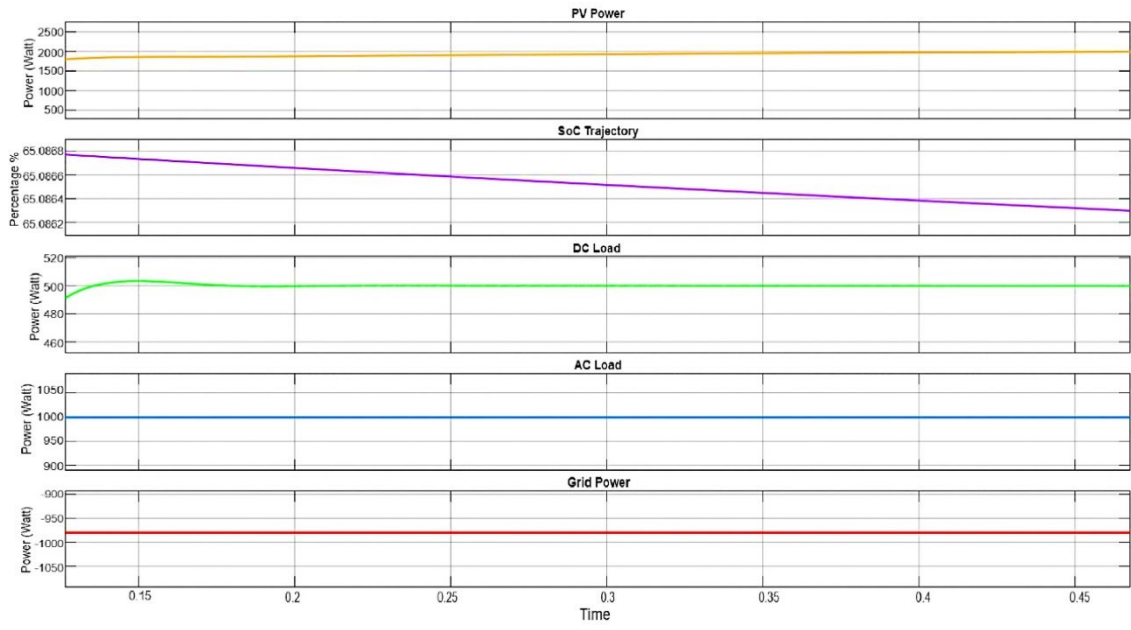
In Figure 4-9(b) Similar to Prosumer 1, Prosumer 2 utilizes the off-peak period for battery charging and serving its non-critical load by making grid interaction, indicating that its PV generation is primarily directed toward serving its critical loads and replenishing its storage, preparing for future periods of high demand or low generation.

Due to limited generation capacity of the Prosumer 3 Figure 4-9(c) it draws large amount of power from the grid to support their loads and store for the peak periods. The primary goal is to sustain its critical loads and slowly recover its battery SoC when possible, which demonstrates the system's focus on resilience for all participants. This behavior confirms the EMS's ability to perform prosumer-centric economic dispatch, making optimal decisions based on real-time capacity and market conditions.

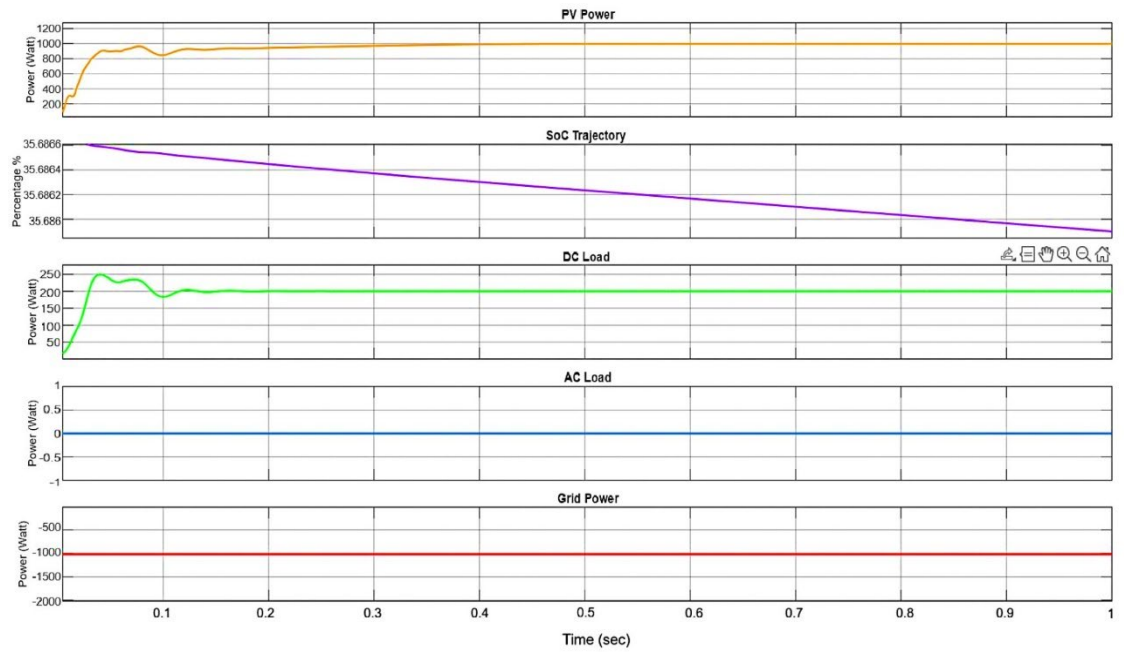
4.2.2 LEC-PCC Mode: Resilient and Fair Power Sharing

In islanded mode, the EMS's two key algorithms are activated, ensuring community resilience.

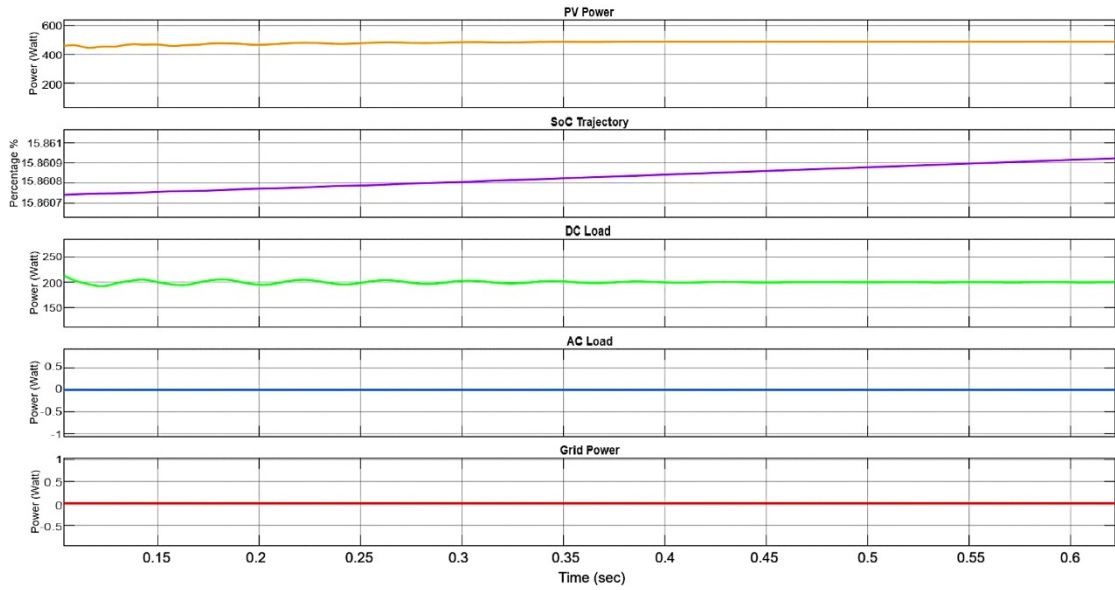
- **Dynamic Master Prosumer Selection:** Based on the calculated Margin, Prosumer 1 (with the highest capacity) is dynamically selected as the master prosumer to provide grid-forming control.
- **Proportional Power Sharing:** The results in *Figure 4-10* and the consolidated view in *Figure 4-11* confirm the successful implementation of the proportional power-sharing strategy.



(a)



(b)



(c)

Figure 4-10 Simulated MPER waveforms of (a) Prosumer 1, (b) Prosumer 2 and (c) Prosumer 3 in LEC-PCC mode operation; From top to bottom: Generated PV power, SoC_{ESS}, Prosumer’s critical load, Prosumer’s non-critical load, and Grid power (-ve power means power flow to PCC)

In LEC-PCC mode, calculated total power demand is 3000W and total available power is around 5900 W. Prosumer 1 Figure 4-10 (a) acts as a key supporter or Master Prosumer of the community microgrid with margin of 3.9 Kw. It supplies its own loads and injects a significant amount of power (984 W) to the common PCC bus, as calculated by the proportional power-sharing algorithm, though the individual share to PCC critical load is lesser as compared to Prosumer 2. It’s high initial SoC and generation capacity make it a natural contributor to supporting the critical PCC load and other deficit prosumers. Prosumer 2 operates in a neutral or slightly supportive role Figure 4-10 (b). It successfully meets its own critical local loads, while make significant contribution to the PCC approx. 1020 W. Its mid-range SoC means it is not in need of support but also does not have a large surplus to share, functioning primarily in a self-sufficient manner within the islanded community.

Lastly, in Figure 4-10(c) Prosumer 3 is clearly identified as a deficit prosumer but it doesn’t draw power from the PCC to maintain its critical load because PV generation is sufficient to meet, also resulting in the positive margin. This result examines the prosumer classification step of the EMS, ensuring that members with low generation

and storage receive support from the community during islanded operation, thereby maintaining overall stability, reliability and community resilience qualitatively. If the margin was zero then it would have absorbed power from the PCC, adding burden to other prosumers.

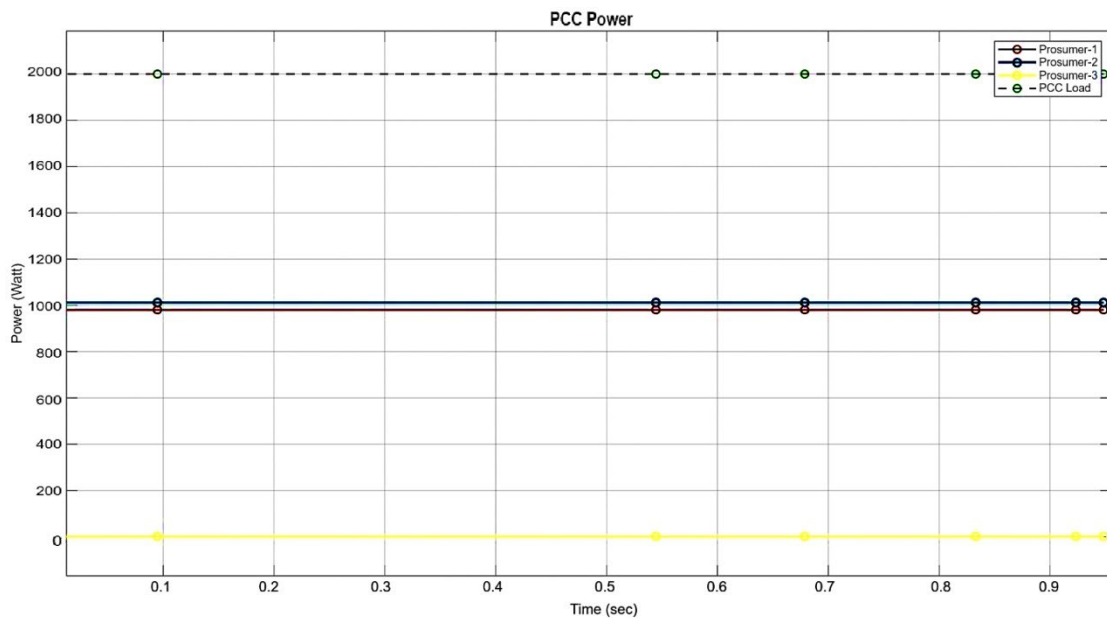


Figure 4-11 Waveform of prosumers' power contribution to PCC under simulation scenario having three prosumers and a PCC load at critical facility in the Energy community.

The total PCC demand is met continuously demonstrating that the prosumer-centric strategy enhances resilience by ensuring the community's critical load is always supported through a fair, decentralized, and capacity-aware sharing scheme, rather than a rigid or equal split.

4.2.3 Power Quality Analysis

The proposed control strategy maintains high PQ in both the LEC-PCC mode and GC mode of operation. The THD of the current is measured to be 2.05% at the LEC-PCC bus *Figure 4-12* with the RMS value of the 50 Hz current 4.310 A to the LEC PCC Critical load and 0.72% at the converter of Prosumer 1 *Figure 4-13* Both values are well within the IEEE 519 standard limit of 5%, confirming that the system maintains clean power waveforms even during decentralized, islanded operation.

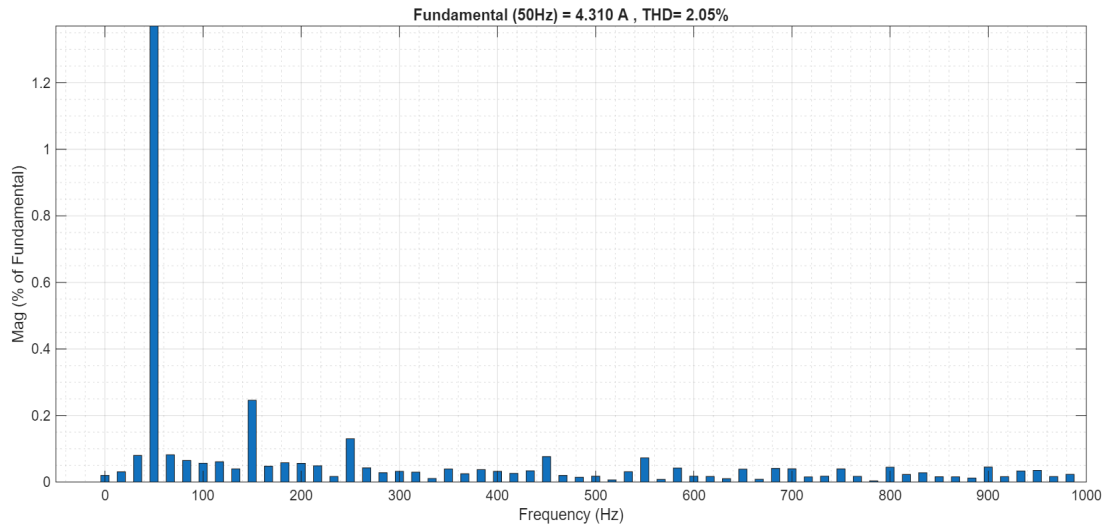


Figure 4-12 THD of the current in LEC-PCC bus in LEC-PCC mode operation

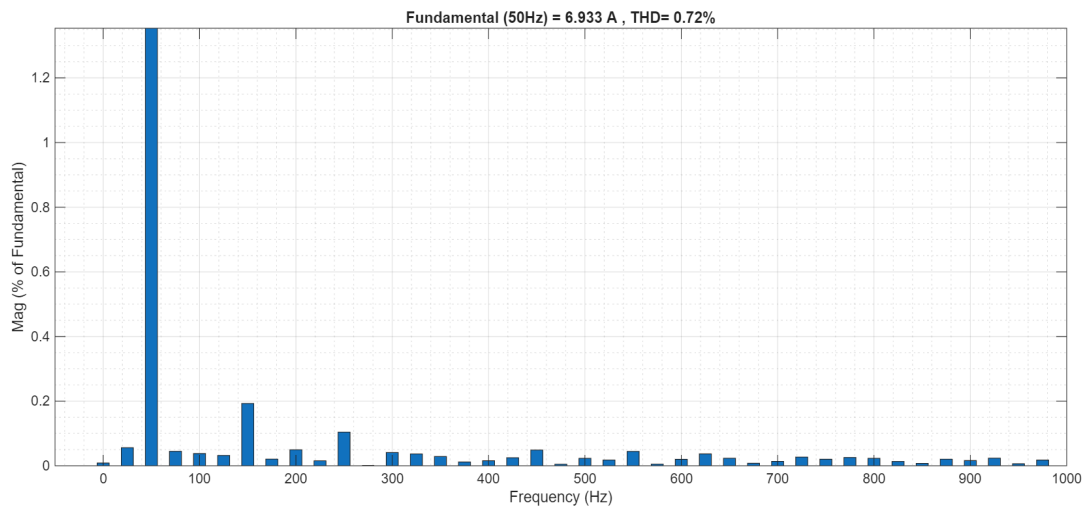


Figure 4-13 THD of the AC-DC converter current of Prosumer 1 in LEC-PCC mode operation

In summary, the developed control strategy integrates fast-acting local controls with intelligent supervisory decision-making controls. This dual-layer framework allows each prosumer to operate independently yet cooperatively, thus ensuring optimal renewable energy usage, smooth transition between operating modes, and enhanced qualitative reliability and resilience across the entire LEC.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

The research presented the design, modeling, and control of a the single-phase MPER for a grid-interactive LEC, based on a novel and straightforward LEC-EMS. The core of the research was to develop and examine of two key concepts: namely, Dynamic Master Prosumer Selection logic and Prosumer-Centric Proportional Power Sharing strategy, both operating on the simple principles of real-time power margin and battery SoC.

The simulation outcomes confirmed that the MPER provides a stable foundation, maintaining DC-bus voltage within $\pm 2\%$ and performing seamless transitions between all operating modes. The LEC-EMS was able to manage operation of a three-prosumer community. When connected to grid in GC mode, it enabled smart economic dispatch with prosumers by injecting peak power at high tariff peak periods and prioritizing battery charging at off-peak durations. In LEC-PCC mode, the system demonstrated its full resilience: the most potential prosumer was dynamically selected as master to form the grid and the excess power was shared among prosumers in proportion to their capacity, which was fair and stable. This decentralized approach was successful to power the critical load of the community, proving the robust and self-organizing model of sharing energy. Furthermore, the system also maintained PQ in complex islanded mode, with current THD at the PCC bus being only 2.05% and current THD at a converter of a prosumer being only 0.72%.

The study indicates the socio-economic applicability of MPER by ensuring the operation of critical community facilities like health posts, schools, street lights, telecommunication offices etc., during grid outages through local clean resources, supporting a sustainable and carbon-neutral community paradigm. This work provides a viable roadmap of enhancing the resilience qualitatively and independence of future community energy systems by demonstrating a fair, decentralized, and economically-conscious system of energy sharing.

Future work will focus on the real-world validation of the proposed MPER system in LEC using hardware-in-the-loop testing, integration of artificial intelligence for predictive energy management, expanding the community scale to the limit of the proposed scheme and finally incorporating hybrid energy storage systems to improve dynamic response of the system and longer lifespan of the storage system. The further

development of such intelligent MPER architectures is essential in the development of resilient, low-carbon, and community-driven power systems of the future.

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APPENDIX A: PUBLICATION NOTIFICATION

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TO WHOM IT MAY CONCERN

This is to formally confirm that the authors listed herein presented their research paper entitled "**Design and Control of a Multi-Port Energy Router for Grid-Interactive Local Energy Community**" during the 4th University Scholar Conference: Engineering, Innovation and Advancements (USC 2025), convened on November 18–19, 2025, at Kathmandu University, Dhulikhel, Nepal.

Authors:

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APPENDIX B: PLAGIARISM REPORT

Sandesh Dhungana

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