

**INTEGRATING PHOTOVOLTAIC SYSTEMS AND SMART MICROGRID
OPTIMIZATION USING NON-DOMINATED SORTING GENETIC
ALGORITHM II**

By

AL-RUBAYE BAQER SALEH MAHDI

**Thesis Submitted to the School of Graduate Studies, Universiti Putra
Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of
Philosophy**

December 2024

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Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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This study explores photovoltaic (PV) system integration and optimization for grid and microgrid applications, emphasizing energy storage and control techniques to improve reliability and efficiency. Two PV systems (250 kW and 1 MW) were analyzed using PI, sliding mode, and MPC control methods. Sliding mode control achieved higher output power levels, while energy storage devices managed power fluctuations effectively. An NSGA-II optimization framework reduced costs, emissions, and energy consumption, validated by MATLAB simulations. A critical challenge in PV system integration lies in the dynamic and static performance of inverter control methods. Ensuring efficient and reliable power delivery under varying conditions necessitates evaluating different control techniques. Comprehensive analysis of PI, sliding mode, and MPC control methods for grid-connected PV systems. Integration of energy storage to address solar variability and peak demands. The development of an NSGA-II optimization framework minimizing costs,

PAR, and CO₂ emissions while improving energy management. Sliding mode control demonstrated superior output power levels. Optimization reduced electricity costs by 19.0%, PAR by 30.7%, and CO₂ emissions by 21.7%. PV systems, particularly in grid-connected configurations, enhance energy reliability and reduce dependency on non-renewable sources. A 250kW system was analyzed using PI, sliding mode, and MPC techniques. Sliding mode control showed higher power output and smoother performance. Similarly, a 1 MW microgrid-connected system tested these methods, with comparable results. The integration of energy storage devices like batteries and DC-DC converters improved system stability, especially under variable solar irradiation and sudden load changes. Energy management strategies allowed batteries to discharge during low solar availability and recharge when supply exceeded demand. Simulink models evaluated a 200 kW PV array with a 380 V grid and 150 kW battery, showing effective grid integration and addressing power shortages. Boost and three-phase inverters enabled efficient power delivery to the grid. An NSGA-II-based optimization methodology for microgrids targeted economic, technological, and environmental goals. By modeling wind speed and solar radiation with beta probability density functions, the approach scheduled power allocation efficiently for residential loads. The framework reduced costs, emissions, PAR, and user discomfort. Three scenarios demonstrated significant improvements in operational metrics, with scenario-3 achieving the best results. MATLAB simulations validated these findings, showcasing reductions in electricity costs, peak-to-average ratios, and carbon emissions. And finally this study underscores the importance of integrating advanced control techniques,

energy storage, and optimization algorithms in PV systems. Sliding mode control and NSGA-II optimization significantly enhance system efficiency and sustainability, offering viable solutions for meeting growing energy demands.

Keyword: Carbon Emission, Hybrid Energy System, Non-Dominated Sorting Genetic, Operating Cost, Smart Grid.

SDG: GOAL 7: Affordable and Clean Energy, GOAL 13: Climate Action



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**MENGINTEGRASIKAN SISTEM FOTOVOLTAIK DAN PENGOPTIMUMAN
MIKROGRID PINTAR MENGGUNAKAN ALGORITMA GENETIK Isih
TIDAK DIDOMINASI II**

Oleh

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Kajian ini meneroka integrasi dan pengoptimuman sistem fotovoltaik (PV) untuk aplikasi grid dan mikrogrid, menekankan teknik penyimpanan dan kawalan tenaga untuk meningkatkan kebolehpercayaan dan kecekapan. Dua sistem PV (250 kW dan 1 MW) telah dianalisis menggunakan kaedah kawalan PI, mod gelongsor dan MPC. Kawalan mod gelongsor mencapai tahap kuasa keluaran yang lebih tinggi, manakala peranti storan tenaga menguruskan turun naik kuasa dengan berkesan. Rangka kerja pengoptimuman NSGA-II mengurangkan kos, pelepasan dan penggunaan tenaga, disahkan oleh simulasi MATLAB. Cabaran kritikal dalam penyepaduan sistem PV terletak pada prestasi dinamik dan statik kaedah kawalan penyongsang. Memastikan penghantaran kuasa yang cekap dan boleh dipercayai dalam keadaan yang berbeza-beza memerlukan penilaian teknik kawalan yang berbeza. Analisis komprehensif PI, mod gelongsor dan kaedah kawalan MPC untuk sistem PV bersambung grid. Penyepaduan storan tenaga untuk menangani

kebolehubahan suria dan permintaan puncak. Pembangunan rangka kerja pengoptimuman NSGA-II yang meminimumkan kos, PAR dan pelepasan CO₂ sambil menambah baik pengurusan tenaga. Kawalan mod gelongsor menunjukkan tahap kuasa keluaran yang unggul. Pengoptimuman mengurangkan kos elektrik sebanyak 19.0%, PAR sebanyak 30.7%, dan pelepasan CO₂ sebanyak 21.7%. Sistem PV, terutamanya dalam konfigurasi bersambung grid, meningkatkan kebolehpercayaan tenaga dan mengurangkan pergantungan kepada sumber yang tidak boleh diperbaharui. Sistem 250 kW dianalisis menggunakan PI, mod gelongsor, dan teknik MPC. Kawalan mod gelongsor menunjukkan output kuasa yang lebih tinggi dan prestasi yang lebih lancar. Begitu juga, sistem bersambung mikrogrid 1 MW menguji kaedah ini, dengan hasil yang setanding. Penyepaduan peranti storan tenaga seperti bateri dan penukar DC-DC meningkatkan kestabilan sistem, terutamanya di bawah penyinaran suria berubah-ubah dan perubahan beban mendadak. Strategi pengurusan tenaga membenarkan bateri dinyahcas semasa ketersediaan solar rendah dan mengecas semula apabila bekalan melebihi permintaan. Model Simulink menilai tatasusunan PV 200 kW dengan grid 380 V dan bateri 150 kW, menunjukkan penyepaduan grid yang berkesan dan menangani kekurangan kuasa. Penyongsang Boost dan tiga fasa membolehkan penghantaran kuasa yang cekap ke grid. Metodologi pengoptimuman berasaskan NSGA-II untuk mikrogrid menyasarkan matlamat ekonomi, teknologi dan alam sekitar. Dengan memodelkan kelajuan angin dan sinaran suria dengan fungsi ketumpatan kebarangkalian beta, pendekatan menjadualkan peruntukan kuasa dengan cekap untuk beban kediaman. Rangka kerja mengurangkan kos, pelepasan, PAR dan ketidakselesaian

pengguna. Tiga senario menunjukkan peningkatan ketara dalam metrik operasi, dengan senario-3 mencapai hasil terbaik. Simulasi MATLAB mengesahkan penemuan ini, mempamerkan pengurangan dalam kos elektrik, nisbah puncak kepada purata, dan pelepasan karbon. Dan akhirnya kajian ini menekankan kepentingan mengintegrasikan teknik kawalan lanjutan, penyimpanan tenaga dan algoritma pengoptimuman dalam sistem PV. Kawalan mod gelongsor dan pengoptimuman NSGA-II meningkatkan kecekapan dan kemampanan sistem dengan ketara, menawarkan penyelesaian yang berdaya maju untuk memenuhi permintaan tenaga yang semakin meningkat.

Kata kunci: Sistem Tenaga Hibrid, Grid Pintar, Kos Operasi, Pembebasan Karbon, Genetik Pengisihan Tidak Didominasi.

SDG: MATLAMAT 7: Tenaga Mampu Milik dan Bersih, MATLAMAT 13: Tindakan Iklim

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TABLE OF CONTENTS

	Page
ABSTRACT	i
ABSTRAK	iv
ACKNOWLEDGEMENTS	vii
APPROVAL	viii
DECLARATION	x
LIST OF TABLES	xiv
LIST OF FIGURES	xv
LIST OF SYMBOLS	xviii
LIST OF ABBREVIATIONS	xix
 CHAPTER	
 1 INTRODUCTION	 1
1.1 Introduction	1
1.2 General Background	4
1.3 Problem Statement	5
1.4 Objectives of Thesis	6
1.5 Research Gap	7
1.6 Contribution	7
1.7 Limitations	9
1.8 Thesis Layout and Organization	10
 2 LITERATURE REVIEW	 11
2.1 Introduction	11
2.2 Energy Systems Challenges	12
2.2.1 Technological Hurdles	12
2.2.2 Limitations of Energy Storage	19
2.2.3 Infrastructure investigated:	24
2.3 Economic Challenges	26
2.4 Market fluctuations	27
2.5 Environmental and Social Challenges	30
2.6 Energy Storage System	38
2.6.1 Configuration of energy storage system	38
2.6.2 Efficiency Model for Energy Storage Systems	39
2.7 Hybrid Energy System Structures (HESS)	40
2.8 Current Challenges and Issues	43
2.9 Critical Issues in Hybrid Energy Systems: In-Depth Analysis and Resolutions	46
2.10 Summary	47
 3 OPTIMAL SELECTION OF CONVERSION, INVERTER AND FILTER	 49
3.1 Introduction	49
3.2 Characteristics of Grid-Connected PV Systems	51

3.3	The DC/AC Inverter Control Techniques in PV System	52
3.4	Controllers Reference Structures	55
3.4.1	abc Reference Scheme	55
3.4.2	dq Reference Scheme	56
3.4.3	$\alpha\beta$ Reference scheme	57
3.5	Maximum Power Point Tracking (MPPT) System	58
3.6	The Proposed Current Controlled System	60
3.6.1	Three Phase Current Controlled Optimization Systems	60
3.6.2	LCL filter with Three Phase Current Controlled Systems	74
3.7	Simulation Results	78
3.8	Summary	86
4	ENERGY MANAGEMENT	88
4.1	Introduction	88
4.2	Configuration of Hybrid System	91
4.3	Energy Management System:	99
4.4	Simulation Results	102
4.4.1	Mode1	103
4.4.2	Mode 2	106
4.4.3	Mode 3	108
4.4.4	Mode 4	110
4.4.5	Mode 5	111
4.4.6	Mode 6	113
4.5	Discussions	115
4.6	Summary	119
5	SMART MICROGRID WITH OPTIMIZATION APPROACHES	121
5.1	Introduction	121
5.2	Overview of Smart Microgrid	126
5.3	System Model	129
5.4	Objective Functions	132
5.5	Smart Grid Constraints Performance and Metrics	133
5.6	Proposed Algorithm	136
5.7	Simulations and Result Analysis	141
5.8	Scenario 1	145
5.9	Scenario 2	149
5.10	Scenario 3	152
5.11	Comparaison Study	157
5.12	Summary	159
6	CONCLUSION AND FUTURE WORK	161
6.1	Conclusions	161
6.2	Suggestions for future work	162
	REFERENCES	164
	BIODATA OF STUDENT	186
	LIST OF PUBLICATIONS	187

LIST OF TABLES

Table	Page
2.1 Compression studies of Unpredictability of Renewable Energy Sources	17
2.2 Compression studies for limitation of energy storage	22
2.3 Infrastructure investigated studies summarization table	25
2.4 Energy market fluctuations summarization table.	29
2.5 Summarization table of environmental and social challenges.	36
2.6 HESS improving intermittent RES [118]	42
3.1 Advantages and disadvantages of the current controller of DC/AC inverter	53
3.2 The proposed PV array specifications	62
3.3 The performance responses of the three controlling methods	85
4.1 PV array specifications	94
4.2 Boost Converter parameters, at duty cycle= $D=0.5$ & Switching Frequency =4 kHz	95
4.3 Comparison between modes 1-6	117
5.1 Summarizes of literature review	125
5.2 Comparison of scenario 1 cost	147
5.3 Comparison of scenario 1 PAR	148
5.4 Comparison of scenario 1 carbon emission	149
5.5 Comparison of scenario 2 cost	150
5.6 Comparison of scenario 2 PAR	151
5.7 Comparison of scenario 2 carbon emissions	152
5.8 Comparison of scenario 3 cost	153
5.9 Comparison of scenario 3 PAR	154
5.10 Comparison of scenario 3 carbon emissions	155
5.11 Comparison of all metric parameters	159

LIST OF FIGURES

Figure	Page
2.1 Micro-grid structure diagram [37]	12
2.2 Typical ESS configurations [107]	39
2.3 ESS Stages	40
2.4 Hybrid energy storage system (HES) integrated with renewable energy sources, including solar and wind energy	41
2.5 Expenses associated with maintenance and technology	44
2.6 Suggestions to solve this problem	45
2.7 The research directions flow chart	46
3.1 The DC/DC and DC/AC conversions diagram [138]	50
3.2 The LCL filter model for a single phase	51
3.3 The abc Reference scheme [151]	56
3.4 The dq Reference scheme [156]	57
3.5 $\alpha\beta$ Reference scheme [160]	58
3.6 Typical P&O MPPT algorithms	59
3.7 250KW three-phase PV grid connected system	61
3.8 The proposed system with the three control DC/AC strategies	62
3.9 DC/AC inverter structure with PI current control technique [166]	66
3.10 DC/AC inverter structure with sliding mode current control technique [165]	68
3.11 MPC current control DC/AC inverter design [166]	74
3.12 1MW three-phase PV grid connected system	75
3.13 Dynamic responses of power for the PV system under changing of weather temperature, radiance and over load conditions	79

3.14	The dynamic responses of current for the PV under the changing of weather temperature, solar radiance and load conditions	80
3.15	The dynamic responses of voltage state for the PV system under many conditions changing	81
3.16	The DC link voltage dynamic responses from the PV system under the changing of many conditions	82
3.17	The dynamic responses of point of common coupling (PCC) voltage and current for MPC technique	83
3.18	The dynamic responses of PCC voltage and current in classical PI current control technique.	84
3.19	The dynamic responses of PCC voltage and current in SMC current control technique	84
4.1	Block diagram of the hybrid system	92
4.2	System Control Diagram	97
4.3	Energy management algorithm	102
4.4	Hybrid System using Matlab/Simulink	103
4.5a	Harmonics of Three Phase Voltage and Current	105
4.5b	The power generated by of the PV system, battery power, and total power of hybrid	106
4.6a	The power generated by of the PV system battery power and total power of hybrid	107
4.6b	The PV power	108
4.7a	The total harmonic distortion THD of voltage	109
4.7b	The power generated by of the PV system battery power and total power of hybrid	110
4.8	Power generated, power of Battery and grid power	111
4.9a	PV power and Battery power	112
4.9b	Harmonics of Three Phase Voltage and Current	113
4.10a	Shows the power generated by of the PV system battery power and total power of hybrid	114
4.10b	Harmonics of Three Phase Voltage and Current	115

5.1	Smart Microgrid	128
5.2	NSGA-II algorithm Steps	137
5.3	The proposed model of the Microgrid operation	140
5.4	Solar intensity and speed of wind	142
5.5	Daily forecast temperatures	142
5.6	Purchased energy cost	143
5.7	Daily battery storage	143
5.8	Overall load demand	144
5.9	The expected RE and ESS charging level	144
5.10	Scenario 1 by NSGA-II	145
5.11	Cost reduction for scenario 1	146
5.12	PAR reduction in scenario 1	147
5.13	Carbon emissions reduction in scenario 1	149
5.14	Cost reduction for Scenario 2	150
5.15	PAR reduction in scenario 2	151
5.16	Carbon emissions reduction in Scenario 2	152
5.17	Cost reduction for scenario 3	153
5.18	PAR reduction in scenario 3	154
5.19	Carbon emissions reduction in scenario 3	155
5.20	UC by PSO	156
5.21	UC by BFA	157
5.22	UC by NSGA-II	157

LIST OF SYMBOLS

α	Alpha
σ	Conductivity
η	Efficiency
φ	Fill factor
Z	Impedance
λ	Lambda
Φ	Magnetic Flux
B	Magnetic flux density
M	Mutual Coupling
Ω	Impedance
ω	Angular frequency
μ	Permeability
ϵ	Permittivity
π	Pie
W	Watts
θ	Line phase shift
P	Pressure

LIST OF ABBREVIATIONS

3Ph	Three-phase
ABC	Artificial bee colony
AC	Alternating current
AI	Artificial intelligence
AMI	Advanced measuring infrastructure
AMI	Advanced metering infrastructure
APOAM	Adaptive perturbation and monitoring algorithm
ATSMC	Adaptive terminal sliding mode control
BARON	Branch and Reduce Optimization Navigator
BD	Bidirectional
BESS	Battery energy storage system
BFO	Bacterial foraging optimization
CCP	Common connection point
CCs	Commercial consumers
CESS	Community energy storage systems
CPISMC	Combined PI and sliding mode control technique
DC	Direct current
DER	Distributed energy resources
DESS	Distributed energy storage systems
DGs	Distributed generations
DISMC	Double integral sliding mode controller
DISMC	Dual sliding mode controller
DO	Disturbance observers
DSM	Demand side management

DWT	Discrete wavelet transform
EM	Energy management
EMS	Energy management system
EREVs	Extended-range electric vehicles
ES	Energy storage
EUCs	Electric utility companies
EVs	Electric vehicles
FC	For excessive
FC	Fuel cell
FESS	Flywheel energy storage systems
FHEVs	Fuel cell hybrid electric vehicles
FPGA	Field-programmable gate array
GA	A genetic algorithm
GA	Genetic algorithm
GEIS	Galvanostatic electrochemical impedance spectroscopy
HAS	Hybrid autonomous system
HESS	Hybrid energy storage system
HESSs	Hybrid energy storage systems
HEVs	Hybrid electric vehicles
HIL	Hardware-in-the-loop
HIL	Hardwire in the loop
ICs	Industrial consumers
ISEMS	Intelligent smart energy management system
ISMC	Improved sliding mode controller
ISMC	Integral sliding mode controller
LCOS	Equal cost of storage
LiBs	Lithium-ion batteries

LOIPs	Layered hybrid organic-inorganic perovskites
MAF	Moving average filters
MAPPO	Multi-agent proximal policy optimization
MC	Monte Carlo
MGTs	Micro gas turbines
MILP	Mixed integer linear programming
MILP	Mixed integer linear programming
MILP	Mixed-integer linear programming
MOGA	Multi-objective genetic algorithm
MOPSO	Multi-objective particle swarm optimization
MOSFET	Metal-oxide-semiconductor field-effect transistor
MPC	Model predictive control
MPC	Model predictive control
MPPT	Maximum power point tracking
NILM	Non-invasive load monitoring
NPV	Net present value
NSC	Nine switch converter
NSGA-II	Non-dominated sorting genetic algorithm II
OGSC	Off-grid self-consumption
P&O	Perturb-and-observe
PAR	Peak-to-average ratio
PCC	Point of common coupling
PDF	Probability density function
PEI	Power electronic interfaces
PHEVs	Plugin hybrid electric vehicles
PHEVs	Plug-in hybrid electric vehicles
PI	Proportional integral

PI	Proportional/integral
PLL	Phase-locked loop
PMSG	Permanent magnet generator
PSO	Particle swarm optimization
PSO	Particle Swarm Optimization
PV	Photovoltaic
PWM	Pulse width modulation
RCs	Residential consumers
RE	Real-world
RE	Renewable energy
RER	Renewable energy resource
RMS	Root-mean-square
RSOC	Reversible solid oxide battery
RTP	Real-time pricing
RVs	Recreational vehicles
SB	Smart building
SCs	Super capacitors
SGAM	Smart grid architecture model
SGSS	Smart grid switching system
SMC	Sliding mode control
SMC	Sliding mode controller
SOC	State of charge
SOC	State of charge
SOC	State of charge
SQP	Sequential quadratic programming
ST-SMC	Super torsional sliding mode control
SVM	Support vector machine

TES	Thermal energy storage system
THD	Total harmonic distortion
THD	Total harmonic distortion
UC	User comfort
UD	Unidirectional
UG	Utility grid
W-CAES	Wave-driven compressed air energy storage
WDO	Wind Driven Optimization
WTs	Wind turbines
P	Active power
Q	Reactive power



CHAPTER 1

INTRODUCTION

1.1 Introduction

Addressing the increasing demand for clean and reliable energy requires the exploration and implementation of advanced technological solutions. The need for inexpensive and sustainable energy solutions is at the forefront of global efforts to reduce environmental impact and ensure safe, long-term energy resources [1]. This chapter introduces the innovative integration of photovoltaic (PV) systems, advanced control techniques, smart microgrid optimization, and other comprehensive strategies that can enhance the efficiency and reliability of renewable energy sources [2], [3], [4]. Chapter one establishes the context for this study, highlighting the urgency and necessity of developing robust sustainable energy systems that meet growing energy demands while addressing pressing environmental challenges [5].

Photovoltaic (PV) Systems: PV systems are crucial in the realm of renewable energy. They convert sunlight directly into electricity using solar cells. The characteristics of PV cells include high efficiency, long lifespan, and low maintenance costs. PV systems have several advantages, such as reducing carbon emissions, providing a clean energy source, and lowering electricity bills. There are different types of PV cells, including monocrystalline, polycrystalline, and thin-film, each with its own benefits and applications.

Monocrystalline cells offer high efficiency and a sleek design, while polycrystalline cells are more cost-effective. Thin-film cells are flexible and can be used in a variety of applications, from large solar farms to small portable devices.

Types of PV Systems: Mainly PV systems are categorized into two primary types which are standalone (off-grid) and grid-connected (on-grid), each with distinct properties and advantages suited to various applications.

Standalone PV systems, often referred to as off-grid systems, are designed to operate independently of the public electricity grid. These systems are particularly beneficial in remote locations where access to the grid is impractical or unavailable. Standalone systems generate and store their own electricity using batteries, which makes them self-reliant and capable of providing power even in the absence of sunlight. This autonomy makes them ideal for applications such as electrifying remote homes, powering recreational vehicles (RVs) and boats, supporting telecommunication sites in isolated areas, and serving as backup power systems during emergencies. For these uses, standalone systems offer a reliable and cost-effective solution, especially where extending the power grid would be prohibitively expensive.

On the other hand, grid-connected PV systems, also known as on-grid systems, are linked to the public electricity grid. These systems have the capability to supply excess power back to the grid and draw power from it when solar energy production is insufficient. This connection to the grid enables net

metering, which allows system owners to receive credits for the electricity they contribute to the grid, thereby lowering their overall energy costs. Grid-connected systems do not typically require battery storage, as the grid itself acts as a backup, balancing the supply and demand of electricity. This issue makes them generally more reasonable to install compared to standalone systems, which need batteries and more complex management systems. Grid-connected PV systems are widely used for powering residential homes, commercial buildings, industrial operations, and urban structure, such as street lighting. They are also central to community solar projects and large-scale solar farms.

When comparing the two PV system types, standalone systems are entirely independent of the grid and rely on battery storage to ensure continuous power availability. This makes them crucial in isolated areas but also more expensive due to the cost of batteries. In contrast, grid-connected systems, which interact with the grid for energy supply and storage, are usually more cost-effective and straightforward to install. They provide high reliability as they can draw from the grid when solar power is insufficient.

The Challenges of PV Systems: Integrating PV systems into the energy grid fetches numerous benefits but also poses challenges. One primary challenge is the variability of solar energy due to weather and time of day [6]. It can employ advanced control strategies designed to improve the stability and reliability of energy outputs from PV systems. Additionally, it explores the concept of smart microgrids-localized energy systems that can operate

independently or in coordination with other microgrids or the main power grid. These smart microgrids are crucial for optimizing energy distribution and use, thus enhancing grid flexibility and sustainability [7], [8], [9], [10].

Integration and Optimization: Combining photovoltaic systems, advanced control methods, and smart microgrids offers a multi-dimensional solution to the energy challenge [11]. It outlines the current landscape of renewable energy technologies, the difficulties faced by traditional grids, and the potential of integrated systems in achieving sustainable energy solutions. By optimizing the interaction between these components and investigating these complex systems, it may provide valuable insights and innovative approaches to the field of sustainable energy [12], [13], [14].

1.2 General Background

The current state of the global environmental conditions is struggling with the adverse effects of the carbon emissions issue, as well as an existential threat necessitating both environmental and energy concerns due to the latter's reoccurrence [15]. In response to these conditions, the technology of the photovoltaic system has emerged as an imperative founding technology, driven by the need to harness solar energy to produce clean energy sources [16]. The deployment of this system has, however, experienced social challenges, including reliable generation, integration, and demand distribution [17], [18]. Advanced measuring and control strategies and micro-grid optimization are necessary conditions for the resolution of these challenges

and criteria to ensure efficient and reliable deployment of the system and any such sources of energy in a more comprehensive energy mix [19].

1.3 Problem Statement

The problem statement can be summarized as the need for innovative solutions that can effectively integrate renewable energy sources with reliable and cost-effective energy storage systems while addressing environmental and social concerns. This includes the development of advanced control techniques, optimization strategies, and materials that enhance the performance and sustainability of energy systems as follow:

1. Controlling how energy moves through large systems. In large PV systems, it will be difficult to control the DC/DC converter and DC/AC inverter stages. Dynamic solar conditions, synchronization with the grid, and scalability issues complicate real-time adjustments and coordination. Advanced control strategies and robust communication protocols are essential for efficient and reliable energy management in such systems.
2. Expanding solar energy systems involves combining traditional methods with advanced technologies that may increase the complexity. Advanced technologies, such as smart inverters, energy storage, and real-time monitoring, introduce new control, communication, and scalability challenges. Proper integration is essential to ensure efficiency, reliability, and adaptability to dynamic energy demands.
3. Solar energy faces challenges in ensuring a reliable power supply due to the variability of PV output caused by changing environmental conditions, limited energy storage capacities, and fluctuating load demands. Balancing supply and demand requires advanced energy management systems, efficient storage solutions, and predictive algorithms to mitigate intermittency and ensure consistent power delivery to consumers.
4. Operating traditional, unoptimized systems can be inefficient, leading to higher costs and increased energy consumption. Transitioning to smart and optimized systems is essential to enhance efficiency, reduce waste, and lower operational expenses, ensuring sustainable and reliable performance.

1.4 Objectives of Thesis

The main objective of this research is to design an optimized PV smart grid system with high efficiency, reliable to address all the challenges.

The objectives of the research are:

1. Evaluate different DC/DC converter control strategies in PV system.

- Compare and analyze the efficiency and reliability of various DC/AC inverter control strategies in three-phase grid-connected PV systems.
- We employed three different DC/AC inverter methods which are (PI, Sliding, MPC) controlling strategies.

2. Improve stability of an advanced control technique by using three different techniques with suitable filters.

- Adding robust EMS that impact the generated energy, storage system, and utilization strategies.

3. Develop a high efficiency PV system with MPPT techniques.

- Investigate EMS that enhances the efficiency of PV systems during normal and abrupt changes.

4. Optimize the operational cost

- With the energy consumption in smart grids.
- Develop optimization strategies to maximize overall effectiveness and sustainability with PV integration into smart grid environments. Like (PSO, PFO and NSGA-II) optimization techniques.

1.5 Research Gap

The research gap identified revolves around the ongoing need for continuous advancements in integrating renewable energy sources with energy storage systems, particularly in enhancing the capacity. Key challenges may include:

1. **Technological Challenges:** Addressing the intermittency and variability of renewable energy sources such as solar and wind, and improving the efficiency and reliability of energy storage systems [20], [21], [22].
2. **Economic Challenges:** Reducing initial investment costs and ongoing operational expenses associated with deploying advanced energy systems. This includes navigating market fluctuations that impact the economic viability of energy projects [23], [24], [25].
3. **Environmental and Social Challenges:** Mitigating the environmental impacts of energy generation and disposal, and overcoming public resistance to certain forms of energy infrastructure [26], [27], [28].

These challenges underscore the critical need for research and development efforts aimed at advancing technologies, optimizing economic feasibility, and addressing environmental and social concerns in the integration of renewable energy and energy storage systems [29], [30], [31], [32].

1.6 Contribution

These contributions underscore advancements in optimizing microgrid and grid-connected PV systems through innovative control strategies, integration of renewable energy sources, and management of energy storage, thereby enhancing efficiency, reliability, and sustainability in energy systems.

1. Analysis of Three-Phase Grid-Connected PV System:

- Analyzed a 250kW expandable three-phase grid-connected PV system using proportional integral (PI), Sliding, and model predictive control (MPC) inverter control techniques. All methods achieved unity power factor with comparable dynamic performance, though the PI method exhibited slightly smoother response. The sliding mode control showed higher output power levels and consistent DC link voltage readings, indicating robust performance under varying grid conditions.

2. Development of 1MW Microgrid-Connected PV System:

- Developed a 1MW three-phase microgrid-connected PV system with PI, Slide, and MPC inverter control methods, each integrated with LCL filters. The systems-maintained unity power factor and met grid and load requirements. The PI method demonstrated smooth responses with low harmonic distortion, while the sliding mode control achieved higher output power levels. MPC ensured accurate and stable DC link voltage levels throughout operation.

3. Integration of Renewable Energy and Energy Management Systems:

- Implemented a system integrating a 200 kW PV array with a 380 V grid and 150 kW battery using MATLAB\Simulink. This system manages low solar irradiation and sudden load changes by dynamically adjusting battery operation (discharge during high demand, charge during excess solar generation). Results demonstrated effective grid integration and ensured reliable power supply under variable solar conditions and fluctuating loads.

4. Optimal Bi-Objective Optimization Methodology for Microgrid Systems:

- Developed a customized methodology using NSGA-II for intelligent microgrid systems. The approach aims to minimize operational costs, CO₂ emissions, peak-to-average ratio (PAR), and energy consumption while enhancing user comfort (UC). Comparative analysis showed significant reductions: electricity costs by 19.0%, PAR by 30.7%, and carbon emissions by 21.7% in scenario-3 compared to an unscheduled case.

1.7 Limitations

The study area involves installing PV systems in the smart grid and hybrid energy systems. Advanced inverter control strategies are built, and energy management systems are developed. Furthermore, optimization algorithms are proposed to ensure the best possible performance for all inverter systems in a smart grid. However, this research has a few limitations. As a result, the technology does not expand to other renewable options, such as wind power or hydroelectric generation. Furthermore, in terms of infrastructure and regulatory support, it might not always be feasible to assume that smart grids will be deployed entirely at every location across the globe.

1.8 Thesis Layout and Organization

The thesis includes five chapters:

Chapter 2: Presents a comprehensive review of hybrid energy systems, highlighting advancements, challenges, and integration methods with an emphasis on storage technologies and their role in enhancing the viability of PV systems.

Chapter 3: Focuses on a comparative study of various DC/AC inverter control techniques, assessing their efficiency and reliability for three-phase grid-connected PV systems.

Chapter 4: Investigates a simple energy management system for a hybrid PV-battery system, evaluating its effectiveness in balancing energy production, storage, and consumption.

Chapter 5: Explores the optimization of operating costs and energy consumption in smart grids, aiming to improve the efficiency and sustainability of the energy infrastructure.

Chapter 6: summarizes the conclusions and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

An energy system is a structured system where energy streams perform specific activities and can be converted into multiples form (energy outcomes). The metric measuring Energy Conversion Efficiency refers to the ratio between energy output and input, which can be smaller or greater than one [33]. In the present-day electricity grids, energy storage systems (ESSs) are gaining prominence as the world transfers towards the future. Various environmental and social factors impact the integration of energy sources ensuring a balance between demand and enhancing grid resilience, energy supply, and reliability [18]. A current expansion in the energy storage field is hybrid energy storage systems (HESSs) which combine ESSs that take advantage of their complementary features to enhance general system performance. HESSs are advanced storage solutions that combine different energy storage systems (ESSs) to enhance performance, efficiency, and cost-effectiveness [34]. These systems as shown in Figure 2.1, which may consist of batteries, super capacitors, flywheels, and pumped hydro storage, provide high power output, fast response times, and the ability to store energy for extended periods [35]. Hybrid energy system modeling is becoming increasingly popular in the field of energy modeling to overcome the drawbacks of traditional top-down and bottom-up models [36].

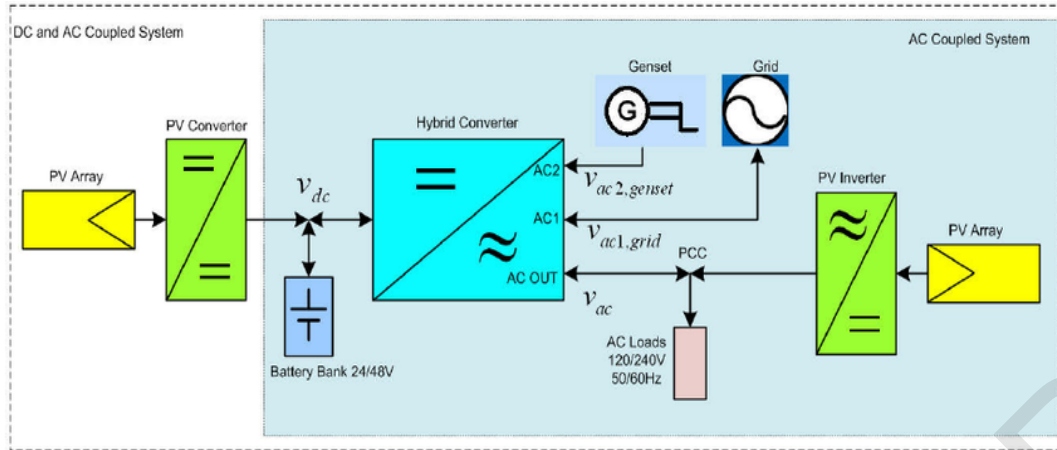


Figure 2.1: Micro-grid structure diagram [37]

2.2 Energy Systems Challenges

Transitioning towards efficient energy systems is a crucial element of contemporary energy strategies. However, this transition comes with its share of obstacles [3]. This section will delve into the difficulties that energy systems encounter in today's landscape.

2.2.1 Technological Hurdles

1. Unpredictability of Renewable Energy Sources:

Sources such, as wind power exhibit intermittency and unpredictability causing fluctuations in energy supply. This intermittent nature poses a challenge, in maintaining an energy grid [38].

Prakash Pawar et al. [39, 2020] proposed an Intelligent Smart Energy Management System (ISEMS) using PSO-based SVM regression for accurate

energy forecasting. IoT integration enabled user monitoring, optimal load scheduling, and secure data analysis based on predicted power and user priorities.

Prashant Singh and J.S. Lather [40, 2020] developed a CPISMC technique to optimize current sharing between the battery and super capacitor, enhancing battery lifespan and DC bus voltage stability. FPGA simulations showed its superiority over traditional methods but did not assess wind and RER variability impacts on battery stress during transients.

Chaouki Ghenai et al. [41, 2020] designed a hybrid off-grid system combining 517 kW solar PV and 750 kW fuel cell technology for a desert community, accounting for high temperatures and dust. The system achieved 40.2% renewable energy usage with 52% from solar PV and 48% from the fuel cell. To meeting a 4.5 MWh daily demand at US\$145/ MWh with zero emissions. However, maintenance challenges from dust and heat were not addressed.

S. Raja Mohamed et al. [42, 2021] designed a hybrid off-grid system combining 517 kW solar PV and 750 kW fuel cell technology for a desert community, accounting for high temperatures and dust. The system achieved 40.2% renewable energy usage, meeting a 4.5 MWh daily demand at US\$145/MWh with zero emissions. However, maintenance challenges from dust and heat were not addressed.

Hocine Guentr et al. [43, 2021] aimed to enhance large-scale electricity storage for better solar and wind integration. They proposed design strategies for HESS using techniques like electrode positioning, linear matrix inequality, PSO, and GA. GA and PSO-based controllers showed superior responsiveness and robustness. The EM strategy handled solar load and radiation variations. However, computational complexity and real-world implementation challenges were not addressed.

Prashant Singh and J.S. Lather [44, 2021] developed a control approach to regulate DC bus voltage in standalone DC microgrids with DESS. The method used a FC for gradual fluctuations and SCs for high-frequency fluctuations, efficiently redirecting excess FC currents to SCs. FPGA-based HIL simulations showed quick, precise voltage adjustments, outperforming conventional methods. However, stability issues from communication failures in real-world scenarios were not addressed.

Alexander Holtwerth et al. [45, 2022] tackled the complexity of scheduling HPS with battery and HS, using MILP formulations for MPC. A new simulation system allowed flexible operating points and data extraction, achieving a 0.234 kW average modeling error. While effective, the model assumed an ideal power grid without power draw restrictions, limiting real-world applicability.

M.D. Morshed Alam et al. [46, 2023] proposed an analytical method to optimize ES in MS by creating a temporal storage profile based on RG and load demand. It maximizes storage use, eliminates wasted capacity, and considers

energy, power limits, and leakage. Two solar-battery case studies showed optimal sizing avoids energy deficits. While useful for energy analysts, the method does not address limitations in forecasting and optimization models, important for real-world applications.

R.M. Nienhuis et al. [47, 2023] introduced the Ocean Battery, an offshore pumped hydro ESS, and developed a model to forecast its performance. Prototype results validated the model, suggesting a larger system could match traditional pumped hydro efficiency. However, the model oversimplified the turbine system, leading to an overestimation of flow rate and inaccurate turbine dynamics.

Han Kun Ren et al. [48, 2023] tackled the challenge of optimizing ES size in MS to maximize usage and minimize inefficiency. They proposed an analytical approach that creates timeline storage pattern, considering energy, power limits, and leakage. Case studies showed that larger storage sizes yield diminishing returns. However, the method's quadratic time complexity with respect to critical points may slow performance as data volume increases.

Soheil Mohseni and Alan C. Brent [49, 2023] proposed a probabilistic model for optimizing hybrid battery/super capacitor systems in microgrids. A New Zealand case study showed that hybrid systems could be 39% cheaper than deterministic models. However, the study lacked methods for addressing uncertainty and long-term investment planning for HESS.

Amir Mohammad Behzadi et al. [50, 2023] enhanced RES with hydrogen storage for peak demand reduction, optimizing energy control using machine learning. Using TRNSYS and the grey wolf optimization algorithm, they achieved energy savings, CO₂ reduction, cost savings, and lower GE use. However, the high initial investment remains a barrier despite the short payback period.

R. Salgado-Pizarro et al. [51, 2023] developed thermal regulation materials using polymorphic layered hybrid organic-inorganic perovskites (LOIPs) for ES and cooling devices. They synthesized LOIP compounds with varying alkylamine chain lengths and analyzed their thermal properties via thermal cycling, DSC, and FTIR-ATR. LOIPs showed no degradation after 200 high-temperature cycles, with longer chains exhibiting the highest enthalpy. However, the study lacked research on material compatibility and morphology for practical use. The above studies can be summarized in the following table 2.1.

Table 2.1: Compression studies of Unpredictability of Renewable Energy Sources

Ref. ID	Challenges	Aim of Study	Method
[39, 2020]	1. Need for reliable and low-cost energy supply due to fossil fuel depletion.	1. Designing an intelligent energy management system. 2. Ensuring accurate forecasting of energy availability, comparing prediction models, and evaluating the system with various configurations. 3. Integrating the IoT environment for user monitoring.	
	2. Growing interest in small rooftop photovoltaic systems.		
	3. Development of accurate prediction models for renewable energy with performance evaluation and parameter tuning.		
	4. Exploration of proposed architecture in real-time energy management, big data analytics, and energy cost solutions.		
[40, 2020]	1. Managing uncertainties and intermittent nature of renewable energy resources.	1. Improve current sharing and voltage stability in energy storage systems.	
	2. Maintaining power demand, voltage stability, and energy storage system lifetime.		
	3. Improving current sharing between batteries and super capacitors.		
[41, 2020]	1. High temperature and dust accumulation affecting solar panels.	1. Design and develop dispatch control strategies for off-grid hybrid. 2. Increasing renewable energy penetration, reducing greenhouse gas emission.	
	2. Optimizing design and control strategies for hybrid off-grid power systems.		
	3. Achieving 40.2% renewable fraction, zero CO ₂ emissions, and a levelized energy cost of 145 \$/MWh.		
[42, 2021]	1. A smart grid switching system (SGSS) is proposed to manage power flow efficiently.	1- Designing and implementing a smart grid switching system (SGSS). 2- Developing a power management algorithm. 3- Ensuring continuous power delivery. 4- Reducing electricity bills. 5- Efficiently utilizing renewable energy sources.	
	2. Ensuring continuous power delivery.		
	3. Reducing electricity bills.		
	4. Utilizing renewable energy sources.		
[43, 2021]	1. Managing unpredictable patterns of energy demand in renewable energy sources (RES) like solar and wind.	1. Developing a robust power management strategy for hybrid electrical energy storage systems (HEES) 2. Comparing control schemes based on transient response time and robustness. 3. Demonstrating the effectiveness of the proposed strategy in photovoltaic (PV) systems.	
	2. Addressing limitations of single electrical energy storage (EES) technologies for diverse applications.		
	3. Developing hybrid electrical energy storage systems (HEES) combining batteries and super capacitors (SCs) to complement battery limitations.		
	4. Designing control strategies for hybrid energy storage systems (HESS) and battery-SC combinations.		
[44, 2021]	1- Addressing the need for centralized power generation alongside renewable energy advancements.	1. Small-signal modeling and stability analysis of autonomous DCMGs. 2. Developing a control method for distributed energy storage systems (DESS). 3. Enhancing DC bus voltage regulation. 4. Improving current-sharing in DCMGs.	
	2- Overcoming regional political challenges in establishing transmission corridors.		
	3- Managing the complexity of DC microgrid (DCMG) systems due to intermittent renewable energy sources (RESs).		
	4- Enhancing power quality and stability with reliance on energy storage.		

Two-stage stochastic mixed-integer linear programming model- Deterministic MILP model

Table 2.1: Continued

[45, 2022]	1- Addressing the nonlinear behavior of electrolyzes and fuel cells.	1- Automated generation of customized models for hybrid energy storage systems (HESS).
	2- Managing volatile electricity generation from renewable energy sources (RES).	2- Development of MILP formulations for steady-state operational behavior.
	3- Reducing the time required for model generation and validation.	3- Utilization of the optimization model for predictive control.
	4- Developing accurate mathematical models for predictive control.	4- Demonstrating model accuracy through a case study.
[46, 2023]	1- High penetration and proper utilization of RES.	1- evaluates the benefits of community energy storage systems (CESS) deployment
	2- Optimization of energy utilization using AI technologies.	2- Reducing daily electricity costs and maximizing PV energy self-consumption .
	3- Provision of subsidies for integrated PV panels.	3- It integrates a deep-learning-based forecasting model with a hybrid optimization technique for optimal control policies and numerical results.
[47, 2023]	1- Modeling pump and turbine dynamics for efficiency analysis.	1- Introduction of a novel offshore pumped hydro energy storage system.
	2- Optimization of devices and systems.	2- Comparison of the Ocean Battery's performance with conventional storage.
	3- Analysis of grid connection and green hydrogen production.	3- Development of an analytical model for pressure and flow predictions.
	4- Addressing anchoring and scour protection.	4- Validation of model predictions with small-scale prototype measurements.
	5- Examining environmental loading, biofouling, and corrosion effects.	5- Estimation of round-trip efficiency.
	6- Integration of underwater energy storage with RES.	
[48, 2023]	1- Renewable intermittency reduces lithium battery life due to usage, time, temperature, and discharge depth.	
	2- The proposed storage sizing algorithm handles non-linear models and optimizes energy storage to meet demand.	1- The study introduces a novel analytical method for determining optimal energy storage size in microgrid systems.
	3- The algorithm calculates critical levels by comparing them with neighboring points, ensuring speed and accuracy.	
[49, 2023]	1- Cost-efficient energy storage technologies are suggested for managing generation and load variability.	1- Investigate impact of preserving model-inherent characteristics in hybrid ESS designs.
		2- Optimize daily system dispatch to narrow reality gaps in hybrid ESS.
[50, 2023]	1- High computation time and investment costs challenge optimization in solar-powered building energy systems.	3- Optimize integration of ESS into grid-connected microgrids.
	2- Improving solar thermal efficiency and reducing heat loss are critical issues.	4- Investigate economics of temporal energy arbitrage using battery banks.
	3- Active and passive energy enhancement approaches are necessary.	1- Develop an Efficient renewable hybridization system.
[51, 2023]	1- Climate change and rising energy demand shift energy storage solutions.	1- Investigates the use of layered hybrid organic-inorganic perovskites (LOIPs) as thermal regulators.
	2- Different materials are needed for efficient energy storage.	2- Analyzes properties based on alkylamine length.
	3- Sensible heat storage, latent heat storage, and thermochemical storage technologies are essential for cooling electronics.	3- Determines phase transition enthalpy stability.
		4- Analyzes crystal, molecular, and thermal properties.
		5- Optimizes performance by selecting alkylamine length.

2.2.2 Limitations of Energy Storage

Currently, the capacity and efficiency of energy storage solutions, which are essential, for balancing supply and demand are relatively limited. The progress, towards developing cost large-scale storage technologies is ongoing [52].

E. Maximiliano Asensio et al. [53, 2020] introduced a control scheme to improve efficiency and prevent battery deterioration in HESS for electric cars, using a low-pass filter and SM. The method effectively maintains battery health but lacks clear guidelines for selecting the filter cutting frequency due to varying vehicle energy demands.

Markus Mühlbauer et al. [54, 2020] evaluated PFCS in a multi-battery ESS using MATLAB/Simulink simulations, finding that PFCS effectiveness varies with energy or load scenarios. However, the study did not explore the impact of heterogeneity on PFCS performance in real-world applications.

Muhammad Kashif Azeem et al. [55, 2020] proposed an adaptive terminal SMC with GA tuning for managing energy in PHEVs with a HESS. The method outperformed traditional controllers in simulations and hardware-in-loop tests. However, it did not address potential limitations of ATSMC in real-world scenarios, such as durability under harsh driving conditions.

Xiuwang Wang et al. [56, 2021] proposed a multi-objective optimization method for home EM using IoT and an enhanced butterfly algorithm, reducing energy costs by 20% daily and improving stability. However, scalability and real-world implementation challenges were not addressed.

Fatima Ez-Zahra Lamzouri et al. [57, 2021] proposed an Improved SMC for managing energy in a wind-solar hybrid system with batteries, outperforming a standard controller under varying conditions. However, the work lacks experimental verification or real-world implementation, relying solely on simulations.

Arunkumar C.R. et al. [58, 2022] proposed a power management system for HESS in DC microgrids with PVS, improving system response and reducing voltage fluctuations. Using variable HESS bandwidth filters and power division control, it minimized DC bus voltage fluctuations, reduced battery strain, and enabled effective super capacitor charging. While performing well in simulations, it lacks empirical verification in real-world environments.

Dario Pelos et al. [59, 2023] compared two HESS configurations for integrating RE into MG: a flywheel battery system and a RSOC/lithium-ion battery system. Both reduced grid dependence by 30% and increased self-consumption by 70%. The flywheel system had a lower LCOS, making it more economically sustainable, while the RSOC system had a higher LCOS. However, the study's economic analysis may not fully capture long-term operational challenges and market volatility.

Alice Tosatto et al. [60, 2023] improved RE usage in District Heating systems by combining large water-based TES with heat pumps (HPs). Their model showed a 6% increase in TES efficiency for insulated tanks and 16% for insulated shallow pits, with CO₂ emissions reduced by 33% and 29%, respectively. However, the simplified approach for estimating the HP's COP may not fully capture real-world complexities.

Reza Sepehrzad et al. [61, 2023] developed the MDMMPC algorithm for power control in an island-based DC microgrid with RE and battery storage, reducing communication requirements through a sequential distributed energy management method. Simulations and HIL testing confirmed its effectiveness in reducing fluctuations and overshooting in the converter. However, the study lacks analysis of connectivity reliability and latency effects on real-world performance. The above studies can be summarized in the following table 2.2.

Table 2.2: Compression studies for limitation of energy storage

Ref.	Challenges	Aim of study	Method
[53, 2020]	1-Hybrid electric storage systems (HESS) facilitate efficient energy exchange. 2-HESS can be classified into passive, semi-active, and parallel active configurations. 3-These configurations require a fast dynamics low-level controller for optimal performance.	1-The study proposes a real-time power-split control strategy for HESS in electric vehicles.	Two-stage stochastic mixed-integer linear programming model - Deterministic MILP model
[54, 2020]	1-Heterogeneity of batteries significantly impacts the analysis of power flow control strategies. 1- Cost and complexity of HESS with three energy storage units (ESUs). 2-Battery's inability to compensate for transients and rapid power variations. 3-Thermal runaway prevention and battery age prediction for lithium-ion batteries.	1-The study analyzes power flow control strategies (PFCS) systematically.	
[55, 2020]	4-Optimal sizing of HESS for efficiency and prolonged storage element life. 5-Combined battery-ultra capacitor (UC) HESS for cost efficiency and enhanced battery life. 6-Limitations of localized control strategies for HESS. 7-Nonlinear nature of mathematical models of hybrid electric vehicles (HEVs). 8-Challenges in stability analysis and control parameter adaptation for HESS. 9-Chattering phenomenon in sliding mode controller (SMC) and need for parameter adaptation.	1-The study focuses on designing and implementing a hybrid energy storage system (HESS) for plug-in hybrid electric vehicles (PHEVs). 2-It develops an adaptive terminal sliding mode control (ATSMC) for the system. 3-Integrates a high-level control algorithm to ensure DC bus and charging voltage stability. 4-Tests the controller using a real-time hardware-in-loop setup.	
[56, 2021]	Using an improved version of the butterfly algorithm. The IoT system uses ZigBee for low energy consumption. Simulation results demonstrate its effectiveness. 1-The study develops an efficient EM strategy for a HS. 2-Addresses nonlinear behavior and improves conventional SMC performance.	The study aims to develop an optimal home EMS focusing on energy consumption cost and user satisfaction, using an improved version of the butterfly algorithm and an IoT system 1-The study develops an efficient EM strategy for a HE. 2-Controls power output to meet demand and extend battery life.	
[57, 2021]	3-Controls the system during power generation regimes, considering battery state. 4-Aims for fast system response and effective control strategies for uncertain dynamic models. 5-Includes experimental validation of the approach.	3-Determines operating modes for wind and PV subsystems. 4-Combines SMC and integral action for robust control. 5-Demonstrates system stability using the Lyapunov function.	

Table 2.2: Continued

[58, 2022]	Improved battery life, and better DC bus voltage regulation.	The study proposes a power management scheme for HESS in a photovoltaic DC microgrid, aiming to improve dynamics, battery life, and voltage regulation.
[59, 2023]	Hybridization of technologies presents both challenges and opportunities, enhancing energy efficiency and device lifespan. It also leads to cost	The reduction of energy withdrawal from the grid and self-consumption, determines the level zed cost of ESS, and examines the impact of market prices and subsidies on HESS profitability.
[60, 2023]	TES systems in DH grids pose technical, economic, and environmental challenges.	The study aims to assess the effectiveness of large-scale thermal ES combined with heat pumps in district heating systems.
[61, 2023]	the need for secondary power controllers to balance generation and consumption, the challenges in power stability and control in grid-connected and islanded MGs, the need for converters and inverters, and the importance of voltage regulation and coordination between converters and ESS units.	The study focuses on EM and control strategies in an islanded DC microgrid, integrating RE sources and battery storage units.

2.2.3 Infrastructure investigated:

The current energy infrastructure is facing challenges due to its aging nature and lack of compatibility with energy sources [62].

Chun Wang et al. [63, 2022] optimized fuzzy control for EV power management using GA, improving energy consumption by 2.6%, 2.4%, and 3.3% at 10 °C, 25 °C, and 40 °C, respectively. The approach enhanced super capacitor reliability and reduced peak current fluctuations but did not address computational complexity or real-time feasibility.

Yifan Yang et al. [64, 2022] explored HESS in EREVs to reduce fuel consumption and extend battery lifespan. Using AVL Cruise and the Rint model, a rule-based strategy cut fuel consumption by 11.33%, while the ECMS strategy caused a 1.61% increase. The Rint model's inaccuracies during pulse currents were noted as a limitation.

Irene Ramón-Álvarez et al. [65, 2023] developed eco-friendly mortar blocks for CSP TES systems, reducing installation volume by 17% and heat exchanger surface area by 29%. The study lacked long-term performance evaluation under real conditions. This work s can be summarized in the following table

2.3.

Table 2.3: Infrastructure investigated studies summarization table

Ref. ID	challenges	aim of study	Method
[63, 2022]	The provided information does not mention a real-time optimization-based strategy.	1-Reduce fuel consumption and prolong battery life in Electric Vehicles 2-Proposing two EM strategies.	Two-stage stochastic mixed-integer linear programming model
[64, 2022]	1-The lack of experimental investigations on thermocline molten salt tanks and the need for pre-heating during commissioning. The lack of competitiveness in concentrated solar power technologies, corrosion issues in molten salt tanks, high CO2 emissions from Portland cement production.	The study focuses on developing and accessing a hybrid steel-concrete tank for thermal energy storage, examining its thermocline performance.	
[65, 2023]		The study investigates thermal energy storage in CSP plants, emphasizing eco-friendly cementations materials.	

2.3 Economic Challenges

Initial investment costs can challenge developing economies transitioning to advanced energy systems [66]. Additionally, high maintenance and technology costs may impede widespread adoption [67].

Seyed Ehsan Ahmadi and Navid Rezaei [68, 2020] proposed a two-tiered EMS for microgrids, using a demand response program to optimize costs and handle uncertainties. Their approach utilizing integer linear programming, improved generation unit performance, reduced costs, and stabilized system voltages.

Soumya Mohanty et al. [69, 2020] designed a Hybrid Autonomous System (HAS) with hydro, photovoltaic, and battery storage, using Nine Switch Converter (NSC) topology. The system maintained voltage and frequency under various load conditions, ensuring uninterrupted power even with SEIG and PV disconnections.

Aqeel Ur Rahman et al. [70, 2020] developed an EMS for HEVs using a fuel cell, battery, and super capacitor controlled by three nonlinear controllers (SMC, ISMC, DISMC). Simulation results showed that DISMC reduced error, minimized chattering, and provided faster adaptation and better long-term stability compared to the other controllers.

Halil İmen et al. [71, 2021] developed a DNN-based NILM model for EM in MG, improving power usage estimation and load identification. Integrated into a residential EMS, the NILM-based system outperformed traditional EMS in cost management and customer satisfaction, with best results using a 0.4 weighting factor to balance losses.

Mahmoud M. Mohamed et al. [72, 2022] used a battery-ultra capacitor system and VSG technology to stabilize RE microgrids. PSO optimized VSG parameters, improving frequency stability and allowing the system to maintain stability during diesel generation interruptions.

Nzube Ntube and Haiyu Li [73, 2023] optimized the sizing of battery ESS in residential solar setups, using mixed integer linear programming and Monte Carlo simulations. Their research demonstrated that accounting for uncertainty results in optimal battery sizing.

Daniel Fernández-Muñoz and Juan I. Pérez-Díaz [74, 2023] optimized day-ahead scheduling for a virtual power plant, using MILP models to manage a Li-ion battery and wind farm. The models were effective with low computational time, influenced by forecasting for secondary regulation reserves.

2.4 Market fluctuations

The market fluctuations can affect the viability of energy projects [75, 76]. It can have an impact, on the energy market due to changes, in policies, subsidies, and commodity prices.

Hesam Fallah Ghavidel and S. Mohammad Mousavi-G [78, 2022] developed a filtered software model for DC-DC converters and used a type-II fuzzy algorithm to manage energy in HS with fuel cells, batteries, and super capacitors. This approach improved voltage stability and power management, reducing steady-state errors in battery charge and superoxide density.

Mustapha Habib et al. [79, 2023] addressed BAS computational limitations in optimizing real-time energy usage and islanding local energy networks to enhance PV share. They proposed an edge computing solution with an optimization-based EMS for a hybrid PV/ESS system. Prototype tests showed feasibility, safety in island mode, and a 6.23% improvement in energy savings over classical EMS. The above studies can be summarized in the following table 2.4.

Table 2.4: Energy market fluctuations summarization table.

Ref. ID	challenges	aim of study	Method
[78, 2022]	1-Rapid changes in power source dynamic response. 2-Uncertainties in EMS rules. 3-DC-bus voltage fluctuations within acceptable range. 4- Battery and super capacitor state of charge maintenance. 5- Current ripple caused by difference between instantaneous and average control models.	dynamic modeling analysis and stable control method for HESS, focusing on avoiding rapid changes in power source dynamic response, ensuring stable DC-bus voltage.	fuzzy algorithm
[79, 2023]	PV power generation fluctuations, ensuring missed power coverage and battery disconnections.	the integration of an edge-based solution into building automation systems, improving data analytics, implementing an optimization-based EMS for PV/ESS hybrid systems.	Optimization-based EMS for PV/ESS hybrid systems.

2.5 Environmental and Social Challenges

Energy systems have a positive environmental impact, but concerns exist over the production and disposal of components like solar panels and batteries [28, 80]. Public opposition to infrastructure like wind turbines can delay projects [81, 82]. Addressing these issues requires coordinated policy, technological, and stakeholder engagement efforts [1, 83].

R. Machlev et al. [84, 2020] reviewed ESS control methods, classifying them as "techniques" and "advanced" approaches. The work highlights ES management challenges and categorizes optimization methods into classical and advanced, emphasizing the rise of stochastic optimization with dynamic programming for complex problems.

Shaharyar Yousaf et al [85, 2020] employed GA and PSO to tune various controllers. Additionally, an intelligent switching algorithm is introduced to ensure cost operation. SMC demonstrates performance in maintaining power stability while PSO proves to be more effective than GA, in optimizing the controllers.

Huy Truong Dinh et al. [86, 2020] presented a HEMS framework that includes particle swarm optimization and binary particle swarm optimization algorithms. The proposed HEMS system resulted in a 19.7% reduction in household energy costs compared to studies while also balancing peak and average energy consumption through multiple objective optimization techniques.

Kamalesh MS et al. [87, 2020] proposed a hybrid control model combining a neural network (NN)-based tuner and SMC to address voltage regulation and current sharing between transformers. The model demonstrated improved performance in controlling voltage and current during transient changes.

Fatima Ez-zahra Lamzouri et al. [57, 2021] developed an ISMC controller for energy management in a hybrid system with wind, solar, and battery storage. The controller ensured system stability, adapting to environmental conditions and outperforming standard SMC in managing energy efficiently.

Peter Sorknæs [88, 2021] explored electric district heating's role in integrating RE, such as wind and solar. Using Energy PLAN, the study found that increasing heat pump capacity facilitates greater integration of variable renewables with minimal impact on total ES costs. Adjusting heat pump and electric boiler capacities influences biomass consumption and renewable integration.

Ridha Benadli et al. [89, 2021] applied sliding mode control SMC to optimize voltage management in a HRES with PV and wind turbines. Combined with an adaptive MPPT tracking algorithm, SMC outperformed conventional PI control, offering better performance, lower harmonic distortion, and improved stability.

Aqeel Ur Rahman et al. [90, 2021] developed a nonlinear ST-SMC controller for hydrogen-based electric cars, reducing hydrogen fuel consumption by 29% compared to FHEVs. The controller's effectiveness and stability were confirmed through Lyapunov analysis and hardware-in-the-loop experiments.

Shubham et al. [91, 2021] addressed frequency stability in an isolated HRES with solar and wind. A PIDF controller improved load frequency control. Simulated in MATLAB, the study showed that the diesel generator and flywheel effectively managed frequency deviations, stabilizing the system with maximum deviations of 0.21 and 0.19 per/unit.

Dogga Raveendhra et al. [92, 2021] introduced a synergistic controller for solar-powered HESS, improving dynamic response, voltage regulation, and charge management over traditional controllers. The system maintained stable DC bus voltage, eliminated chatter, and outperformed PI and SMC.

Shirin Cupples et al. [93, 2021] proposed a two-step optimization to maximize the net present value (NPV) of a grid-connected HRES under real-time grid pricing. The method optimizes hourly load management and system capital costs, achieving up to 45% annual electricity savings through cost-effective power scheduling.

Akash S et al. [94, 2021] developed a fuzzy logic-based EMS for a wind-solar-battery hybrid mini-grid, featuring control algorithms and power converters. The system enhances performance, reduces costs, and supports independent operation and testing of power management strategies.

Ali Jafarian Abianeh and Farzad Ferdowsi [95, 2021] addressed HESS control in DC microgrids with pulsed loads using SMC to regulate battery discharge and enable supercapacitor charging. A rate limiter replaced the low-pass filter

to separate HESS currents. The system outperformed conventional algorithms, ensuring uninterrupted super capacitor charging during transients.

Syeda Shafia Zehra et al. [96, 2022] developed NBF-FOSMC for EM in a DC microgrid with HESS combining hydrogen and electricity, using fuzzy logic to balance power and generation needs.

Xin Wang et al. [97, 2022] proposed a K-ILC strategy with MAF to manage power between super capacitors and batteries in urban rail systems, stabilizing bus voltage and extending battery life. Testing showed convergence after 10 iterations.

Naghmash Ali et al. [98, 2022] proposed DISMC for efficient power management in HEVs using fuel cells, super capacitors, and batteries, with LCC-S for wireless charging. EMS effectively allocates power, validated through Lyapunov stability, MATLAB/Simulink simulations, and real-time trials. DISMC outperformed PID and Lyapunov controllers in precision and tracking.

Xiaoguang Chu [99, 2022] proposed a nacelle suspension strategy for wind turbines using an inverse system and DO to improve tracking and reduce synchronization errors. The method eliminates coupling, ensures fast dynamic response without overshoot, and minimizes synchronization errors, excelling under sudden interference.

M.Y. Ayad et al. [100, 2022] designed a hybrid power supply with a SMC for fuel cells, batteries, and super capacitors, ensuring efficient power management in all modes. Simulations validated the nonlinear slip control principle.

Shujian Ma et al. [101, 2023] proposed a wave-driven compressed air energy storage (W-CAES) system, integrating a heaving buoy wave energy converter with compressed air storage. The system showed improved energy storage efficiency (60.5%) and round-trip efficiency (47.1%), with a 30% higher power output in Tasmania wave conditions compared to traditional wave energy converters.

Sven Myrdahl Opalic et al. [102, 2023] optimized energy costs in a smart warehouse with BESS, TESS, photovoltaic power, and cooling systems using an ARS-ANN algorithm. It improved performance by 30% over ARS and doubled the benchmark algorithm's efficiency with reduced computational resources.

Shahed Motaman et al. [103, 2023] studied thermal performance and wind age loss in high-speed FESS, using ANSYS Fluent to model turbulent Taylor vortices. A 40% pressure reduction resulted in a 20% decrease in flywheel temperature and 30% lower wind age loss, enhancing energy conversion efficiency.

Hao Zhang et al. [104, 2023] proposed RVSF and PCI strategies to balance SOC in distributed energy storage systems, improving capacity usage. Simulations and experiments confirmed the approaches' effectiveness in enhancing system load capacity.

Miguel Robayo et al. [105, 2023] used Discrete Wavelet Transform (DWT) for efficient power management in electric vehicles with batteries and SC. Strategies C and D optimized SC support during driving and braking. DWT predicted power demand, helping SC manage high demand and recovery. The study used a fixed battery and SC size based on the Nissan Leaf without optimizing HESS sizing.

Simone Barcellona et al. [106, 2023] proposed a unified model for electrochemical storage systems, including LiBs, using finite space Warburg impedance to account for diffusion and capacitance. Experimental tests and GEIS measurements validated the model's accuracy, aligning with phase transitions in electrode materials. The above studies can be summarized in the following table 2.5.

Table 2.5: Summarization table of environmental and social challenges.

Ref.	Challenges	Aim of study	Method
[84, 2020]	1-Linear programming needs linear functions, while dynamic programming is widely used . 2-Real-time predictions improve residential energy storage control, and determining optimal PV panel size and storage capacity is crucial.	Recent works on optimal control of energy storage systems focus on identifying suitable optimization methods for different applications, addressing theoretical and numerical challenges, and analyzing trends in both classic and advanced methods.	Two-stage stochastic mixed-integer linear programming model - Deterministic MILP model
[85, 2020]	Not mentioned.	The study aims to analyze and compare controller techniques for optimal control of a smart nano-grid, optimize photovoltaic array, wind turbine, and fuel cell power using GA and PSO algorithms.	
[86, 2020]	1-Over-current protection, dynamic charging/discharging limitations . 2-Battery health and thermal management, overcharging/discharging protection.	- The study aimed to optimize a mixed objective function.	
[87, 2020]	Insufficient voltage regulation leads to transient perturbations, stability issues, and circulating currents, especially during nighttime and sudden battery power supply.	The project aims to create a hybrid control strategy for a renewable energy load bus, enhance voltage regulation and current sharing in multipoint converters, and ensure stability in battery charging applications.	
[88, 2021]	This article covers over-current protection, dynamic limitation on energy storage units, battery system evaluation, overcharging /over-discharging protection strategy.	The study aims to develop an efficient energy management strategy Using a nonlinear sliding mode controller, improve its performance by introducing integral action, and consider battery state of charge.	
[89, 2021]	Over-current protection, dynamic energy storage limitations, battery system evaluation.	The impact of electrification on the district heating sector, compares future energy system scenarios for Austria and Denmark.	
[90, 2021]	This article covers over-current protection, dynamic limitation on energy storage units, battery system evaluation.	The study investigates the application of sliding mode control to a hybrid renewable energy system, focusing on optimal performance of PV and wind turbine generators.	
[91, 2021]	Not mentioned	The project proposes a super twisting sliding mode control for a hybrid energy storage system.	
[92, 2021]	Over-current protection, dynamic limitation on energy storage units, battery system evaluation.	The study involves modeling an isolated hybrid renewable energy system, analyzing frequency change, studying diesel generator efficiency.	
[93, 2021]	This article covers over-current protection, dynamic limitation on energy storage units, battery system evaluation, overcharging /over-discharging protection strategy.	Synergetic control-based controller for a solar-powered hybrid energy storage system in a Remote Area Power system.	

Table 2.5: Continued

[94, 2021]	Solar conversion unable to generate electricity due to low solar irradiation. wind energy and solar PV unavailable in certain cases.	Small-scale hybrid wind-solar-battery microgrid's energy management system.
[95, 2021]	Power quality Challenges in the electricity grid due to power electronics integration.	The study proposes a new control system for hybrid energy storage systems in DC microgrids, incorporating a battery.
[96, 2022]	The controller effectively manages a system with unknown disturbances, preventing overestimation of gains and demonstrating smooth power tracking.	The study aims control system for a hybrid hydrogen-electric energy storage system in a DC microgrid.
[97, 2022]	High energy consumption in urban rail systems. Limited capacity of single energy storage devices	The study proposes a variable gain K iterative learning control strategy for urban rail hybrid energy storage systems.
[98, 2022]	Covers over-current protection, dynamic charging/discharging limitations, battery system evaluation.	The study proposes a double integral sliding mode controller for hybrid electric vehicles.
[99, 2022]	The article focuses on The Challenges of nacelle suspension.	The study aims to examine the suspension of the nacelle for the MWYS.
[100, 2022]	The study explores the use of fuel cells and super capacitors as hybrid power sources.	Designing a sliding mode controller for a hybrid power source structure, incorporating fuel cells, batteries, and super capacitors.
[101, 2023]	This document covers over-current protection, dynamic charging/discharging limitations, battery system evaluation.	The study proposes a novel wave-driven compressed air energy storage system, evaluates its hydrodynamic characteristics.
[102, 2023]	This document covers over-current protection, dynamic charging/discharging limitations, battery system evaluation, overcharging/over-discharging protection strategy, master-slave unit selection.	The study optimizes energy costs in a smart warehouse by controlling battery and thermal energy storage systems.
[103, 2023]	The study uses simplified geometry for numerical analysis, a flywheel designed for light-duty automotive applications.	The study aims to develop a numerical technique for modeling thermal performance and windage loss in flywheel energy storage systems.
[104, 2023]	Over-current protection, dynamic charging/discharging limitations, battery system evaluation, overcharging/over-discharging protection strategy, master-slave unit selection.	This study proposes fast SOC Balancing Control strategies for battery energy storage systems, improving carrying capacity, achieving energy interaction.
[105, 2023]	DWT filtration has disadvantages, is complex, and can cause exacerbated energy circulation.	The study evaluates the role of a super capacitor in hybrid energy storage systems, assesses implementation strategies for a DWT-based energy management system.
[106, 2023]	Parameter estimation errors, current rate, temperature, and lithium-ion diffusion into the electrolyte and electrodes.	The study aims to create a unified model for electrochemical storage systems, extend the existing model for EDLCs and LICs.

2.6 Energy Storage System

Population growth and urbanization have increased energy consumption, emissions, and fossil resource depletion [107]. Addressing these issues requires energy optimization, emission reduction, and clean energy promotion [108,109]. Solar, biomass, wind, tidal, and hydropower are vital, but the intermittency of solar and wind necessitates ESS [110]. Integrating IEEE standard AC1A ESS enables ES during peak production, blackout management, renewable energy integration, and grid stability [111].

Microgrids (MGs) are low/medium voltage systems with loads, DGs, and ESS, optimizing voltage, managing power, reducing emissions, and enhancing demand response [112]. MGs support CHP systems [113], function as utility-managed units [114], and stabilize frequency in grid-linked modes. On islands, DGs and ESSs ensure stable operation despite frequency control challenges [16,115]. MGs enable energy dispatch and storage but face RER costs, ESS optimization, maintenance, regulations, and privacy concerns [116]. MG-ESS integration priorities include energy pricing, emissions reduction, client engagement, and privacy protection [26]. Computer-aided ESS integration improves load management, spinning reserve, and voltage reserve during blackouts or isolation [19].

2.6.1 Configuration of energy storage system

ESS in MGs is categorized into two and distributed types. Figure (2.2) shows constant power flow from DERs to the PCC bus [106]. Aggregated ESS

maximizes storage capacity to reduce power fluctuations but increases costs [94]. Distributed small-scale ESS offers reliable power regulation by integrating directly with sources via PEI [108]. However, PEI introduces harmonics, complicating power network control [96], and causes storage losses in DERs and ESS [109].

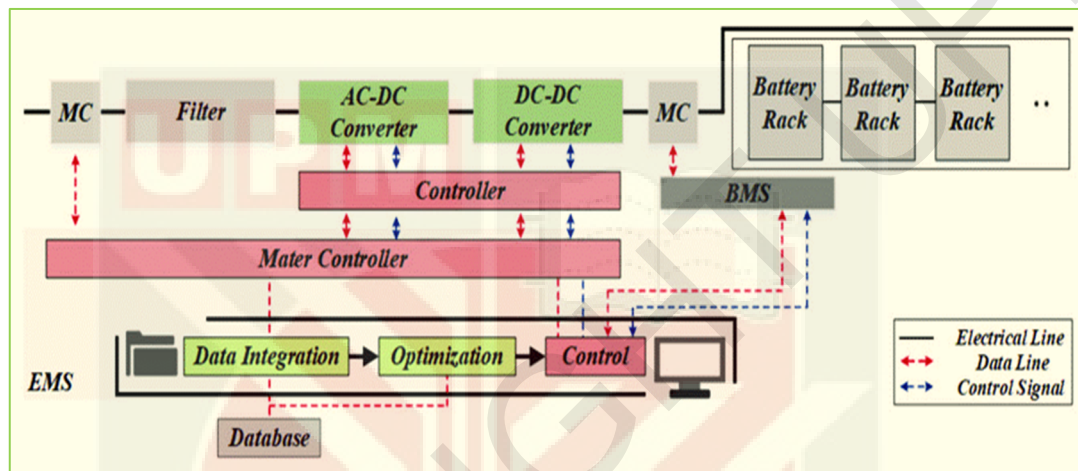


Figure 2.2: Typical ESS configurations [107]

2.6.2 Efficiency Model for Energy Storage Systems

ESS efficiency involves converting electrical energy into another form, such as mechanical energy [110]. The storage process (Figure 2.3) has three stages:

1. Central storage, where energy is stored after conversion [111].
2. Power transition, enabling bidirectional flow between networks.
3. Control, using sensors to monitor charge/discharge levels. Energy losses occur at each stage [112].

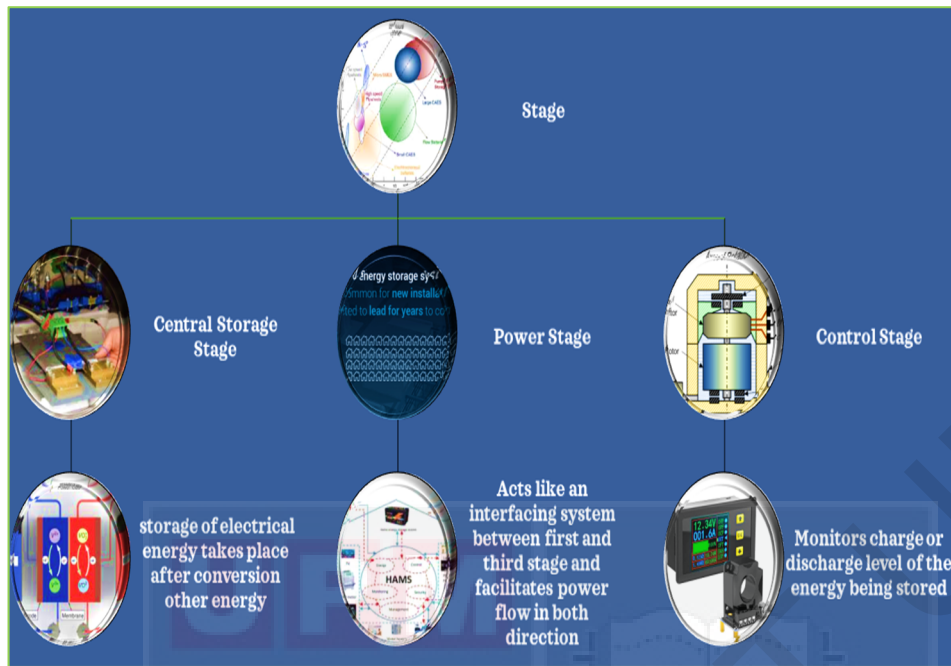


Figure 2.3: ESS Stages

2.7 Hybrid Energy System Structures (HESS)

HESS addresses wind and solar variability [114], combining low- and high-speed reflexes to smooth wind power more effectively than single ESS [115]. A wavelet-based HESS manages short- and long-term wind power changes [116], optimizing battery and SC deployment based on RES power frequency dispersion. SFES with batteries stabilizes large-scale wind farm production more efficiently than batteries alone [113,117,118]. MGs and RESs face challenges like inconsistent power, poor quality, and frequent ESS cycling, which increases costs and reduces lifespan [119]. HESS improves efficiency, reduces costs, and extends ESS lifespan in MGs and RES [120].

HESS (Figure 2.4) integrates ES devices like batteries and super capacitors, selected for energy density and characteristics, converting stored energy to

AC for loads or the grid. Local loads use HESS power, while the grid (P_{grid}) manages excess or deficient power. Solid lines represent power flow; dashed lines indicate control and data flow. HESS maximizes renewable energy use, minimizes grid dependence, and stabilizes supply despite solar and wind variability. The above studies can be summarized in the following table 2.6.

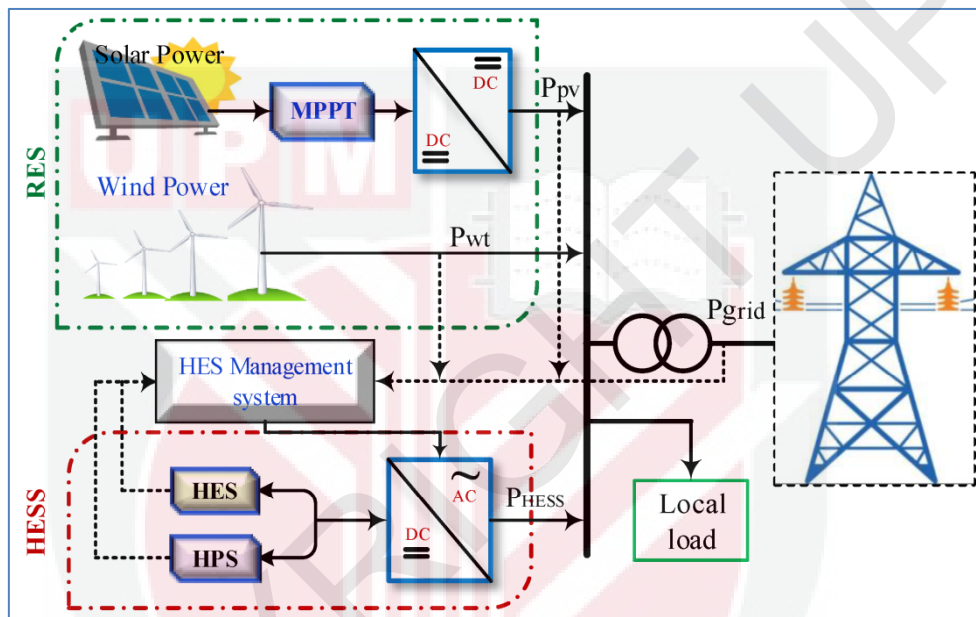


Figure 2.4: Hybrid energy storage system (HESS) integrated with renewable energy sources, including solar and wind energy

Table 2.6: HESS improving intermittent RES [118]

Ref.	MG type	MG Configuration			Energy Sources	Storage Technology	Summarization
		Grid-connected Mode	Islanded Mode				
115	AC/DC	X	✓		✓ Diesel ✓ PV	Bat / Bat	To calculate HESS power, this study divided unbalanced power into time-varying components. PSO was used to optimize HESS capacity. HESS capacity is sized statistically. A frequency management mechanism has also been proposed to control storage output power. This method varies storage system production, load, and discharge timings. PAM is used to construct sizing curves for various time scales. The super capacitor energy controller is utilized in this study to size the capacity of the super capacitor (SC) rather than its voltage. This research calculates HESS capacity utilizing the grid frequency fluctuation and differential evolution. This effort involves sizing HESSs and optimizing multi-attribute combinations. The goal function considers yearly cost, environmental effect, fluctuation smoothing, and safety.
116	AC	X	✓		✓ PV ✓ WT	Bat / SC	
117	AC/DC	X	✓			Bat / SC / FC	
118	AC	✓	X		✓ PV	Bat / SC	
119	AC	✓	X		✓ WT	Bat / SC	
120	AC	✓	X		✓ WT ✓ PV	Bat/SC/flywheel/CASE	

2.8 Current Challenges and Issues

The challenges and problems can be summarized as follows: -

1. Technological Obstacles:

The unpredictable nature of energy sources, such, as wind power poses challenges. Additionally, there are limitations in energy storage capacity and efficiency along with ageing infrastructure that's not compatible with energy sources [122].

- ✓ **Innovation in Energy Storage:** Developing new materials and technologies to enhance the capacity and efficiency of energy storage systems. This includes solid-state batteries, flow batteries, and other new storage solutions [123].
- ✓ **Grid Modernization:** Invest in modernizing the existing electrical grid to be more flexible, flexible, and compatible with renewable energy sources. This includes the integration of smart grid technologies that can dynamically respond to changes in energy supply and demand [124].
- ✓ **Improved forecasting techniques:** Improve forecasting models for renewable energy production, especially wind and solar, to better predict and manage fluctuations in power generation [125].

2. Economic Challenges:

High initial investment costs pose a hurdle in developing economies.

Fluctuations in the market can also impact the feasibility of energy projects.

There are expenses associated with maintenance and technology as shown in the Figure (2.6) below.

Below are some suggestions to solve this problem:

- ✓ **Incentives and subsidies:** Implement financial incentives, such as tax breaks, grants and subsidies, to reduce the initial investment costs of renewable energy projects and technologies [126].
- ✓ **Innovative financing models:** Develop new financing models that reduce financial risks for investors and make it easier for developing economies to adopt renewable energy solutions. This could include green bonds, public-private partnerships, and microfinance schemes [127].
- ✓ **Cost reduction through technology:** Focus on R&D to reduce the cost of renewable energy technologies over time, making them more competitive with traditional energy sources [128].

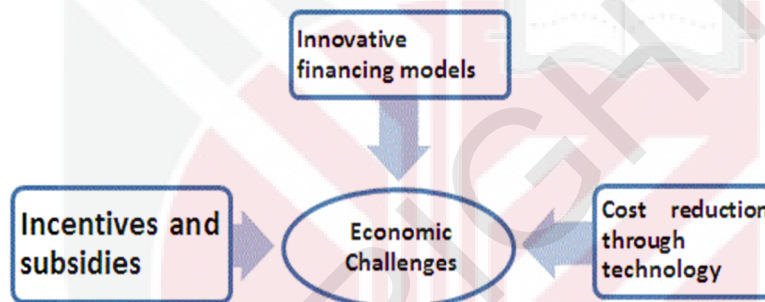


Figure 2.5: Expenses associated with maintenance and technology

3. Regulatory and Policy Challenges:

The lack of policies across regions presents difficulties. Furthermore, policies often lag advancements hindering progress. Below are some suggestions to solve this problem: As shown in the figure (2.7) below.

- ✓ **Coherent policies:** Work to coordinate energy policies at the regional and international levels to create a more coherent framework for renewable energy development [129].
- ✓ **Policy flexibility:** Develop policies that can adapt quickly to technological advances and market changes, ensuring that regulatory frameworks are supported and the latest innovations in the energy sector are fostered [130].

- ✓ **Catalyzing sustainable practices:** Implement regulations that stimulate the sustainable production, use, and disposal of energy components, such as solar panels and batteries, to address environmental concerns [131].

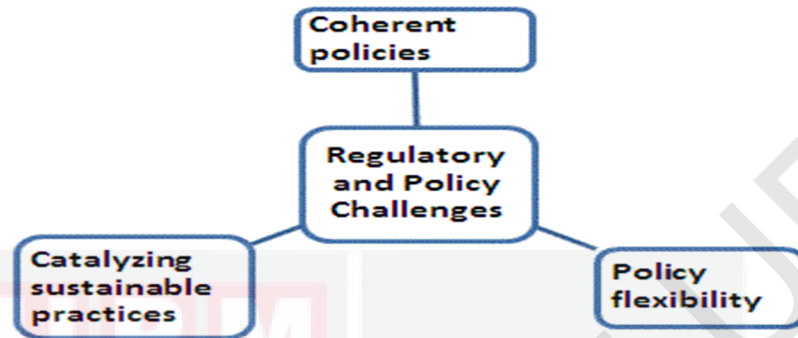


Figure 2.6: Suggestions to solve this problem

4. Social Challenges:

Concerns arise regarding the impact of producing and disposing of components like panels and batteries. Moreover, public opposition, to energy infrastructure projects adds to the challenges faced.

Public Engagement and Education: Increase public awareness and understanding of the benefits and challenges of renewable energy through educational campaigns, community engagement, and transparent communication [132].

- ✓ **Community Projects:** Encourage the development of community-based energy projects that involve local stakeholders in the planning and decision-making process, helping to reduce opposition to new energy infrastructure [133].
- ✓ **Sustainable Production and Recycling:** Invest in thesis and development for more sustainable production methods and energy component recycling technologies to reduce environmental impact and address public concerns about waste [134].

By addressing these issues through a combination of technological innovation, economic strategies, regulatory adjustments, and social participation, it is possible to overcome the challenges facing the energy sector and move towards a more sustainable and resilient energy future [135].

2.9 Critical Issues in Hybrid Energy Systems: In-Depth Analysis and Resolutions

In this section, figure (2.9) suggests the research directions as flow chart, which include.

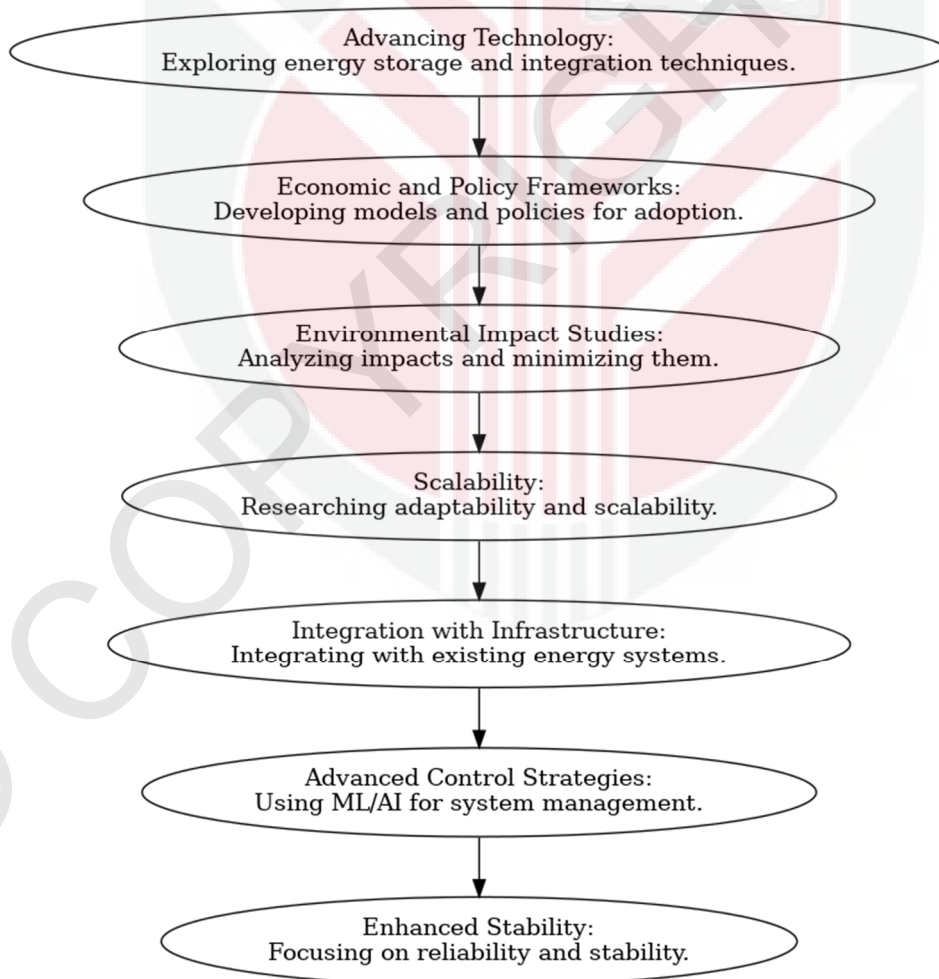


Figure 2.7: The research directions flow chart

These research directions aim to drive progress in the field of energy systems by addressing areas such, as technology advancement, environmental impact, economic support, adaptability, integration, control strategies, reliability and stability.

2.10 Summary

In pursuit of sustainable energy solutions, the integration and optimization of energy storage and optimization (ESS) systems has emerged as pivotal challenges against the backdrop of the intermittent nature of renewable sources and the complex energy requirements of modern infrastructure. The review work delves into the multifaceted dimensions of ESS, highlighting key developments in wave power, smart warehouse optimization, high-speed flywheels, distributed power systems, hybrid energy management for electric vehicles, and accurate modeling of lithium-ion batteries. At the heart of these studies is the challenge of addressing the mismatch between energy supply and demand, which is particularly evident in the use of wave energy due to its intermittent nature. Innovations such as the wave-driven compressed air energy storage system are showing promise, achieving significant improvements in energy storage efficiency. Similarly, smart repositories represent a complex energy puzzle, elegantly handled by the application of enhanced random search algorithms and artificial neural networks, leading to a significant improvement in the costs of Energy. Furthermore, the thermal performance and efficiency of high-speed flywheel energy storage systems are examined under different operational conditions, as the results indicate notable

improvements in energy conversion efficiency through improved pressure and temperature. The rapid balance of charge status in distributed energy storage systems is another frontier explored, where new control strategies offer notable improvements in load capacity usage. Electric vehicles, a fast-growing sector, require efficient energy management between batteries and super capacitors. The discrete wavelet conversion methodology emerges as a powerful approach to managing energy requirements and improving the capabilities of hybrid energy storage systems. Finally, the quest to extend the life and operational efficiency of lithium-ion batteries culminates in a unified electrochemical storage system model, supported by Warburg's space-limited resistance to consider diffusion processes, thereby ensuring good operating conditions and mitigating degradation. The conclusions drawn from the review emphasize the need for continuous innovation and improvement in energy storage technologies. With the developments discussed, the prospects for more efficient, reliable, and cost-effective energy storage solutions stand on a more solid ground, paving the way for a more sustainable and secure energy future.

CHAPTER 3

OPTIMAL SELECTION OF CONVERSION, INVERTER AND FILTER

3.1 Introduction

PV (photovoltaic) systems have many advantages, including flexibility, non-polluting, noise-free operation, low-maintenance, and ease of installation in any location with sun irradiation availability. Customers in many countries are being encouraged to install solar systems in order to support traditional energy sources and enhance the contribution of renewable energy and reduce global warming. The typical layout of a PV based grid connected system needs different transformers, inverters and PV arrays. The transformers convert the voltages to the appropriate value, while the inverters are used to convert the DC to either DC and then to AC voltage (like, multistring inverter) or directly DC to AC voltage (like, central inverter). The central inverter is suitable for the large-scale PV system (around 1 to 100MW) whereas the multistring inverter is used to boost the maximum power point for the solar cell operation. The multistring inverter is more efficient than the central inverter. However, the cost and maintenance of the second type is better. The DC power generated from PV modules is transferred as real power injected into the power grid. MPPT controls the DC/DC conversion that is depending on the environment conditions like temperature and irradiation. Utilizing PWM or SVM technique in the DC/AC part, power transformation and grid synchronization will be done. Different procedures such as current or/ and voltage references and the active

power references can be employed to control the overall system [136], [137].

The complete diagram of DC/DC and DC/AC conversions is as shown in Figure 3.1.

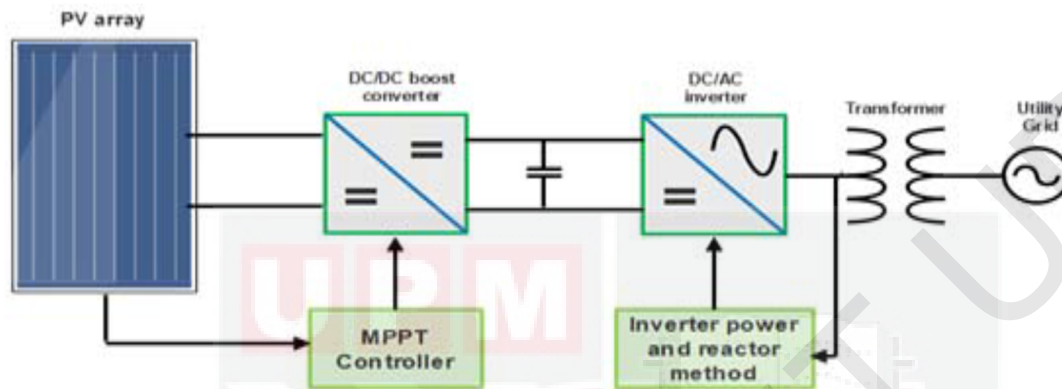


Figure 3.1: The DC/DC and DC/AC conversions diagram [138]

The output voltage waveform is coordinated with the grid voltage. As a result, the utility grid will get ripple current from the PWM inverter. The output LCL filter is used to filter away high-switching frequency components from the inverter's output current. It is connected to the output of the three-phase VSI in order to boost the connection with the utility grid. The ripple current is chosen as a compromise between inductor size, IGBT switching, conduction losses, inductor and core losses. Smaller ripple currents result in reduced IGBT switching and conduction losses, whereas larger inductors result in larger coil and core losses. The ripple current is usually set at (10–25) % of the rated current. Consider a ripple current of 10% at the rated current [139]. The capacitor is selected based on a trade-off between reactive power and coil inductance at fundamental frequency. The larger capacitance, the more reactive power flows into the capacitor, drawing more current from the inductor

and switches, and hence lowering efficiency. Furthermore, a capacitance that is too low is unattainable. Otherwise, the inductance will be high due to the reduced capacitance, and the voltage drop across the inductor will be significant to meet the attenuation requirements. In this design, the reactive power is chosen to be 10% of the rated power [140]. The LCL filter model for a single phase is shown in Fig. 3.2, where L_i is the inverter side inductor, L_g is the grid-side inductor, C_f is the filter capacitor with a series R_f damping resistor, V_i and V_g are the inverter and grid voltages.

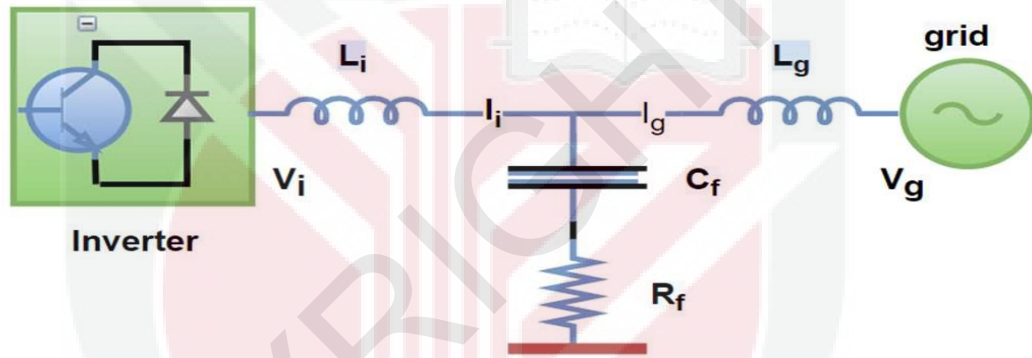


Figure 3.2: The LCL filter model for a single phase

3.2 Characteristics of Grid-Connected PV Systems

Based on numerous PV researches [141], [142], [143], [143], [145], [146], [147], [148], [149], the most essential features of PV grid on systems are:

Almost all existing PV-based inverters are incapable of supplying any reactive power or voltage. As a result, PV systems normally operate at unity power factor, and VAR supplies are handled by the utility. By regular standards, when the voltage/frequency grid deviates from its standard ranges, the inverter

should immediately separate itself from the power grid until returning normal conditions. When the power grid is available, the photovoltaic generators and their inverters must be connected in a parallel arrangement to the general grid, and the loads will be supplied correctly. Moreover, the energy produced by photovoltaic generation will reduce the apparent power demand and then the excess energy will flow into the electrical grid. Many factors related to the environment of PVs including weather, location, day-time and nighttime are crucial and must be taken into account while designing PV systems. There is a lack of coordination between photovoltaic resources and other conventional plants. For very high PV production, the reactive power management for linked feeds is not built correctly. Because of the systems lower cost; it's preferable to work without considering extra energy storage devices. It's challenging to have enough capacity to deploy photovoltaic system auxiliary services. A large-scale solar power system with two stages and a 250KW-1MW three-phase on-grid system was proposed in this thesis. It demonstrated effective electrical management solutions for controlling DC/AC conversion characteristics in order to maintain proper synchronization between the PV side and Grid side.

3.3 The DC/AC Inverter Control Techniques in PV System

The synchronization of designed PV system with main grid and loads is satisfied by designed suitable control mechanisms. The control mechanisms of the DC/AC inverter have been designed in this part to suit the grid and load requirements. In comparison to other types of DC/AC inverters, the three

phase three level NPC voltage source DC/AC inverter with current controlling was chosen because of its numerous suitable technical qualities [150]. The synchronization of designed PV system with main grid and loads is satisfied by designing suitable control mechanisms. Three phase three levels NPC voltage source DC/AC inverter has been used because of its several suitable technical properties compared with other types of DC/AC inverters. The current controller is employed to control the injected power values to the utility grid and loads by adjusting the injected current values according to reference or desired values of the injected currents. Table 3.1 describes the advantages and disadvantages of the current controller of DC/AC inverter.

Table 3.1: Advantages and disadvantages of the current controller of DC/AC inverter

Advantages	Disadvantages
Design: Simple	Voltage regulation: DC-link voltage regulation is required
Static and dynamic response: Stable and fast	Complexity: As stage level increases, the complexity to balance the DC-link rises
Switches voltage rating: Low rating	
Efficiency: High Power output	
control: It has the capacity to give a redundant supplementary ride through facility	

Table 3.1 provides a clear trade-off analysis between simplicity, efficiency, and system control challenges.

1. Advantages: 1. Design: Simple

- Justification: The simplicity of the design reduces development and implementation time, making it cost-effective and easier to deploy. A simpler

design also means fewer components, which reduces failure rates and maintenance needs.

2. Static and Dynamic Response: Stable and Fast

- Justification: Stability and fast response are crucial for maintaining a steady power supply, especially in grid-connected systems. A fast dynamic response ensures that the inverter can quickly adapt to changes in load or input conditions, reducing downtime and improving reliability.

3. Switches Voltage Rating: Low Rating

- Justification: A lower voltage rating for switches means reduced cost and energy losses during switching, making the system more efficient.

4. Efficiency: High Power Output

- Justification: High efficiency translates into maximum energy conversion from DC to AC with minimal losses. This is critical for renewable energy systems where maximizing the available energy is a priority.

5. Control: Redundant Supplementary Ride-Through Facility

- Justification: This ensures the system can maintain operation even during short power interruptions or faults. This feature is critical in improving system reliability in areas with unstable grids.

Disadvantages:1. Voltage Regulation: DC-Link Voltage Regulation Required

- Justification: Controlling the DC-link voltage adds complexity to the system. If not managed properly, fluctuations in DC voltage can cause instability in the power output.

2. Complexity: Balancing DC-Link as Stage Level Increases

- Justification: As the system expands or more stages are added, balancing the DC-link voltage becomes increasingly complex. This can require more sophisticated control strategies and additional hardware.

3.4 Controllers Reference Structures

Grid-connected inverters generally use a variety of control approaches. According to the reference kinds, these approaches can regulate and measure the reference control parameters current or voltage. They are divided into three types depending on the stage levels: single, double, and triple stage systems. These controller types are briefly illustrated as:

3.4.1 abc Reference Scheme

In abc reference approach as shown in Figure 3.3 where each phase grid current is separated without any transformation and applied directly to control the synchronization. The type of connections (star or delta), necessity be taken into consideration while designing this controller [151], [152], [153], [154], [3], [155].

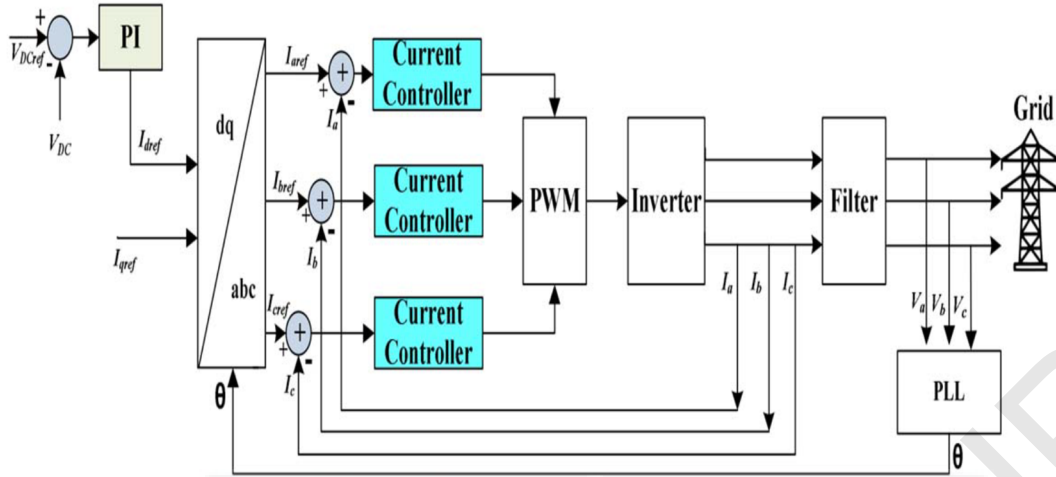


Figure 3.3: The abc Reference scheme [151]

3.4.2 dq Reference Scheme

The three-phase (abc) current and voltage are converted into synchronous current and voltage components (I_d / V_d and I_q / V_q) using Park transformation as shown in equations (1), (2). The control variables are transformed from the sinusoidal domain into reference coordinate system (dq0 coordinates) which can easily be controlled and filtered with good steady state output values as shown in Figure 3.4. [156], [157], [158], [159]

$$[Park\ Matrix] = [P] = \sqrt{\frac{2}{3}} \times \begin{bmatrix} \cos(wt) & \cos(wt - 120^\circ) & \cos(wt + 120^\circ) \\ -\sin(wt) & -\sin(wt - 120^\circ) & -\sin(wt + 120^\circ) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (3.1)$$

$$\text{Where, } \begin{bmatrix} X_d \\ X_q \\ 0 \end{bmatrix} = [P] \times \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \quad (3.2)$$

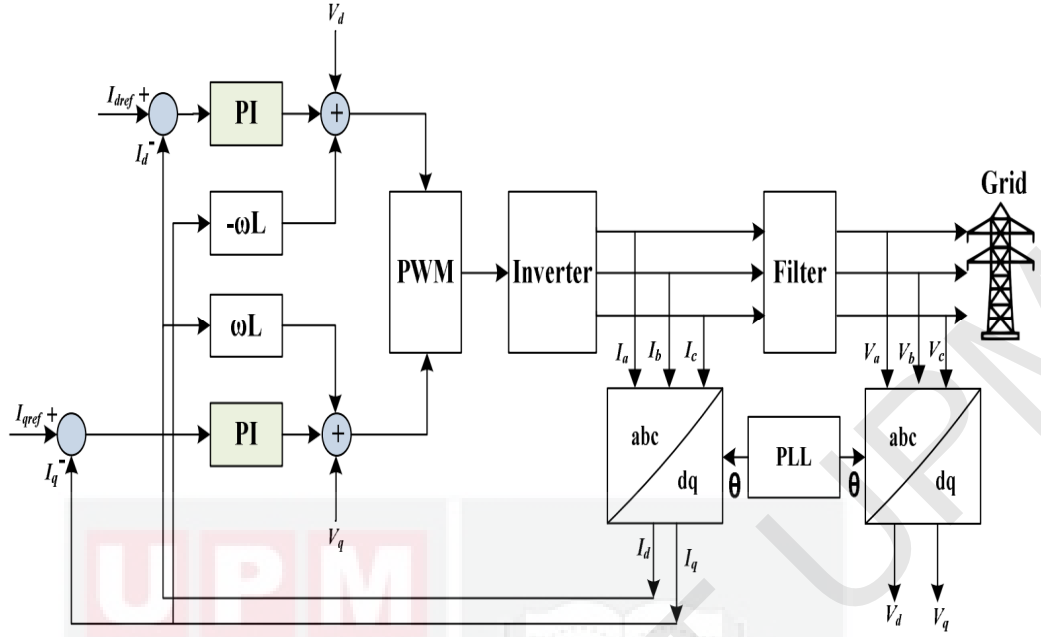


Figure 3.4: The dq Reference scheme [156]

3.4.3 $\alpha\beta$ Reference scheme

In this reference frame, the three phase currents (I_a , I_b , and I_c) and voltages (V_a , V_b , and V_c) are altered into angle $\alpha\beta$ variables (I_α and I_β) and (V_α and V_β) using a Clark transformation respectively. It works in both three-phase and single-phase systems. The Clark transformation has symmetrical form as in equations (3-4): [160], [161], [162]

$$[\text{Clarke Matrix}] = [C] = \sqrt{\frac{2}{3}} \times \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (3.3)$$

$$\begin{bmatrix} X_{\alpha_inv} \\ X_{\beta_inv} \end{bmatrix} = [C] \times \begin{bmatrix} X_{a_inv} \\ X_{b_inv} \\ X_{c_inv} \end{bmatrix} \text{ and } \begin{bmatrix} X_{\alpha_grid} \\ X_{\beta_grid} \end{bmatrix} = [C] \times \begin{bmatrix} X_{a_grid} \\ X_{b_grid} \\ X_{c_grid} \end{bmatrix} \quad (3.4)$$

Although the hardware of the $\alpha\beta$ frame is complex as shown in Figure (3.5), the control variables are converted easily into two stable sinusoidal quantities, which can reduce the steady-state errors and achieve a high gain around resonance frequency (f_r).

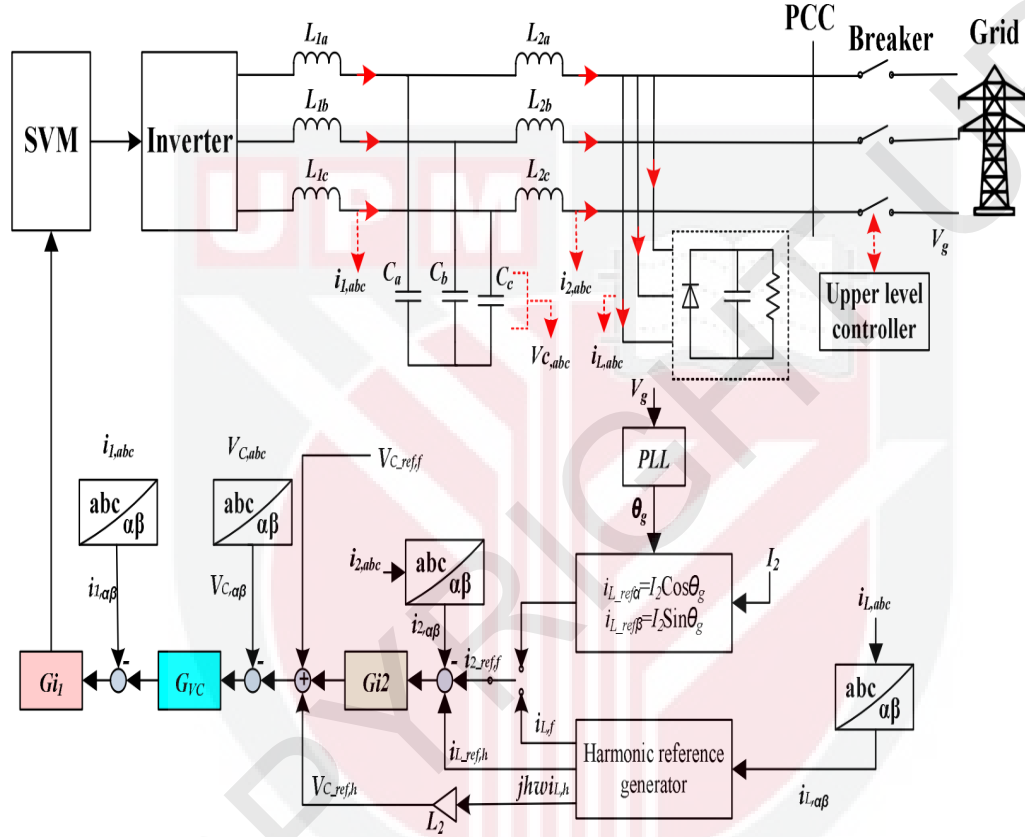


Figure 3.5: $\alpha\beta$ Reference scheme [160]

3.5 Maximum Power Point Tracking (MPPT) System

The efficiency of solar panels is very low. Moreover, the PV voltage and current is time-variant and depend on the irradiation quantity and environment temperature. As a result, it's crucial to keep track of the solar modules' maximum power point and operate at that level. Perturb-and-observe (P&O)

[163], [164], one of numerous MPPT algorithms that can maximize the power point, is the most extensively used algorithm due to its simplicity and ease of implementation. Figure 6. shows the flowchart for the P&O algorithm. It changes the duty cycle (D) by small increasing or decreasing duty cycle step size (ΔD) and then measuring the change in PV power (P). If $P > 0$, the operating point has moved closer to the maximum power point MPP, and thus the duty cycle has been perturbed further in the same direction; otherwise, the direction has been reversed. Until the MPP is reached, this process is repeated on a regular basis.

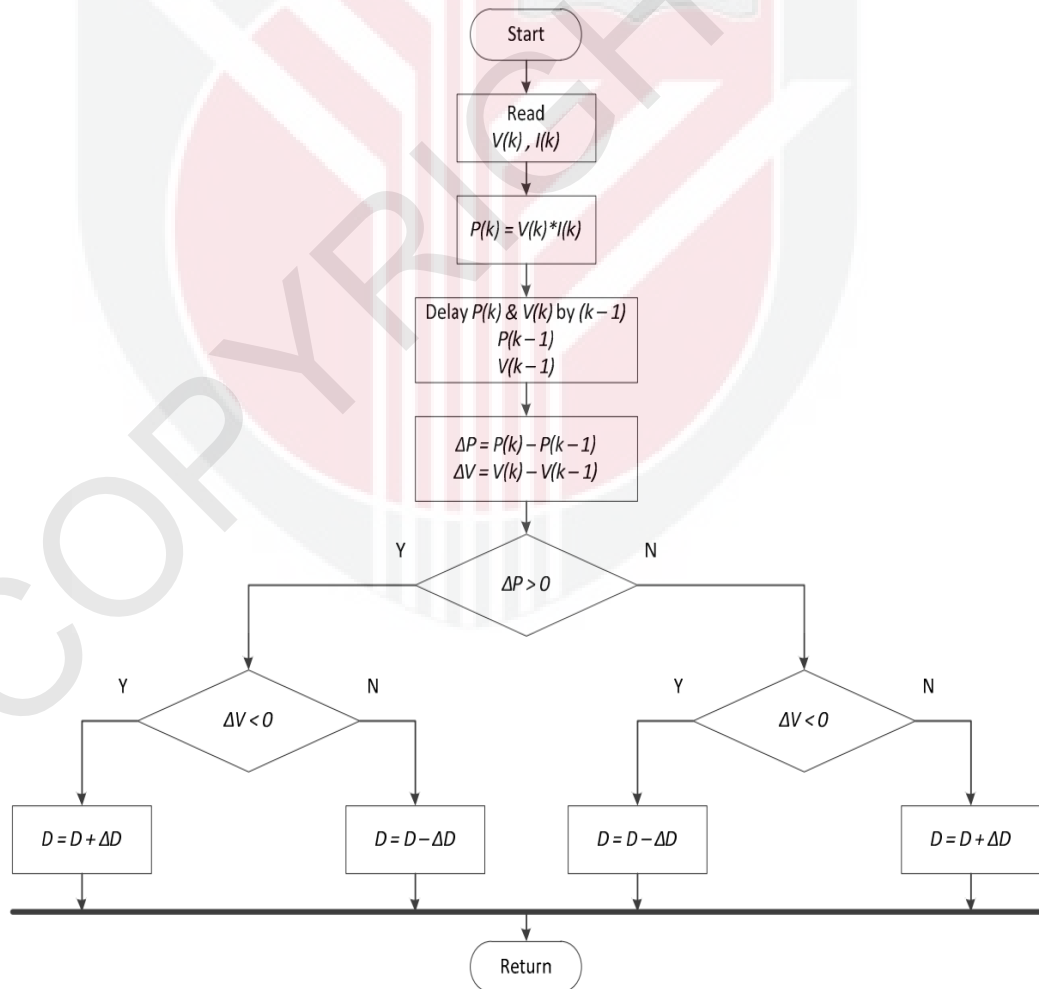


Figure 3.6: Typical P&O MPPT algorithms

3.6 The Proposed Current Controlled System

The proposed current controlled system is divided into two implemented sub-systems, the first handles the optimization techniques that can control the resultant voltages, currents, and powers utilizing three different control nature approaches which are Proportional Integral (PI), Sliding Mode Control (SMC), and Model Predictive Control (MPC), while the second part handles how to choose and connect the appropriate LCL-filter to these three approaches.

3.6.1 Three Phase Current Controlled Optimization Systems

The simulations were conducted on a single PV array controlled by a DC-to-DC boost converter using a duty-based P&O method, as well as a DC/AC inverter with various current control strategies. All simulations were performed in the MATLAB/SIMULINK environment. Three different DC/AC inverter control mechanisms were proposed, implemented, and compared, as illustrated in Figure 3.7. These mechanisms include three-phase, three-level NPC current control techniques employing Proportional-Integral (PI) control, sliding mode control, and discrete-time Model Predictive Control (MPC). The PV setting is illustrated as in Table 3.2. The simulation setup incorporated local environmental data from PV systems in Iraq, including irradiation, temperature, rise time, and other relevant parameters. These inputs were critical for modeling realistic operating conditions and ensuring the simulations accurately reflect the challenges and behavior of PV systems in this region. The dataset used provided insights into typical variations in environmental conditions and

their impact on system performance, enabling a comprehensive evaluation of the proposed control strategies. In Iraq, solar irradiation ranges from 5.5 to 6.5 kWh/m²/day annually, with peak summer values reaching up to 8 kWh/m²/day. Ambient temperatures vary from 35–45°C in summer to 10–20°C in winter, with module temperatures typically 20–30°C higher. Sunrise occurs around 5:30–6:00 AM in summer and 7:00–7:30 AM in winter. Other factors include moderate to high dust accumulation, wind speeds of 1.5–5 m/s, and low humidity in desert regions. These parameters influence system performance and can be incorporated into simulations for accurate modeling.

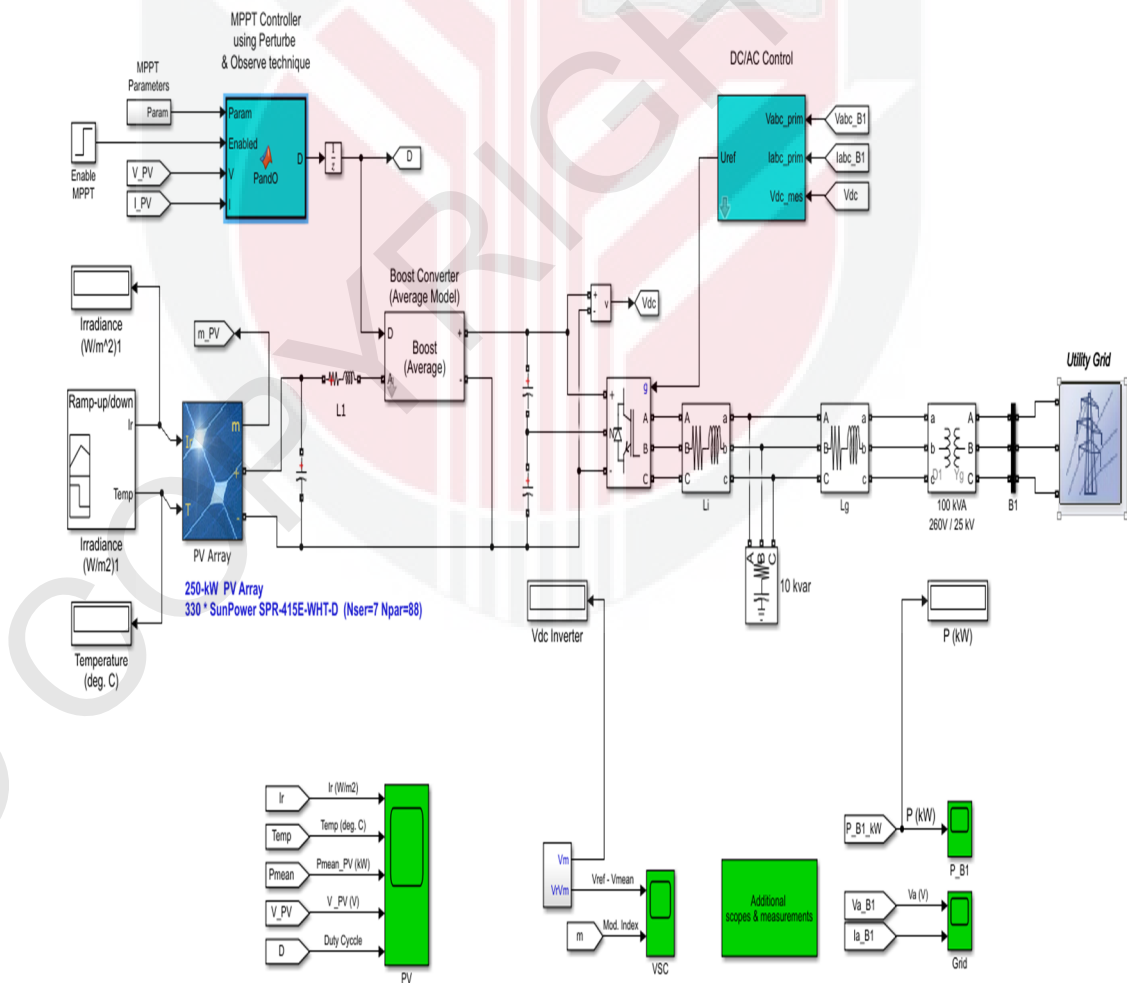


Figure 3.7: 250KW three-phase PV grid connected system

Table 3.2: The proposed PV array specifications

Parameters	Value
No. of Series Panel	7
No. of Parallel Panel	88
Maximum power of panel	405 W
Max. PV voltage	30 V
Max. PV current	13.5 A
DC link voltage	400 V

The whole grid connected PV system with the control mechanisms can be illustrated as in Figure 3.8 below:

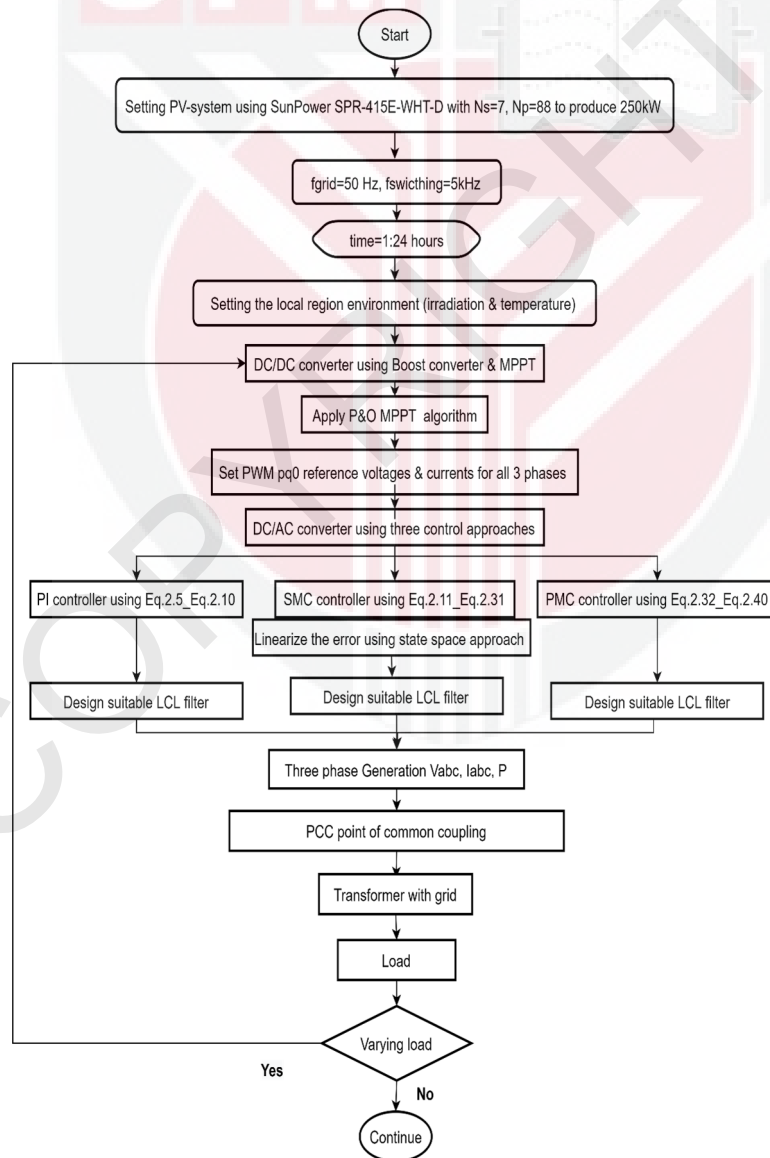


Figure 3.8: The proposed system with the three control DC/AC strategies

Figures 3.7 & 3.8 illustrate the design and operation of a 250kW grid-connected photovoltaic (PV) system, highlighting key components, control strategies, and processes. The system begins with the setup of Sun Power SPR-415E-WHT-D modules configured with 7 modules in series ($N_s=7$) and 88 parallel strings ($N_p=88$), producing 250 kW capacity. Key parameters such as grid frequency ($F_{grid}=50$ Hz) and switching frequency $f_{switching}=5$ kHz are defined, with simulations run over 24 hours. Environmental conditions, including solar irradiation and temperature, are set to reflect real-world operations that were collected from real Iraqi dataset. The DC output from the PV modules is processed using a boost converter, where the Perturb and Observe (P&O) MPPT algorithm dynamically adjusts to maximize power output based on the algorithm of Figure 3.6. A d_q -reference frame transformation is employed to generate three-phase reference voltages and currents, while a Pulse Width Modulation (PWM) scheme provides precise switching signals. The DC/AC converter operates under three control strategies that are drawn on the top right of Figure 3.7 with green box and labeled with DC/AC Control. These control techniques are widely explained in the next sections as: Proportional-Integral (PI) Control to minimize steady-state error, Sliding Mode Control (SMC) for robustness against system nonlinearity, and Model Predictive Control (MPC) to optimize future states, each employing state-space linearization for enhanced response. LCL filters are designed for all control schemes to suppress high-frequency harmonics and improve power quality. The system generates key three-phase outputs, including voltages (V_{abc}), currents (I_{abc}), and power (P), which are monitored continuously. These outputs are connected to the point of common coupling

(PCC), where the PV system integrates with the grid. A transformer adjusts voltage levels for compatibility, delivering power to the load while accommodating varying load conditions through adaptive control mechanisms. The process ensures efficient, stable, and reliable system operation, enabling seamless energy transfer between the PV system, grid, and load under dynamic scenarios.

3.6.1.1 Proportional Integral (PI) Current Control Technique

The main objective of PI current controller is to control the injected power values to the utility grid and loads by adjusting the injected current values according to the reference or desired values of the injected currents. Figure 3.9 illustrates the complete PI control structure of the DC/AC inverter with LCL filter. It should be mentioned that before applying the Park's transformation, the phase of the utility grid has to be attained by using PLL mechanism [165], [166]. According to almost all current controlled systems, the first control loop is the DC voltage regulator step. The difference between the measured DC voltage and the reference DC voltage is used to determine the reference active current value I_{d_ref} which is then passed through proportional integral control loop. The injected active and reactive power can be calculated in dq frame as:

$$P = V_d I_d + V_q I_q \quad (3.5)$$

$$Q = V_q I_d + V_d I_q \quad (3.6)$$

Where V_d , V_q are the dq voltages at the point of common connection, I_d , I_q are the dq components of the injected current. The grid frequency was locked on

via a phase locked loop, and V_q was set to zero [167]. The corresponding active and reactive power values are also written in dq coordinate system as;

$$P = V_d I_d \quad (3.7)$$

$$Q = V_d I_q \quad (3.8)$$

Which means that if the V_d is quite constant, I_d and I_q can govern the real and reactive power injections from the PV array. I_d is controlled to follow a defined direct reference current I_{d_ref} to be able to inject real power from the inverter, the quadrature reference current I_{q_ref} is set to zero in order to make the reactive power equal to zero and provide a unity power factor. The reference or control voltage are assigned according to equations (9 and 10) below for generating switch pulses to control DC/AC inverter as [168]

$$V_{d_ref} = K_P (I_{d_ref} - I_d) + K_I \int (I_{d_ref} - I_d) . dt - \omega L I_q + V_d \quad (3.9)$$

$$V_{q_ref} = K_P (I_{q_ref} - I_q) + K_I \int (I_{q_ref} - I_q) . dt + \omega L I_d + V_q \quad (3.10)$$

Where K_P and K_I are the PI controller constants.

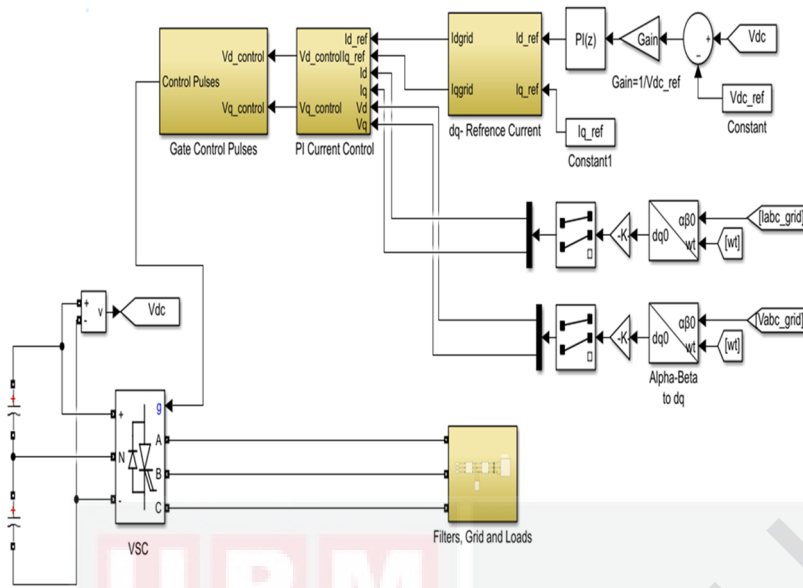


Figure 3.9: DC/AC inverter structure with PI current control technique [166]

3.6.1.2 Sliding Mode Current Control Technique (SMC)

The sliding mode control (SMC) approach can be used to control a three phases grid connected PV system effectively. It has a large capacity for disturbances and a robust response in steady state outputs [169]. Figure 3.10 shows the entire structure of the three phase three level sliding mode current control grid connected DC/AC inverter. There are two control loops, the first is the outer control loop that is also identified as voltage controller which is used for generating reference injected current in the grid side, and hence active and reactive reference power and the second is the inner control loop, also known as the current controller, which was designed involving the sliding mode current control technique. The system has three phases, each phase with two sides (inverter and grid) and three terminals (inverter, grid and filter). It may demonstrate the following using the basic principle of electrical circuit basis: Inverter terminal and for phase a:

$$L_i \frac{di_{a_inv}}{dt} = V_{a_inv} - V_{a_fil} \quad (3.11)$$

Grid terminal and for phase a:

$$L_g \frac{di_{a_grid}}{dt} = V_{a_fil} - V_{a_grid} \quad (3.12)$$

Filter terminal and for phase a:

$$C_f \frac{dv_{cap}}{dt} = (I_{a_inv} - I_{a_grid}) = I_{a_cap} \quad (3.13)$$

$$\text{Where, } V_{a_fil} = V_{cap} + (I_{a_inv} - I_{a_grid}) \cdot R_f = V_{cap} + I_{a_cap} \cdot R_f \quad (3.14)$$

The (abc) natural coordinate system is converted to the (dp) rotating reference coordinate system for ease of use after performing Park's transformation.

Inverter side:

$$\begin{bmatrix} \dot{I}_{inv_d} \\ \dot{I}_{inv_q} \end{bmatrix} = \frac{1}{L_i} \left[\begin{pmatrix} V_{inv_d} \\ V_{inv_q} \end{pmatrix} - \begin{pmatrix} V_{cap_d} \\ V_{cap_q} \end{pmatrix} - \frac{3}{2} \omega L_i \begin{pmatrix} -I_{inv_q} \\ I_{inv_d} \end{pmatrix} \right] \quad (3.15)$$

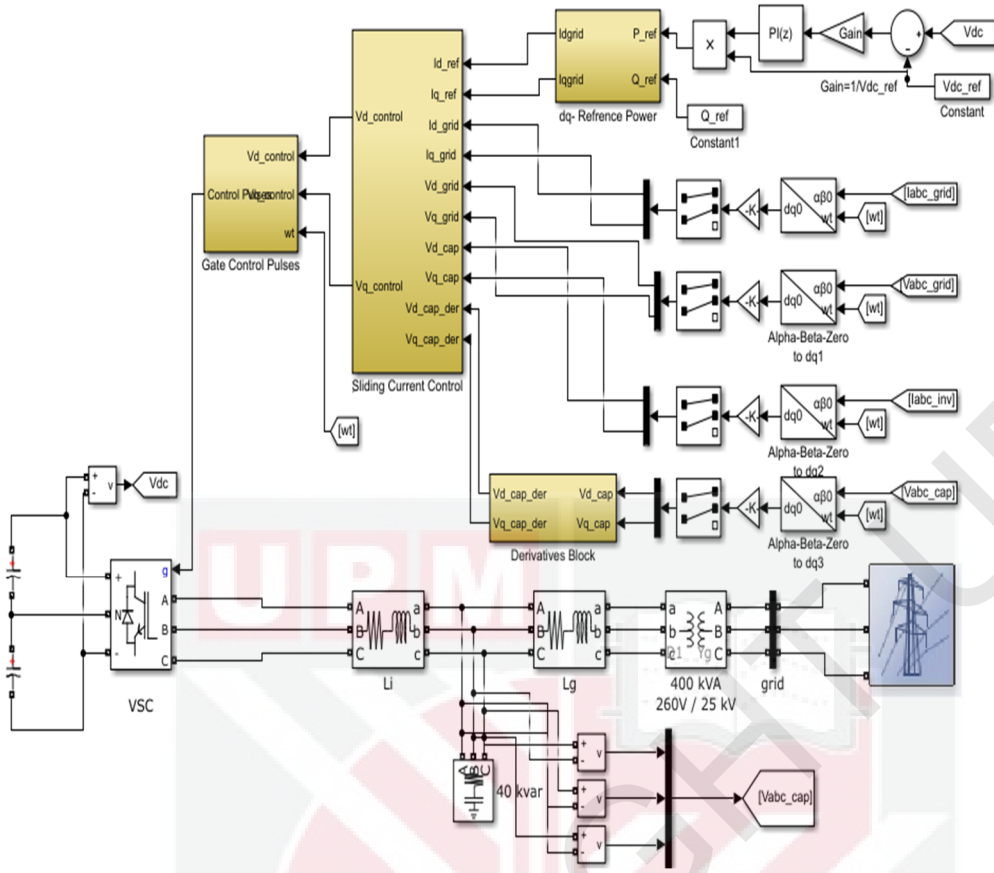


Figure 3.10: DC/AC inverter structure with sliding mode current control technique [165]

Grid side:

$$\begin{bmatrix} \dot{I}_{grid_d} \\ \dot{I}_{grid_q} \end{bmatrix} = \frac{1}{L_g} \begin{bmatrix} (V_{cap_d} - V_{grid_d}) - \frac{3}{2} \omega L_i (-I_{grid_q}) \\ (V_{cap_q} - V_{grid_q}) - \frac{3}{2} \omega L_i (I_{grid_d}) \end{bmatrix} \quad (3.16)$$

Filter terminal:

$$\begin{bmatrix} \dot{V}_{cap_d} \\ \dot{V}_{cap_q} \end{bmatrix} = \frac{1}{C_f} \begin{bmatrix} (I_{inv_d} - I_{grid_d}) - \frac{3}{2} \omega L_i (V_{cap_q}) \\ (I_{inv_q} - I_{grid_q}) - \frac{3}{2} \omega L_i (-V_{cap_d}) \end{bmatrix} \quad (3.17)$$

The grid side or the injected reference active and reactive power is obtained by employing a voltage controller in the dq0 coordinate as follows:

$$P_{REF} = \frac{3}{2} [V_{grid_{d_{ref}}} \cdot I_{grid_{d_{ref}}} + V_{grid_{q_{ref}}} \cdot I_{grid_{q_{ref}}}] \quad (3.18)$$

$$Q_{REF} = \frac{3}{2} [V_{grid_{q_{ref}}} \cdot I_{grid_{d_{ref}}} - V_{grid_{d_{ref}}} \cdot I_{grid_{q_{ref}}}] \quad (3.19)$$

According to the unity power factor, $I_{grid_{q_{ref}}}$ and Q_{REF} are adjusted to zero, thus

$$I_{grid_{d_{ref}}} = \frac{2}{3 \cdot V_{grid_{d_{ref}}}} \cdot P_{ref} \quad (3.20)$$

Sliding mode control technique has nonlinear control mechanism [170], it can depend on the errors (e) and their derivatives ($\dot{e}$ and $\ddot{e}$) that are result from an appropriate sliding with

$$S_1 = c_1 e_1 + c_2 \dot{e}_1 + c_3 \ddot{e}_1 = 0 \quad (3.21)$$

$$S_2 = c_1 e_2 + c_2 \dot{e}_2 + c_3 \ddot{e}_2 = 0 \quad (3.22)$$

Where the c_1 , c_2 and c_3 are positive constant values.

The errors e_1 and e_2 can be assigned as:

$$e_1 = I_{grid_{d}} - I_{grid_{d_{ref}}} \quad (3.23)$$

$$e_2 = I_{grid_{q}} - I_{grid_{q_{ref}}} \quad (3.24)$$

To satisfy the stability and convergence criteria, S_1 and S_2 are set to zero and their derivatives $\dot{S}_1$ and $\dot{S}_2$ are set to zero as:

$$\dot{S}_1 = c_1 \dot{e}_1 + c_2 \ddot{e}_1 + c_3 \dddot{e}_1 = 0 \quad (3.25)$$

$$\dot{S}_2 = c_1 \dot{e}_2 + c_2 \ddot{e}_2 + c_3 \dddot{e}_2 = 0 \quad (3.26)$$

The $\dot{e}_1$ is calculated as:

$$\dot{e}_1 = -I_{grid_q} = -\left[\frac{V_{cap_d}}{L_g} + \frac{3}{2}\omega I_{grid_q}\right] \quad (3.27)$$

The $\ddot{e}_1$ is calculated as:

$$\ddot{e}_1 = -\left[\frac{V_{cap_d}}{L_g} + \frac{3}{2}\omega I_{grid_q}\right] \quad (3.28)$$

The $\ddot{e}_1$ is calculated as:

$$\ddot{e}_1 = I_{grid_q} \left[\frac{1}{L_g C_f} + \frac{9}{4}\omega^2 \right] - \frac{3\omega}{L_g} V_{cap_d} - \frac{I_{inv_d}}{L_g C_f} \quad (3.29)$$

It can calculate $\dot{e}_2$, $\ddot{e}_2$, and $\ddot{e}_2$ by the same procedure, thus the general control values for d and q components are proved as:

$$V_{d_control} = \left[\left[\frac{V_{cap_d}}{L_g} + \frac{3}{2}\omega I_{grid_q} \right] \left[\frac{1}{C_f L_g} + \left(\frac{3}{2}\omega \right)^2 \right] - \frac{3\omega}{L_g} V_{cap_d} - \frac{V_{d_control} + V_{cap_d}}{L_i L_g C_f} - \frac{3\omega}{2C_f L_g} I_{inv_q} + MS_1 + \text{sign}(S_1) \right] L_i L_g C_f \quad (3.30)$$

$$V_{q_control} = \left[\left[\frac{V_{cap_q}}{L_g} - \frac{3}{2}\omega I_{grid_d} \right] \left[\frac{1}{C_f L_g} + \left(\frac{3}{2}\omega \right)^2 \right] - \frac{3\omega}{L_g} V_{cap_d} - \frac{V_{d_control} + V_{cap_d}}{L_i L_g C_f} - \frac{3\omega}{2C_f L_g} I_{inv_q} + MS_2 + \text{sign}(S_2) \right] L_i L_g C_f \quad (3.31)$$

Where $M = \frac{2}{3 \cdot V_{grid_q_ref}}$

SMC is a nonlinear system as compared to the PI control which is a linear system. The SMC method has been linearized by approximating the nonlinear system around a steady-state equilibrium point using small-signal perturbations. Here, we first identify the nonlinear terms, such as the S-functions and higher-order derivatives of errors like $\dot{e}_1$, $\ddot{e}_1$, and $\dddot{e}_1$. Assuming the system operates close to a steady state, where errors are small, then approximate these nonlinear terms by treating the $\text{sign}(S)$ function as a constant (e.g., $\text{sign}(S) \approx 1$) and simplifying the higher-order derivatives to linear terms. The control law, which involves the inverter, grid, and filter voltage and current references, is linearized by expressing these references as linear functions of the state variables (currents and voltages) in a state-space form, where the system's state (currents and voltages) evolves over time based on control inputs. This state-space model, expressed as $\dot{x} = Ax + Bu$, where the matrix A represents the system's internal dynamics, describing how the state variables (like currents and voltages) evolve based on their current values and matrix B represents how external control inputs, such as injected reference currents or voltages, influence the state variables. As a result, the state space model simplifies the analysis and allows for the use of traditional linear control methods like PI control or state feedback. The result is a linearized system that is easier to analyze and control.

3.6.1.3 Model Predictive Control (MPC) Technique

Although model predictive control (MPC) is one of many current control techniques, it has many advantages, including efficient ability to track

reference voltage and current to meet the needs of the utility grid, fast dynamic response, easy implementation, less sensitivity to disturbances, and good capability of handling the nonlinearities of power system plant. The discrete time model predictive with limited switching states current control approach was employed as finite state model predictive control. The MPC algorithm determines predicted voltage and current values based on these finite sets of switching states. MPC mode current control grid connected DC/AC inverter for three phase's three levels is implemented as in Figure 3.11. In this model, the state variables are the current of the grid side inductor and the voltage of the filter capacitor. The inverter side then estimates the current values utilizing first order Euler forward approximation in the DC-AC inverter. The producing active reference power and current, as well as the corresponding reactive reference power and current, are adjusted depending on the difference between the reference and predicated DC link voltages, as with the sliding approach. In each terminal of the three phase's three levels NPC DC-AC inverter, there are four controllable switch points. After identifying the switching states, the inverter output voltage values are determined by calculating the DC link voltage, which is represented by VDC, by one switching condition of the switching states [171], [172].

$$V_{ph_inv} = V_{DC} \cdot S \quad (3.32)$$

At the inverter and filter capacitor sides, the state variables can also be created using Kirchhoff's voltage law as:

$$V_{ph_inv} = L_i \frac{dI_{ph_inv}}{dt} + R_f \frac{dV_{cap_ph}}{dt} + V_{cap_ph} \quad (3.33)$$

$$V_{ph_inv} = L_i \frac{dI_{ph_inv}}{dt} + R_f (I_{ph_inv} - I_{ph_grid}) + V_{cap_ph} \quad (3.34)$$

Using the simplest form of the first order Euler forward equation as follows, the incremental change in inverter side currents can be predicted:

$$\frac{dI}{dt} \approx \frac{I_{inv}(k+1) - I_{inv}(k)}{T_s} \quad (3.35)$$

Where, T_s is the sampling time. So, equation (36) can be formed as:

$$V_{ph_inv} = L_i \frac{I_{ph_inv}(k+1) - I_{ph_inv}(k)}{T_s} + R_f (I_{ph_inv}(k) - I_{ph_grid}(k)) + V_{cap_ph} \quad (3.36)$$

Employing Clark transformations, the dynamic model equation of the three phase three level NPC grid connected DC-AC inverter with LCL filter system is written in stationary reference coordinate system (coordinates) as in general form. The dynamic model equations of the three phase three level NPC grid are stated in stationary reference coordinate system (coordinates) using Clark transformations as:

$$V_{\alpha_inv} = L_i \frac{dI_{\alpha_inv}}{dt} + R_f (I_{\alpha_inv} - I_{\alpha_grid}) + V_{cap_a} \quad (3.37)$$

$$V_{\beta_inv} = L_i \frac{dI_{\beta_inv}}{dt} + R_f (I_{\beta_inv} - I_{\beta_grid}) + V_{cap_b} \quad (3.38)$$

The predicted inverter side currents have been obtained by using this first order Euler forward approximation as

$$I_{\alpha_predicated}(k+1) = I_{\alpha_inv}(k) + \left(\frac{T_s}{L_i}\right) [V_{\alpha_inv}(k) - V_{cap_ph}(k) - R_f (I_{\alpha_inv}(k) - I_{\alpha_grid}(k))] \quad (3.39)$$

$$I_{\beta_predicated}(k+1) = I_{\beta_inv}(k) + \left(\frac{T_s}{L_i}\right) [V_{\beta_inv}(k) - V_{cap_ph}(k) - R_f (I_{\beta_inv}(k) - I_{\beta_grid}(k))] \quad (3.40)$$

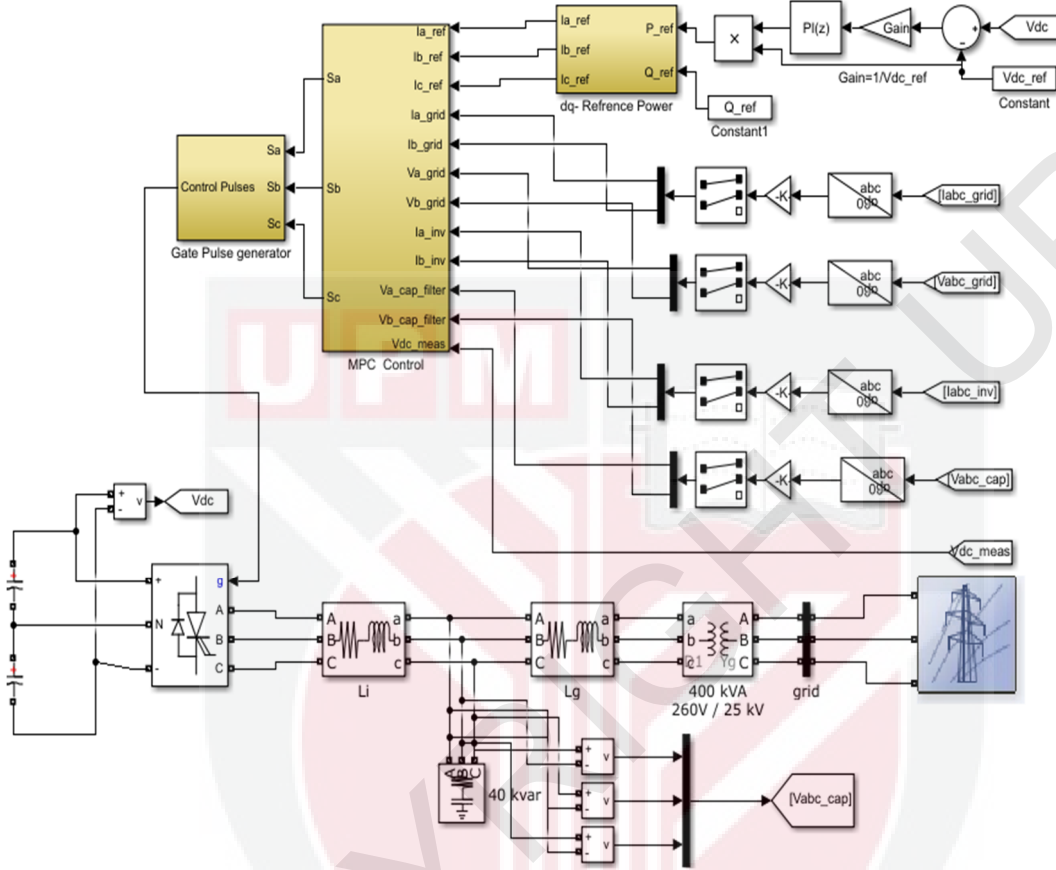


Figure 3.11: MPC current control DC/AC inverter design [166]

3.6.2 LCL filter with Three Phase Current Controlled Systems

Fig. 3.12 shows the system configuration for the grid connected photovoltaic (PV) inverter with LCL filters. PV panels are connected to the grid with three phase voltage source inverters. The total system includes inverter and grid inductances as well as a filter resistance, and capacitance. IGBTs are semiconductor devices that are used extensively for the inverter switching. PCC (point of common coupling) is the circuit breaker to connect or disconnect

the PV system to the grid. There are many DC-AC inverter current control techniques. Three different approaches of three phase three levels of DC-AC inverter control mechanisms are proposed, implemented and compared.

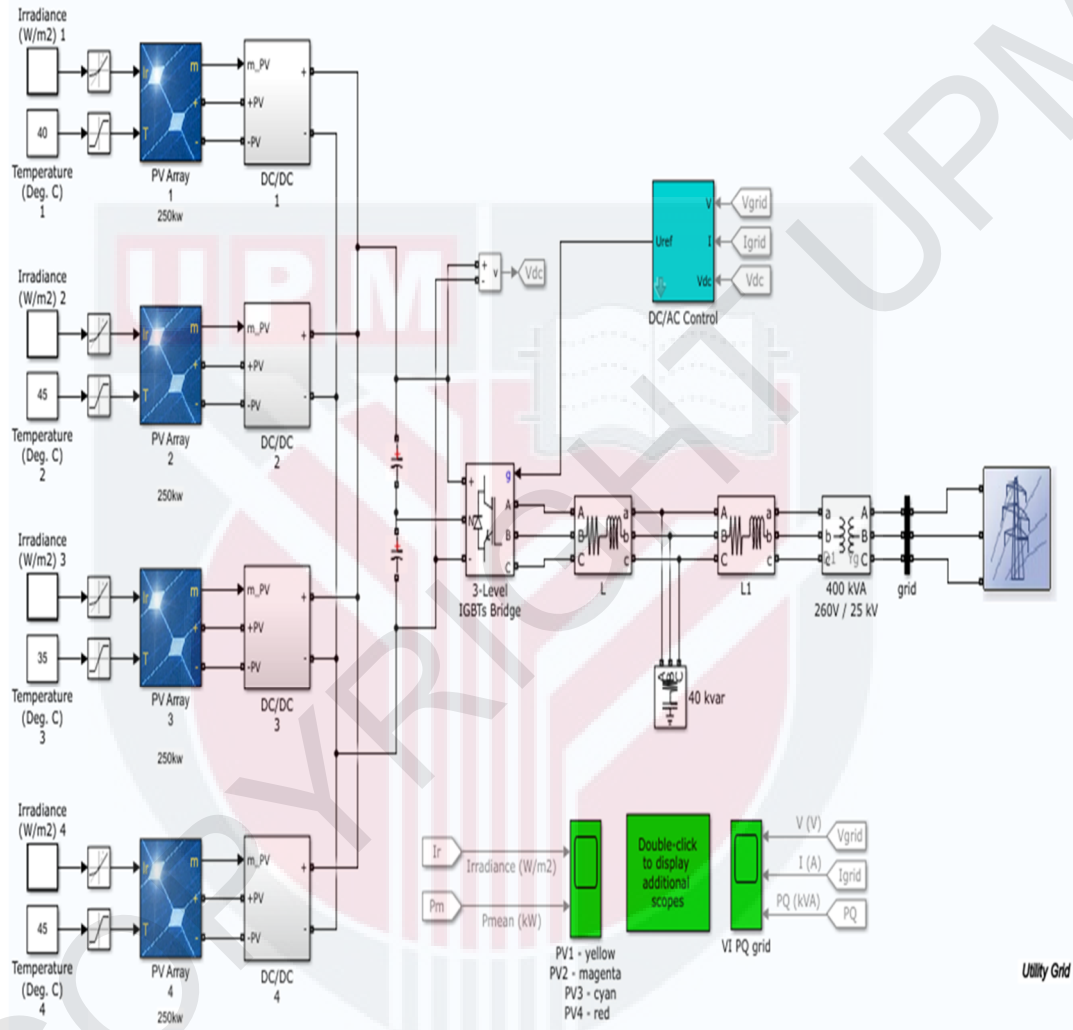


Figure 3.12: 1MW three-phase PV grid connected system

Depending on following system parameters:

$$P_n = 1\text{Mw}, V_L=400\text{v}, V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{400}{\sqrt{3}}=230\text{V}. v_{cc} = 0.04 \text{ and } F_{grid}=50\text{Hz}$$

$$I_{max} = \frac{\sqrt{2} \cdot P_n}{3 \cdot V_{ph}} \quad (3.41)$$

$$I_{max} = \frac{\sqrt{2} \cdot 10}{3 \cdot 230} = 2050A$$

The filter capacitor with its minimum value is calculated as:

$$C_f = \frac{V_{cc} \times P_n}{V_{l^2} \times W_{grid}} \quad (3.42)$$

$$C_f = \frac{0.04 \times 10^6}{400^2 \times 2\pi \times 50} = 0.8mf, (Y) \text{ and } = \frac{0.8mf}{3} (\Delta) \text{ [for the classical PI technique]}$$

$$\text{And } C_f = 1.6mf (Y) \text{ and } = \frac{1.6mf}{3} (\Delta) \text{ [for the SMC and MPC techniques]}$$

$$\Delta I_{max} = \frac{2V_{DC}}{3L_i} \cdot m(1 - m) \cdot T_{sw} \quad [\text{For the SMC}] \quad (3.43)$$

And equation 44 is used for the classical PI and MPC techniques

$$max = \frac{2V_{DC}}{8L_i} \cdot m(1 - m) \cdot T_{sw} \quad (3.44)$$

For moderate modulation, $m = 0.5$

$$\Delta I_{max} = \frac{V_{DC}}{6L_i f_{sw}} \quad (3.45)$$

$$\Delta I_{max} = \frac{V_{DC}}{16L_i f_{sw}} \quad (3.46)$$

Since, $\Delta I_{max} = 10\% I_{max}$

$$\text{So, } L_i = \frac{V_{DC}}{6L_i f_{sw}}$$

$$I_i = \frac{V_{DC}}{0.6L_{max} \cdot f_{sw}} \quad (3.47)$$

and

$$Li = \frac{V_{DC}}{0.16L_{max} \cdot f_{sw}} \quad (3.48)$$

The normal switching frequency of the power electronic switching devices is between (2 KHz and 15 KHz), let $f_{sw} = 5 \text{ KHz}$ for the following reasons:

- Efficiency and Loss Management: A switching frequency of 5 kHz strikes a good balance between reducing switching losses and maintaining high efficiency for medium-power PV systems like the 250 kW or 1 MW capacity in this case.
- Harmonic Compliance: At 5 kHz, the harmonic distortion is sufficiently reduced to meet grid connection standards when combined with the LCL filter.
- Component Selection: This frequency allows the use of cost-effective components with manageable heat dissipation and size.
- EMI and Noise: At 5 kHz, electromagnetic interference and audible noise are minimal, making it suitable for PV applications.

$$Li = \frac{400}{0.6 \times 2050 \times 10^3} = 0.26 \text{ mH(Y) and } 0.26 \text{ mH } 3(\Delta) \quad [\text{For the SMC}].$$

$$Li = \frac{400}{0.16 \times 2050 \times 5 \times 10^3} = 0.97 \text{ mH(Y) and } 0.97 \text{ mH } 3(\Delta) \quad [\text{For the classical PI and MPC techniques}].$$

The response frequency is usually limited by

$$10f_{grid} < f_{res} < \frac{f_{sw}}{2} \rightarrow 10 \times 50 < f_{res} < \frac{5\text{KHz}}{2} \rightarrow 0.5\text{KHz} < f_{res} < 2.5\text{KHz}$$

Let $f_{res} = 1.5 \text{ KHz}$.

Since, the resonance frequency is

$$W_{res} = \sqrt{\frac{Li+Lg}{Li \times Lg \times Cf}} \quad (3.49)$$

$$\therefore 2\pi \times 1.5KHz = \sqrt{\frac{0.975m+Lg}{0.975m \times Lg \times 0.8m}} \rightarrow Lg = 0.014mH(Y) \quad \text{and} \quad 0.014mH \times 3(\Delta)$$

[for the classical PI], $L_g = 0.007mH$ (Y) and $0.007mH \times 3(\Delta)$ [for the SMC] and $L_g=0.0011mH(Y)$ and $0.011mH \times 3(\Delta)$ [for the MPC].

$$R_f = \frac{1}{3\omega_{ref}C_f} = \frac{1}{3 \times 2\pi \times 1.5K \times 0.8m} = 0.044ohm(Y) \quad \text{and} \quad 0.044 \times 3 ohm (\Delta) \quad [\text{For the classical PI}],$$

and $R_f = 0.022ohm$ (Y) and $0.022 \times 3ohm(\Delta)$ [for the SMC and MPC]

3.7 Simulation Results

Figure (3.13) depicts the dynamic responses of the PV system's power case when weather temperature, solar radiance, and overload conditions change. The undershoot values of the sliding mode and model predictive current control approaches are clearly little more than that of classical PI approach.

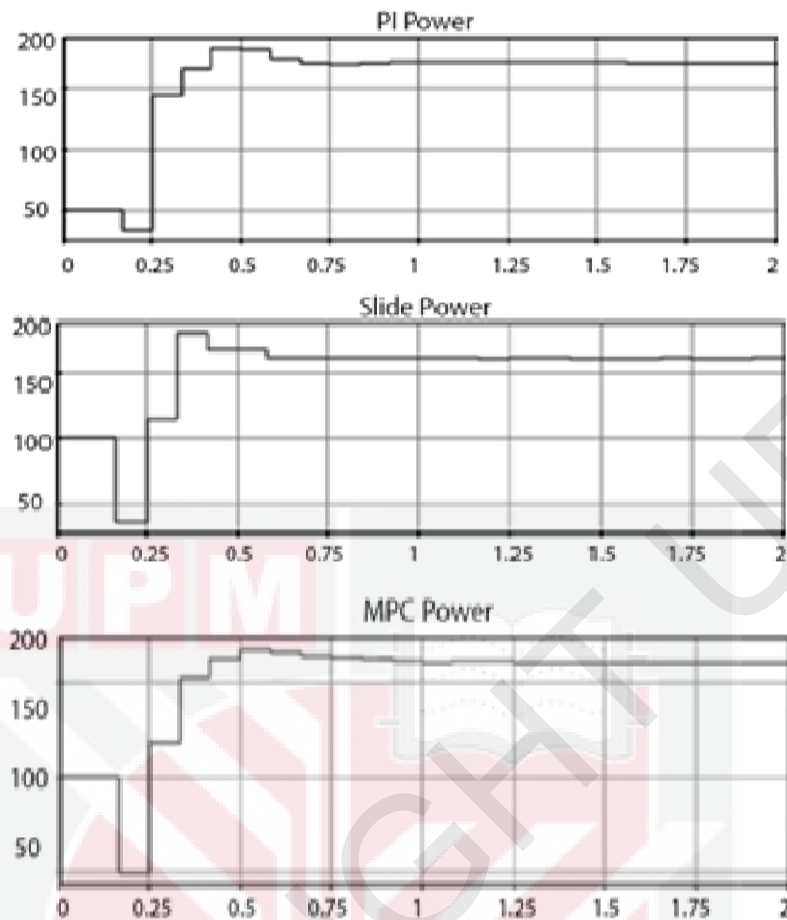


Figure 3.13: Dynamic responses of power for the PV system under changing of weather temperature, radiance and over load conditions

Furthermore, as demonstrated in Figure (3.13), the undershoot response in the current dynamic responses of the classical PI current control approach is slightly better than sliding mode and discrete time model predictive current control techniques.

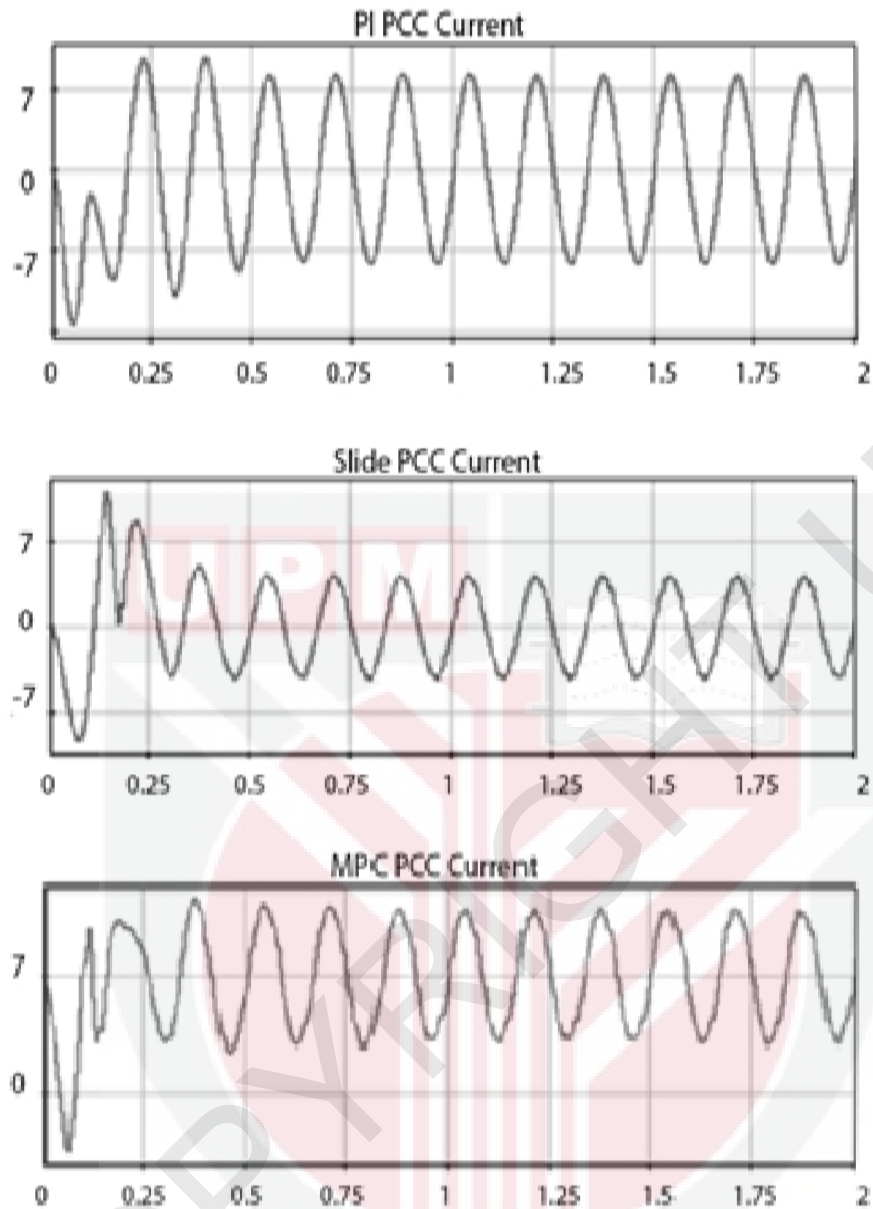


Figure 3.14: The dynamic responses of current for the PV under the changing of weather temperature, solar radiance and load conditions

The dynamic responses of operating voltage from the PV system that has been managed with the three different inverter current controllers are roughly the same, as shown in Figure (3.15).

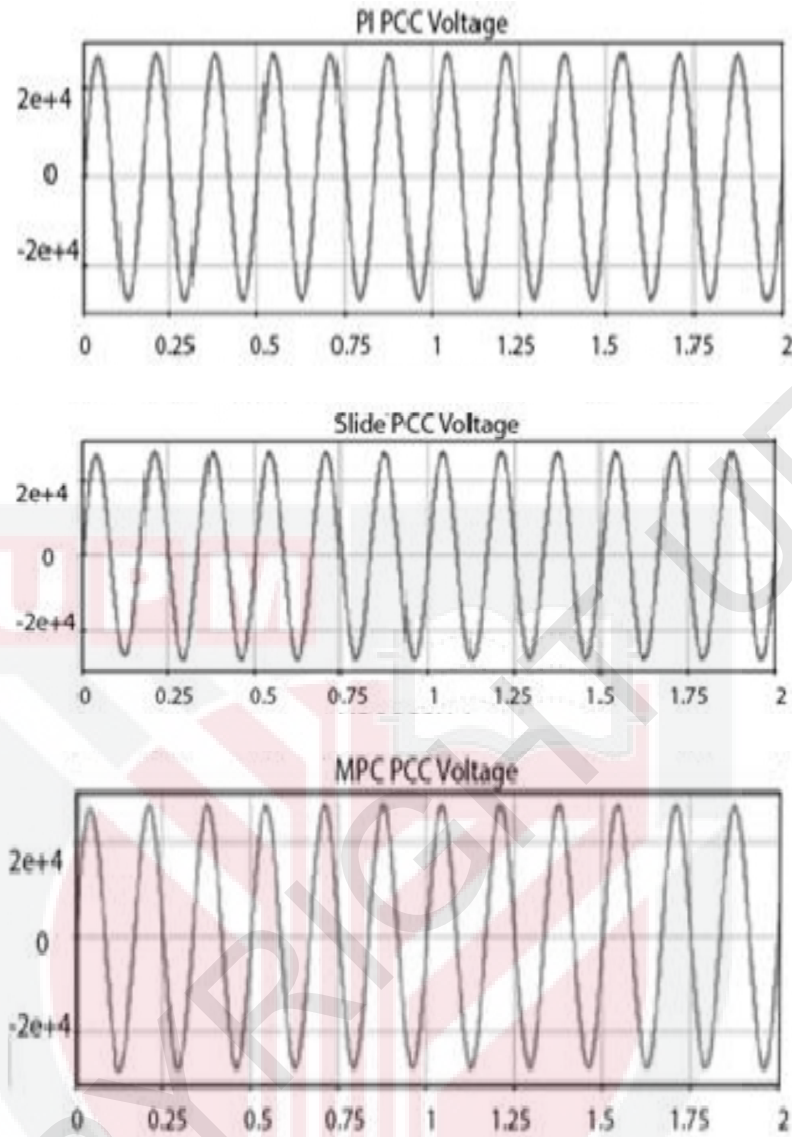


Figure 3.15: The dynamic responses of voltage state for the PV system under many conditions changing

The dynamic responses of the three distinct inverter control techniques in terms of their ability to keep DC link voltage value steady at the predetermined DC link voltage value under different environments and load conditions is as given in Figure (3.15). Little DC link voltage overshoot values with fine responses in the PI and MPC types as compared to sliding mode type. However, these overshoot values do not affect the performance of the designed system so they are negligible. The phase voltage and current

dynamic responses of the grid connection side have been given in Figures (3.16-3.19). It is clear that the dynamic performances of the three inverter current control techniques are almost identical. They have smooth response with approximately no ripple or drop. They can satisfy the unity power factor under the changing of weather temperature and solar radiance levels, less load and over load operating conditions.

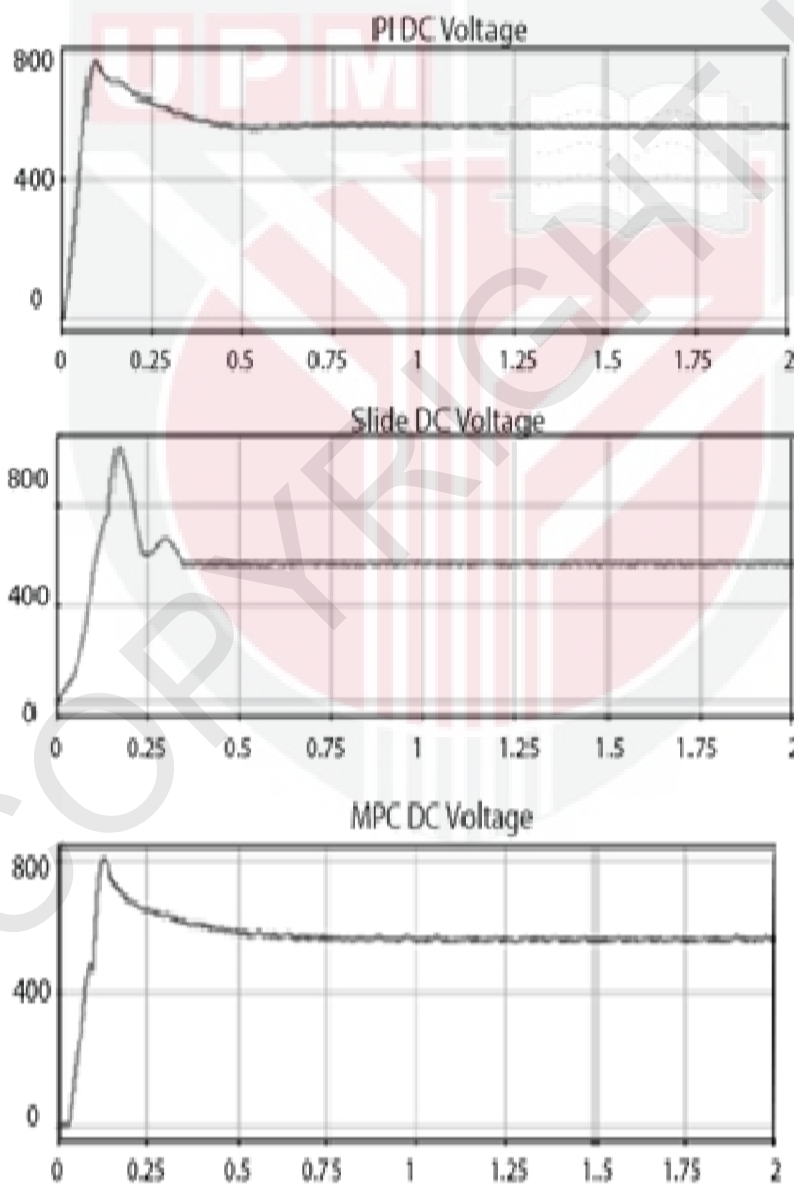


Figure 3.16: The DC link voltage dynamic responses from the PV system under the changing of many conditions

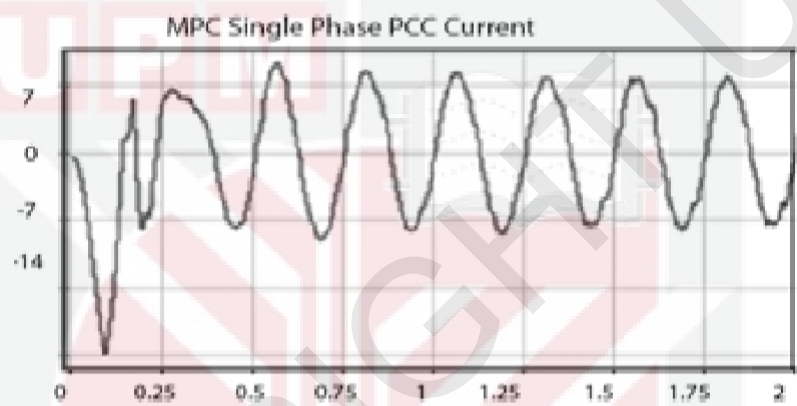
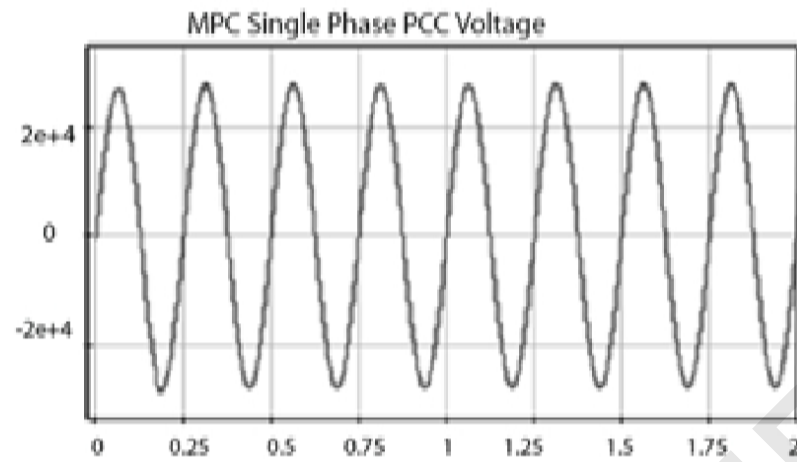
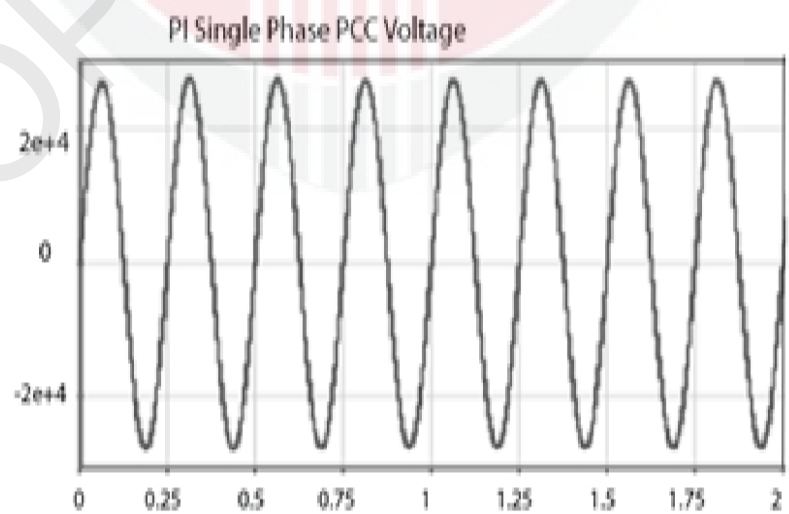


Figure 3.17: The dynamic responses of point of common coupling (PCC) voltage and current for MPC technique



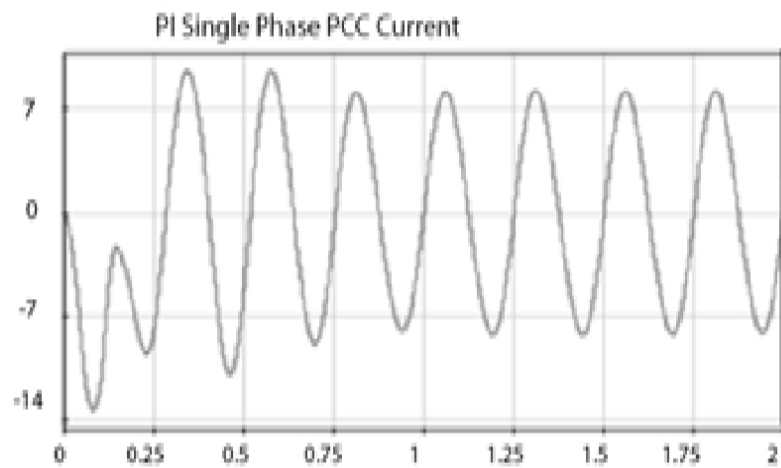


Figure 3.18: The dynamic responses of PCC voltage and current in classical PI current control technique.

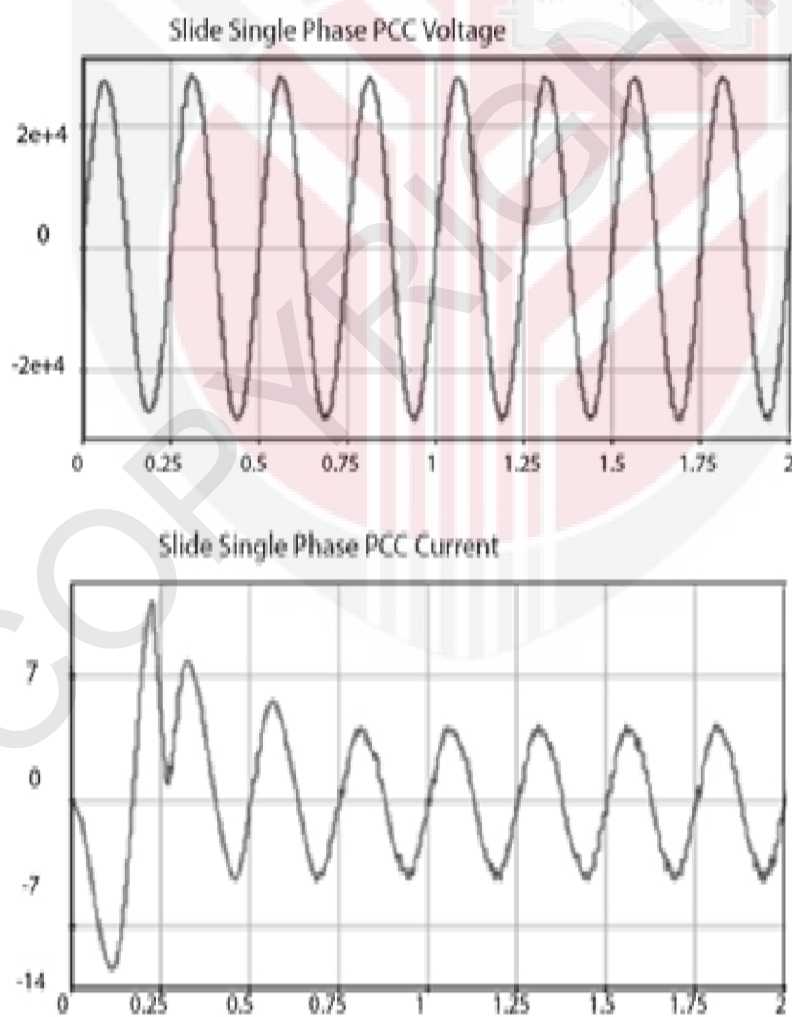


Figure 3.19: The dynamic responses of PCC voltage and current in SMC current control technique

Table 3.3 illustrates the performance responses of the three controlling methods including transient response with maximum overshoot, rise time and settling time as below:

Table 3.3: The performance responses of the three controlling methods

Output parameters	Controlling approach	Responses		
		Overshoot (%)	Rise time (s)	Settling time (s)
PV power	PI	10	0.51	0.74
	SMC	17.5	0.315	0.62
	PMC	15	0.58	0.86
DC Link voltages	PI	20	0.12	0.45
	SMC	25	0.2	0.32
	PMC	23	0.14	0.5

From Table 3.3, the performance evaluation of the three control methods PI, SMC, and PMC offers valuable insights into their behavior under different scenarios. These methods were analyzed based on their overshoot, rise time, and settling time, which are key indicators of stability, responsiveness, and control effectiveness.

For PV power control, PI emerged as the most stable option, with minimal overshoot, making it highly suitable for applications where steady and reliable performance is a priority. SMC, on the other hand, demonstrated the quickest response, with the fastest rise and settling times, but at the cost of a higher overshoot. This reflects its aggressive nature, which prioritizes speed over absolute stability. PMC struck a middle ground, balancing responsiveness and optimization. While its overshoot and settling time were slightly higher than PI, it remained more controlled than SMC, making it an effective choice for systems requiring a measured approach.

When it came to regulating DC link voltages, PI once again showcased its strength in providing stable and consistent results, with the lowest overshoot and the fastest rise time. These qualities make it a dependable choice for maintaining smooth voltage transitions. SMC stood out for its rapid stabilization, achieving the quickest settling time, though it exhibited higher overshoot, indicative of its assertive control strategy. PMC, while slightly slower in its response, offered a well-rounded balance of stability and optimization, particularly beneficial in managing dynamic and complex system behaviors.

In summary, PI is ideal for applications where stability and low overshoot are critical. SMC is the go-to choice for scenarios that demand rapid response and minimal delay, albeit with some compromise on overshoot. PMC shines in situations requiring predictive capabilities and adaptive control, providing a balanced approach to system management. The choice of control strategy should align with the specific priorities of the application, whether it's stability, speed, or optimization.

3.8 Summary

This chapter presents the analysis and development of grid-connected photovoltaic (PV) systems with a focus on inverter current control techniques and LCL filters. Two separate systems are studied: one with a 250KW power capacity and expandable property, and another with a 1MW capacity.

In the first system, three inverter control techniques, PI, Slide, and MPC, are implemented and tested. The dynamic performances of these techniques are

comparable under grid-connected conditions, with the PI control technique exhibiting slightly better and smoother dynamics. All techniques achieve unity power factor, but the sliding mode inverter control method produces higher output power levels.

In the second system, the same three control techniques are employed along with LCL filters. Again, the dynamic performances are similar, with the PI method providing smooth responses and low harmonic distortion. The sliding mode inverter control approach generates greater output power levels compared to the PI and MPC methods.

Although Under grid connected operating conditions, the steady state and transient responses of the three inverter control techniques are nearly identical, the results are as follows:

- **PI:** Provides smooth responses with minimal harmonic distortion, achieving unity power factor.
- **SMC:** Provides higher output power levels compared to PI and MPC, while maintaining unity power factor.
- **MPC:** Ensures stable operation with accurate and constant DC link voltage readings, meeting the intended voltage levels.

Overall, both systems demonstrate that the selected control techniques, along with LCL filters, effectively meet grid and load requirements while maintaining unity power factor. The sliding mode inverter control method consistently outperforms the other techniques in terms of output power levels. Additionally, the MPC method ensures stable operation with accurate and constant DC link voltage readings.

CHAPTER 4

ENERGY MANAGEMENT

4.1 Introduction

The total global energy derived from renewable energy (RE) sources is estimated to exceed 4GW by the end of 2023 [172]. Photovoltaic (PV) energy is a significant source of RE and accounts for approximately 47% of all newly installed RE generation systems [173]. In order to increase the use of novel technologies in the form of RE sources, like wind turbines, PV, and biomass, which are regarded as sustainable and eco-friendly with zero fuel costs and easy access, many nations have changed their policies pertaining to the generation of electricity. Photovoltaic (PV)-based renewable systems can operate in both stand-alone and grid-connected modes. The production, control, and communication units are the major components of a microgrid. The optimum usage of various energy sources may yield economic and environmental advantages [174]. Microgrids also priorities network efficiency, financial feasibility, power distribution, and long-term energy storage (ES). It may comprise several or one single linked component that relies on alternating current (AC), hybrid, or direct current (DC) links as the common connection point (PCC) [175]. Multiple studies have examined energy management (EM) systems as well as numerous control methods and controllers to create energy units [176-180]. The EM system is considered a top-level control system for supervisory control and data acquisition [181-185].

Renewable energy (RE) systems are designed to operate within certain limits in normal circumstances. However, these systems are susceptible to power distortions with varying effects, durations, and intensities that can impact their performance. One notable challenge with hybrid grid-connected systems is EM using an EM system. Energy management (EM) systems handle a variety of tasks, like effectually charging and discharging the storage battery from the grid or PV plant setups. By supplying customers with high-quality, uninterrupted power during disruptions, this mechanism plays a crucial part in guaranteeing the safety and effectiveness of power systems. To overcome these issues, control methodologies, such as converters that ascertain deviations between measured values and reference values, are used. The current, voltage, and the amount of power delivered can all deviate from the norm. Therefore, these control techniques' main goal is to improve hybrid systems' performance in the presence of disruptions. One example is maintaining a balance between the amount of power generated and the load demanded. When the load demand is light, the excess energy generated by a PV system is stored in a battery. However, when power distortions occur and the load demand abruptly exceeds the power generation capacity of the PV system, the battery discharges the stored energy to ensure system stability within acceptable limits. Many research works have, in recent years, concentrated on the EM capabilities of such setups under normal as well as abnormal situations, thanks to the improvements in RE systems and the growing global tendency towards hybrid grid-connected systems, given their aforementioned benefits. The behavior of hybrid systems under different forms of disturbances is covered in this section through a few quick summaries of

key studies that discuss how to optimize the performance of hybrid systems and ensure their resilience under challenging circumstances. [186-188] used multi-objective or stochastic optimization methods to optimize EM in uncertain energy shift scenarios. Meanwhile, [189] proposed a control strategy and EM system with a managerial control which takes into account the difference between real-time and offline schedules to analyze the grid-connected and islanded modes. The proposed method used low-level decentralized control to control the local distribution generator and high-level centralized control to address bidirectional (BD) power sharing and communication issues. The ideal dispatching method for a medium voltage islanded microgrid with a storage setup is a heuristic evolutionary algorithm. While [190] thought about operation scenarios for zone-based multiple microgrids, [191] provided a comparison and substantiation of a real microgrid. [192] explored decentralized EM systems and intelligent controls for autonomous poly-generation microgrids, and the algorithms used fuzzy cognitive maps to create the desalination system. Decentralized control was used in microgrids powered by PV cells and battery storage, and the results were only displayed virtually. In order to demonstrate the efficacy of hierarchical EM models for DER [193–194], advanced optimization techniques such as neural networks, swarm optimization, and sequential quadratic programming were used in simulations or a hardware in the loop (HIL) setting. [195] investigated the use of a static synchronous compensator (STATCOM) along with a decentralized control approach for a hybrid AC-DC microgrid. To substantiate the recommended strategy's superiority, it was contrasted with the droop controller-based approach. A standardized approach for comparing the relative cost-

effectiveness of microgrids propelled by lead-acid and lithium-ion batteries was presented by [196]. Utilizing lithium-ion batteries appears to be 6 to 7% more lucrative when grid power costs, state of charge (SOC), and power balancing modes in EM systems are considered.

This present study aimed to examine and analyze the behavior and performance of a battery-PV hybrid grid-connected system during disruptions; such as abrupt load changes and rapidly changing levels of solar irradiation. The microgrid and the potential power disruptions were simulated in MATLAB® Simulink with a 200-kW PV array linked to a 380 V grid. Three distinct control strategies were introduced; namely, maximum power point tracking (MPPT) for the boost converter, pulse width modulation (PWM) for the ES system, and PWM for the three-phase (3Ph) inverter. The primary objective was to assess how effectively these strategies uphold system performance and stability in the face of power disruptions.

4.2 Configuration of Hybrid System

As seen in Figure 4.1, the microgrid was configured as a PV system linked to a DC link by a boost-based unidirectional (UD) converter and comprised an inverter with two levels linked to a inductor and capacitor (LC) filter, a battery storage setup linked to a buck and boost-based BD converter to maintain system stability in various modes, and a variable load for the test system linked at the PCC. The entire setup was linked to the main grid by an inverter.

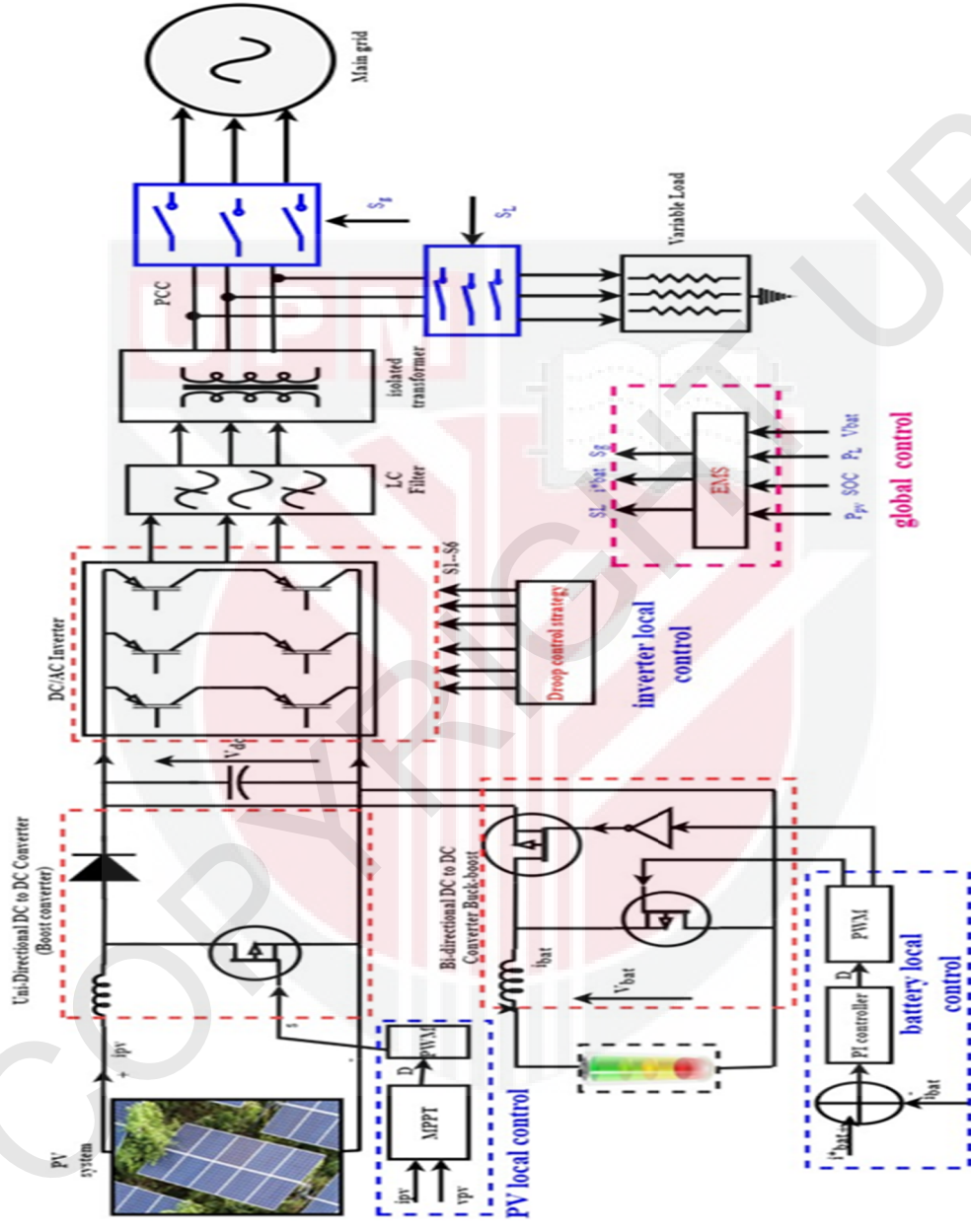


Figure 4.1: Block diagram of the hybrid system

Equations 1 and 2 yield the battery and PV systems' power:

$$P_{pv} = V_{pv} I_{pv} \quad (4.1)$$

$$P_{bat} = V_{bat} I_{bat} \quad (4.2)$$

The battery system's voltage-current characteristics can be expressed as:

$$P_{bat} = V_0 - K \frac{C_b}{C_b - \int I_{bat} dt} + A \cdot e^{(-\int I_{bat} dt)} - R_b I_{bat} \quad (4.3)$$

where R_b and C_b are the battery's internal resistance and maximum capacity, respectively, τ is the time constant, A is an exponential area amplitude, and $\int I_{bat} \cdot dt$ is the capacity of the battery. Equation 4 was used to calculate the required SOC, which was used to govern the battery storage system's discharge and charge cycles.

To preserve the life cycle of the battery, the SOC should be maintained within the SOC_{min} and SOC_{max} which are, based on the battery's characteristics, its lowest and highest allowable limits. The eventual formula for the active and reactive output power in $dq0$ with $v_d = V, v_q = 0$ is as follows:

$$P = 3v_d i_d \quad (4.4)$$

$$Q = 3v_d i_q \quad (4.5)$$

Where i_d and i_q are the inverter's output currents.

Equation 6 was used to balance the power and meet the load demanded when in the grid-connected mode:

$$P_g = (P_{pv} + P_{bat}) - P_L - P_{LOSSES} \quad (4.6)$$

Where P_g and P_L is the grid and load powers, respectively, P_{pv} and P_{bat} are the PV and battery powers, respectively, and P_{Losses} are the power losses of the LC filters. Equation 6 was used in the power management algorithm to supervise the whole system and maintain it in the balance mode. Table 4.1 provides the detailed specifications of the proposed PV system.

Table 4.1: PV array specifications

Parameters	Value
No. of Series Panel can be connected	9
No. of Parallel Panel can be connected	58
Maximum power of panel	400.2 W
voltage Open Circuit of PV System	768 V
Rated Current of the PV System	312.9 A
Rated voltage	656 V
Total Rated Power	205 kW
Total Short Circuit Current	334.5 A

The above specifications are specified for the proposed system where each paragraph is selected to achieve an integrated system. The amount of energy output by solar systems can be optimized using MPPT. Of the many methods of achieving maximum output power, this present study used the perturb-and-observe (P&O) algorithm [197]. The maximum power point (MPP) may be determined by varying the duty cycle of the boost converter and comparing the prior and current levels of power (P) and voltage (V). When the $\Delta P/\Delta V$ is negative, the operating point is on the right side of MPP and vice versa. A

boost- based UD converter was used to increase the DC voltage from 656 V to 800 V. The converter was able to get the most out of the PV system by adjusting the duty cycle.

This present study also used a capacitance filter to filter the output voltage and mitigate high-current circuit losses. Equations 7 and 8 specify the inductor and the output capacitor of the boost converter:

$$L_{min} = \frac{D (1-D)^2 R}{2 f} \quad (4.7)$$

$$C = \frac{D}{R \left(\frac{\Delta V_o}{V_o} \right) f} \quad (4.8)$$

Where $\left(\frac{\Delta V_o}{V_o} \right)$ is the output ripple voltage, R is the output resistance, and f is the frequency [198]. The resistance of the output capacitor and inductor were assumed. Table 4.2 lists the boost converter settings utilized.

Table 4.2: Boost Converter parameters, at duty cycle=D=0.5 & Switching Frequency =4 kHz

Parameters	Value	Parameters	Value
Input Voltage	656 V	Output Voltage	800V
Inductor	0.68mH	Output Capacitor	2.4 mF

A DC link capacitor was used to decrease the voltage variance of the DC connection between the power converters as well as maintain a continuous supply of power to the inverter. Equation 9 was used to calculate the root-mean-square (RMS) of the capacitor's ripple current:

$$I_{cap,r.m.s} = I_{N,r.m.s} \sqrt{\left[2m \left\{ \frac{\sqrt{3}}{4\pi} + \theta \left(\frac{\sqrt{3}}{4\pi} - \frac{9}{16}m \right) \right\} \right]} \quad (4.9)$$

Where $I_{N,r.m.s}$ is the inverter's output phase current, which was delayed with a θ phase delay and m is the modulation index [200]. The minimum capacitance value was calculated as follows:

$$C_{dc-link} = \frac{I_{cap,r.m.s}}{\omega_s * V_{ripple}} \quad (4.10)$$

The DC-link capacitor is equal to 14.8 mF, when $m = 0.6$, $\theta = 0$, $V_{ripple} = 1\%$, $\omega_s = 2\pi \times 4$ kHz and the power transfer through the inverter is 200 kW. A 3Ph voltage source inverter block was locked into the correct operating frequency to keep the frequency stable and manage the voltage and frequency, balance and level the load, and decrease the amount of total harmonic distortion (THD) that occurred. Figure 4.2 depicts the control strategy that was used to concurrently accomplish all the above-mentioned objectives in both the grid and islanded operation modes and maintain a constant output voltage during changes in the amount of power generated or load power profile.

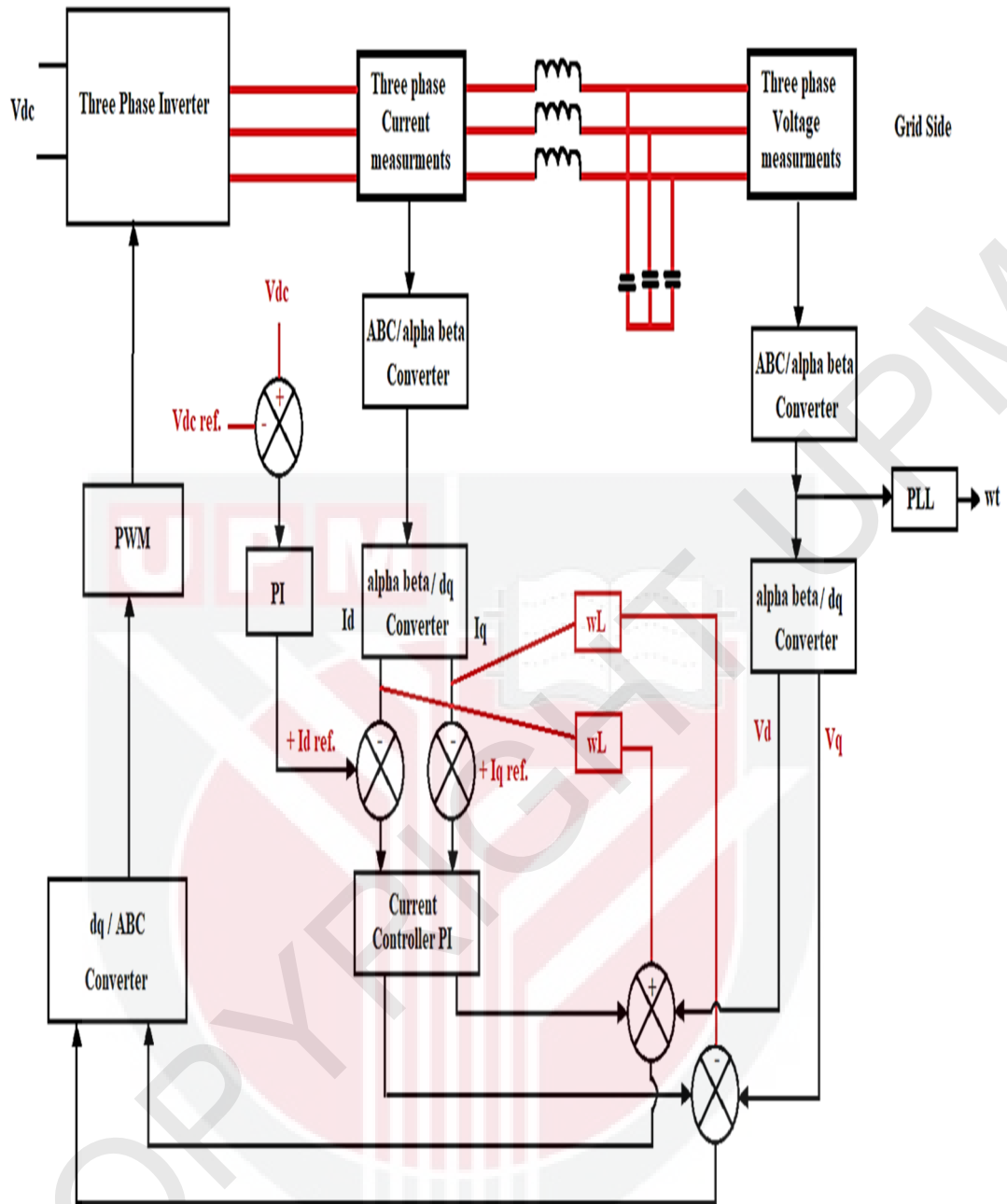


Figure 4.2: System Control Diagram

The 3Ph voltages and currents were measured and converted into two components; d and q ; then compared with reference values. They were then applied to a proportional integral (PI) and PWM controller to control the input signal of the inverter [199]. A buck and boost-based BD converter [200] has immense potential for efficient energy transfer as both switches play a pivotal

role in directing the flow of power. The metal-oxide-semiconductor field-effect transistor (MOSFET) (1) switch functions as a buck converter and channels power to the ES battery as well as ensures the optimal utilization and preservation of power while the MOSFET (2) switch kicks in when power has to be channeled to the grid, thereby, facilitating the seamless exchange of energy.

The BD DC-to-DC converter's inductor is built for the circuit's operating mode and can be computed as follows:

$$L = \frac{V_{inmin} (V_{inmax} - V_{out})}{f_s * \Delta IL_{max}} \quad (4.11)$$

Where V_{inmin} and V_{inmax} are the battery's voltage (V_{bat}) and the DC bus' voltage ($V_{Dc bus}$) or vice versa, f_s is the switching frequency, and ΔIL_{max} is the maximum allowable change in inductor current. For example, if the input V_{bat} is 740 V and the output $V_{Dc bus}$ is 800V, the ripple of the output and input current is assumed at 1% and the switching frequency is 4 kHz, the suitable inductor current is 3.7mH. The BD converter was controlled by comparing the deviations of the DC bus voltage and battery current with their respective reference values. Two PI controllers were combined with PWM to generate pulses for the two switches. The BD converters comprised buck and boost converters. The buck converter operated when the amount of PV-generated power available exceeded the power load demanded and the boost converter operated when the power load demanded exceeded the amount of PV-generated power available. This control strategy also accounted for the

battery's voltage and SOC during operation. Variations in the voltage of the battery can also be referred to as changes in the operation modes [201].

The primary function of an LC filter is to decrease the THD of the waveforms of the generated currents and voltages as they may cause losses and distortions in the output power. They are commonly used as they are both simple to use and inexpensive. Empirically, the LC filter can be set at induction (L_f) = 0.25mH and capacitance (C_f) = 46 μ F.

4.3 Energy Management System:

The flow chart as shown in Fig 4.3 provides a structured approach to optimizing the use of renewable energy sources, balancing grid interaction, and managing battery operation to ensure efficient and reliable power supply. It serves as a foundation for implementing control strategies in real-world renewable energy systems. The primary purpose of the proposed EM system is to efficiently balance the generation of electricity from the PV panels, the demand for electricity by loads, and the state of charge (SOC) of the battery to optimize energy utilization. It has many points of view:

1. **Data Collection:** The procedure starts by collecting real-time data, including PV power generation (P_{PV}), battery SOC, load power demand (P_{load}), and battery voltage (V_{bat}).
2. **Load and PV Generation Forecasting:** Load demand is forecasted ($P_{load-pred}$), and PV power generation is estimated ($P_{PV-pred}$) to anticipate future energy requirements.
3. **Mode Selection:** Based on real-time data and forecasts, the code selects an operating mode:

- **Grid-Connected Mode:** When PV power exceeds the load demand, surplus energy can be injected into the grid ($P_{injected}$), or power can be drawn from the grid (P_{grid}) if load demand exceeds PV generation.

- **Battery Charging Mode:** If PV generation exceeds load demand and the battery SOC is below a minimum threshold (SOC_{min}), the excess energy is used to charge the battery.

- **Battery Discharging Mode:** When PV generation is less than load demand and the battery SOC is above a maximum threshold (SOC_{max}), the battery discharges to supplement the load.

- **Islanded Mode:** In this mode, the code ensures that PV generation is utilized to meet the load demand while considering battery discharge limits.

4. **Battery Operation Management:** Depending on whether the battery is in charging or discharging mode, the code calculates the appropriate power level ($P_{battery-charge}$ or $P_{battery-discharge}$) to adjust the battery SOC and voltage. It also considers battery degradation models and ensures that the battery power stays within predefined limits.

The differences between the proposed EM algorithm and existing EM algorithms:

1. **Real-Time Data Collection:** Incorporates real-time inputs like P_{PV} , SOC, P_{load} , and V_{bat} for dynamic adaptability.
2. **Predictive Analytics:** Uses load forecasting ($P_{load-pred}$) and PV generation prediction ($P_{PV-pred}$) to anticipate future energy needs.

3. Operational Mode Flexibility: Defines clear modes (grid-connected, battery charging/discharging, islanded) to optimize energy flow based on scenarios.
4. Advanced Battery Management: Actively adjusts SOC and voltage while considering degradation models to extend battery lifespan.
5. Optimized Grid Interaction: Balances surplus energy injection (P_{injected}) and grid power utilization (P_{grid}) efficiently.
6. Robust Islanded Mode: Prioritizes load demand and battery management for reliable off-grid operation.
7. Dynamic Thresholds: Adjusts SOC and other operational thresholds dynamically based on real-time conditions.
8. Holistic Efficiency: Combines real-time data, predictive analytics, and operational modes to optimize energy usage, reduce wastage, and ensure reliability.

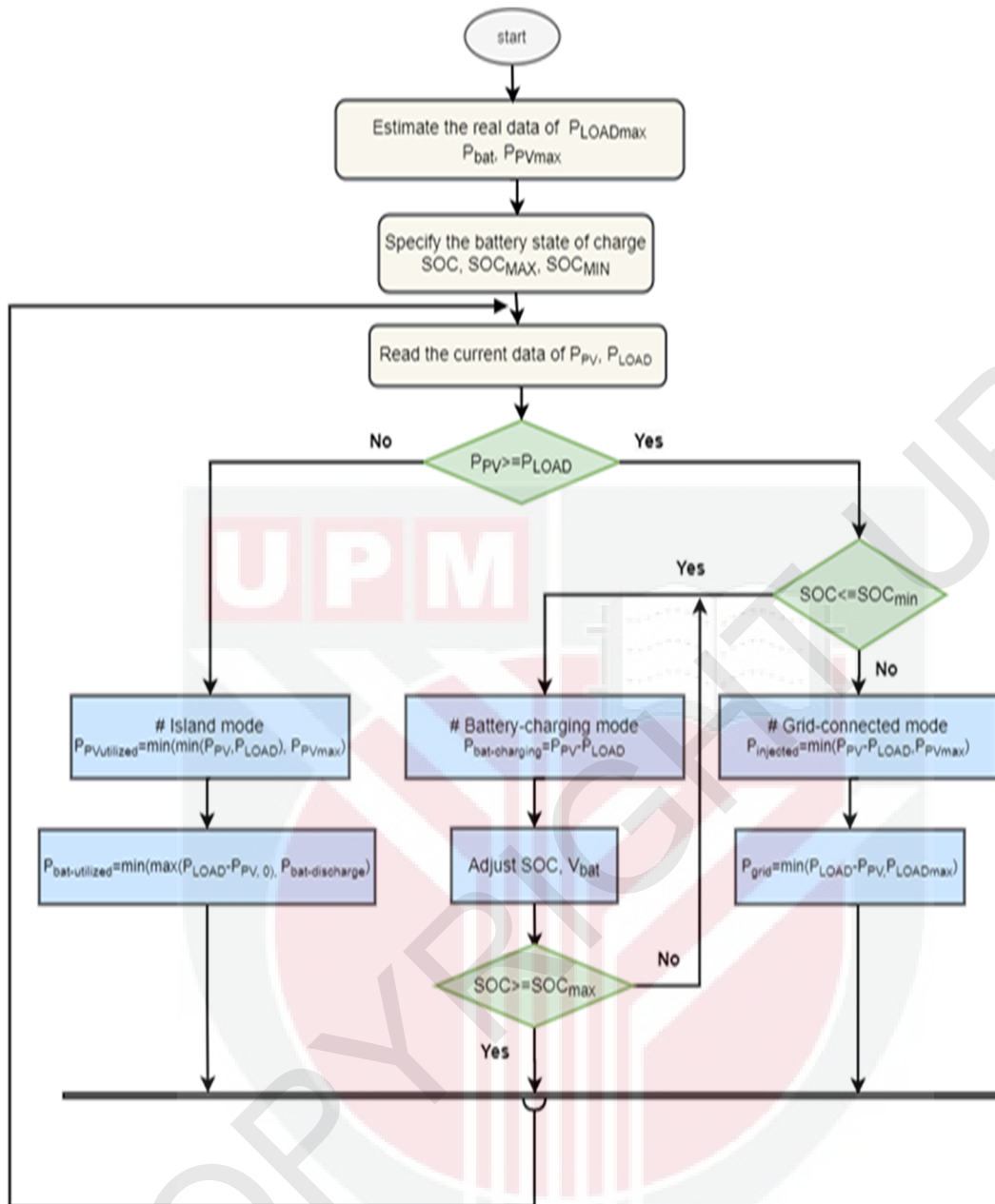


Figure 4.3: Energy management algorithm

4.4 Simulation Results

In the simulation, the PV system was connected to the grid *via* the boost and 3Ph inverters that were used to supply the AC load. A battery was also used to supply the required power if the PV-generated power was insufficient and store the excess power generated. As seen in Figure 4.4, MATLAB Simulink

was used to implement the hybrid system. The capacities of the battery-PV system were 205kW and 150kW, respectively, while the loads were connected parallel at 100 kW and 150 kW.

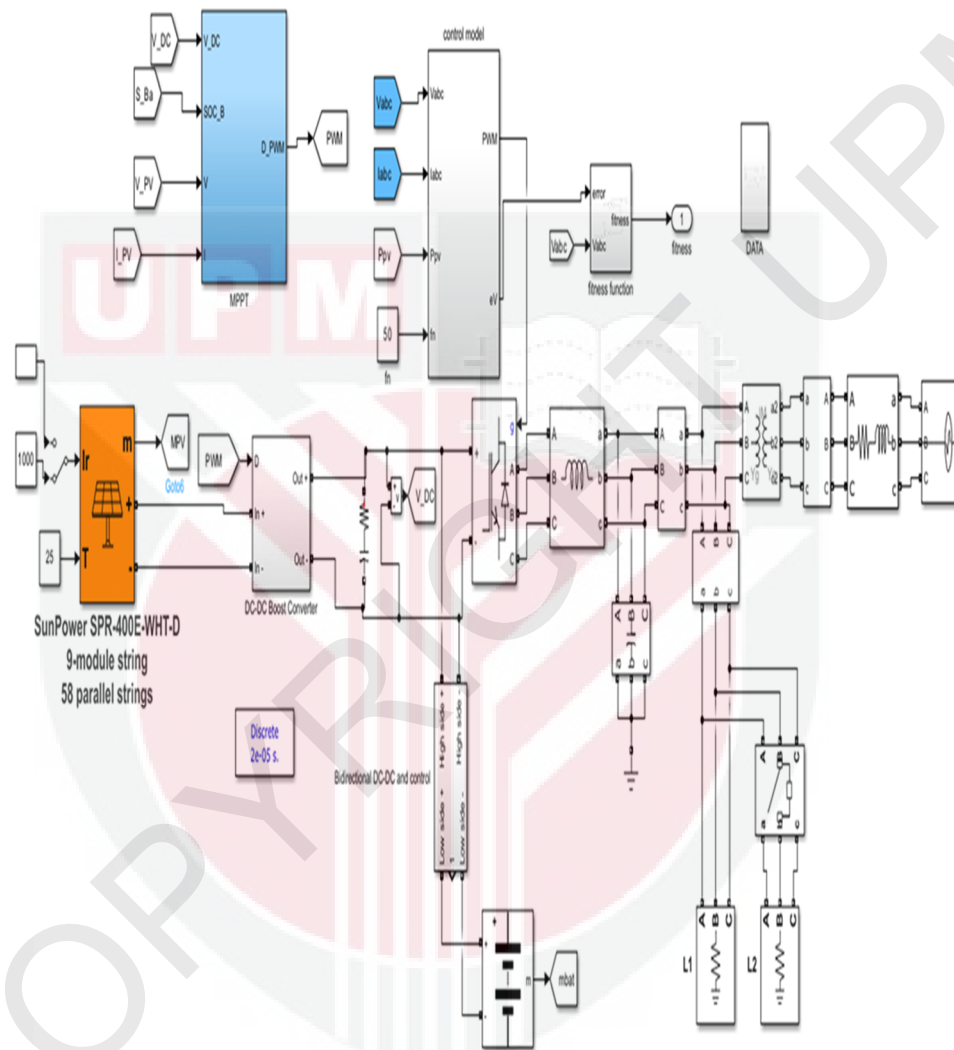


Figure 4.4: Hybrid System using Matlab/Simulink

4.4.1 Mode1

In this mode, the load demanded was assumed to be constant and close to 100 kW while the irradiation, which was supplied at 25°C, changed from 1000 to 500 W/m² in 1 second (s). The variable irradiance decreased the amount of

PV power generated from 200 to 100kW in 1 s and the battery discharged to supply the load demanded after 1 s. The current also remained constant as the load remained constant when the amount of PV power generated changed in relation to changes in irradiation. Figure 4.5a depicts the THD of the 3Ph voltage and current. As seen, this began at 0.6 s as three cycles at a frequency of 50Hz and caused a THD of 3.7%. The battery satisfied the EM requirements by continuously supplying to the load demanded. However, as seen in Figure 4. 5b, there was a delay between switching from the PV-generated power to the battery to supply the load demanded. Nevertheless, the system was able to ensure a balance of power between the total amount of power generated by the inverter, the ES system, and the constant load voltage and current while keeping the power smooth and within an acceptable THD distortion range. Therefore, the battery system failed to supply the load demanded.

In this mode:

From time 0-0.12 sec PV power fail to supply power, so the battery will do this for this short time until the PV generate the power. From time 0.12 -1 sec PV Power > Load Power. So the battery in charging state. (The generated power greater than load power then the battery observes current to charge itself).

From time (1-2) sec. PV Power = Load Power (PV operate in MPPT)

From time 1-2 sec battery operates in idle mood because the generated power equals to the load power so the battery neither charging nor discharging.

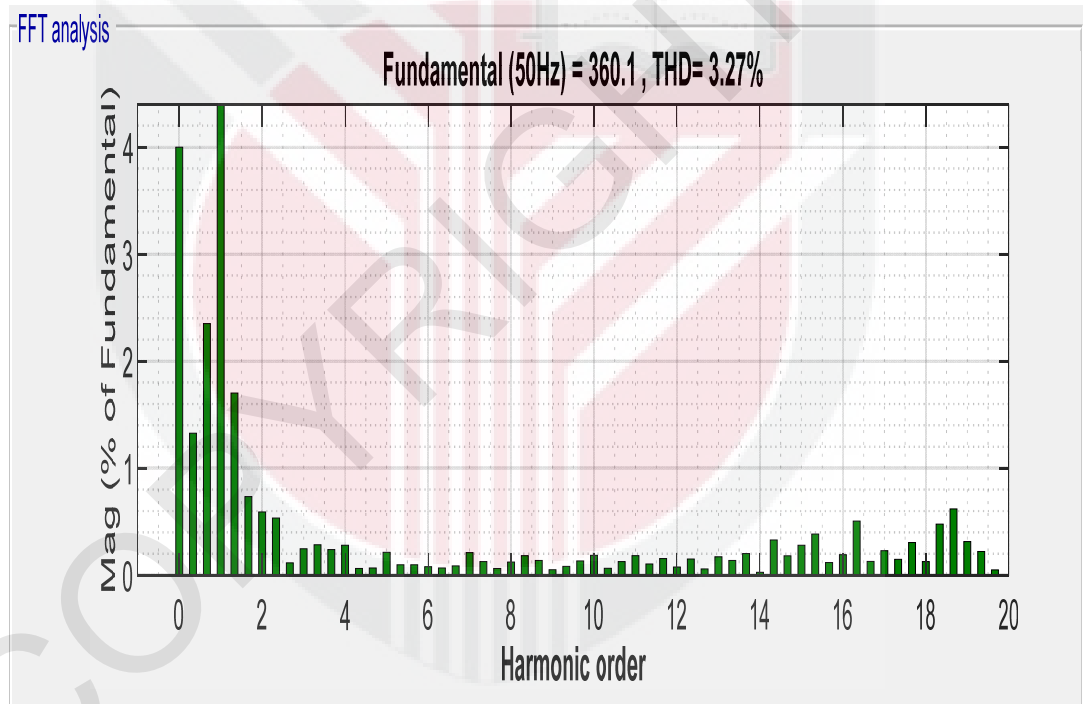
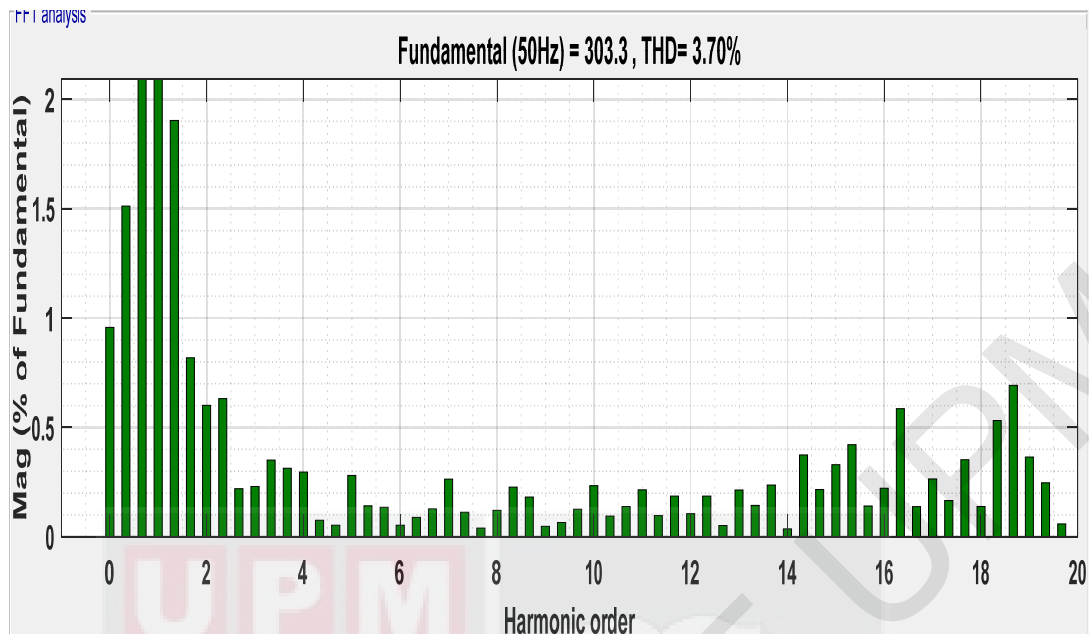


Figure 4.5a: Harmonics of Three Phase Voltage and Current

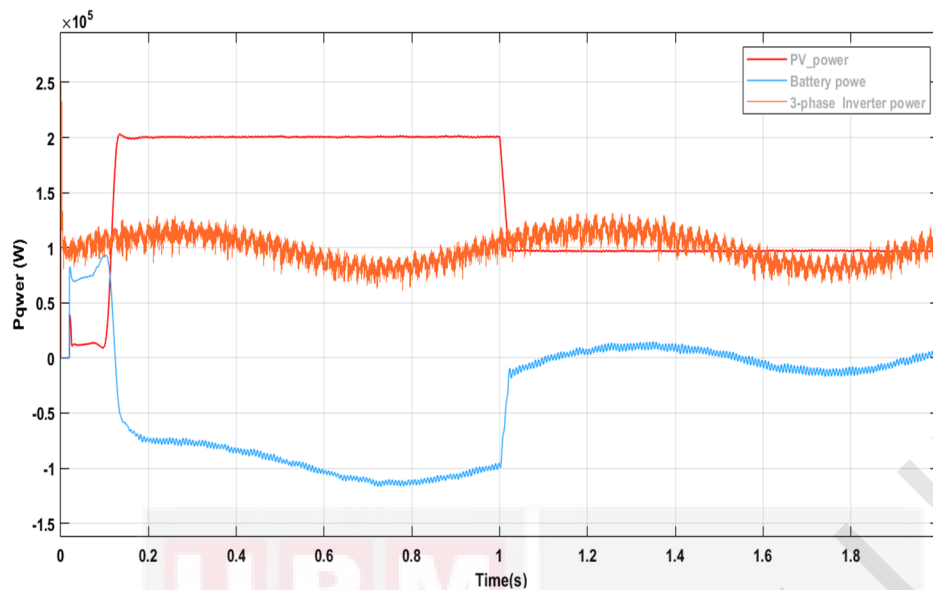


Figure 4.5b: The power generated by of the PV system, battery power, and total power of hybrid

4.4.2 Mode 2

The conditions were the same as that of the previous mode except that was load demanded close to 250kW. The amount of PV power generated changed from 200 to 100 kW in 1 s Figure 4.6a. Figure 4.6a depicts the total amount of power generated by the battery-PV hybrid system.

In this mode: Between 0 to 0.12 s, the PV cells failed to supply the load demanded and the battery supplied it between 0.12 to 1 s, until the PV cells generated the load demanded. Between 0.12 to 1 s, the amount of PV power generated was less than the load demanded. As such, the battery was in the discharging state. Between 1 to 2 s, the amount of PV power generated was still less than the load demanded. As such, the battery remained in the discharging state between 1 to 2 s as amount of PV power generated was insufficient to meet the load demands.

The battery remained in the discharging state throughout the specified time. This mode is dangerous for the system as the battery may run out if the duration is long. Therefore, the system should be equipped with a backup system to address such scenarios. This, however, is not discussed in this present study.

Off-Grid Self-Consumption (OGSC) Off-grid hybrid battery-PV system use self-consumption to ensure continuous power supply [20] (Figure 6b). This approach utilizes a battery to store the excess energy generated by a PV system after the load demanded has been fulfilled. The excess energy is stored in the battery until it reaches its maximum capacity, which is an efficient use of the generated power.

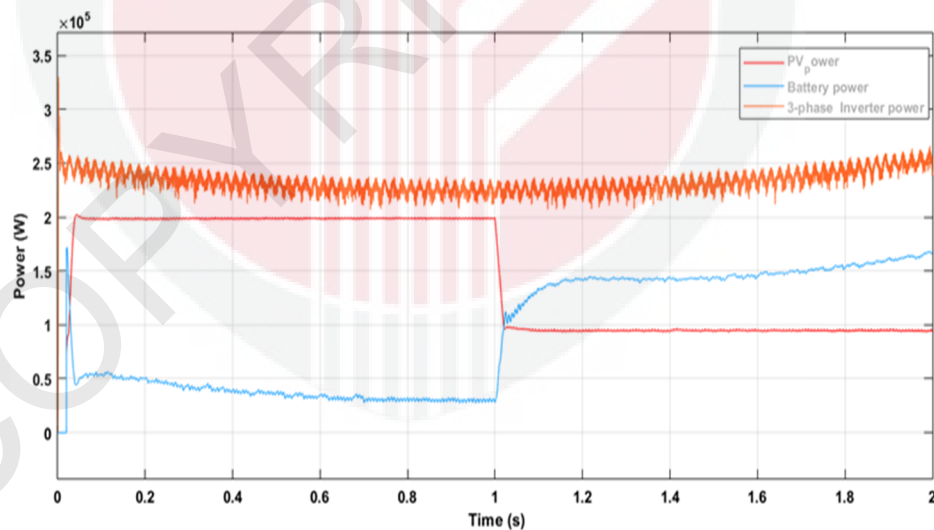


Figure 4.6a: The power generated by of the PV system battery power and total power of hybrid

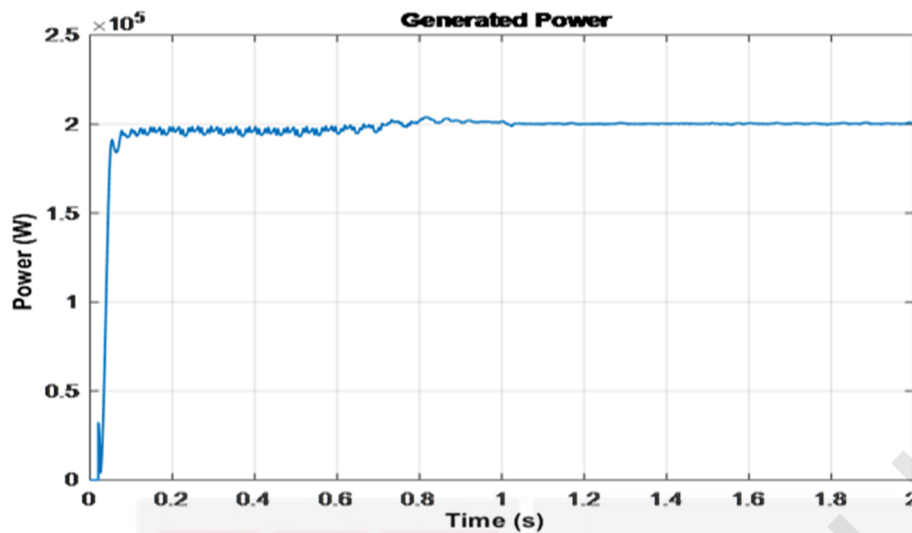


Figure 4.6b: The PV power

4.4.3 Mode 3

In this mode, the irradiance was assumed to be constant and supplied at 25°C and 1000 W/m² while the load demanded changed from 100 to 250 kW in 1 s. Figure 4. 7b provides the amount of power generated by the PV cells. The voltage and current were 656.1V and 312.9A, respectively. The DC-Bus voltage remained constant throughout the mode. The voltage remained constant during the disturbance in the load but the current increased as the load increased when the PV power was constant to 200kW. Figure 4.7a depicts the THD of the 3Ph voltage and current waveforms. As seen, at 0.6 s, the three cycles at a frequency of 50Hz caused a THD of 4.38% while that at 0.8 s caused a THD of 3.48%.

In this mode: Between 0 to 1s, the amount of PV power generated exceeded the load demanded. As such, the battery was in

a charging state. Between 1 to 2 s, the amount of PV power generated was less than the load demanded. At this stage, the PV system entered a mode called the PV-curtail operation, which is when the battery's SOC reaches or exceeds its upper limit. The battery discharges power to make up for the difference and supply the balance load when the PV cells fail to generate sufficient power to meet the load demanded. The PV system works at its MPP when it does not produce sufficient power to satisfy the load demanded but the battery's SOC remains within its operating threshold. Failures, however, may occur when

the hybrid battery-PV system is unable to fulfill the load demanded. As seen, the load demanded was less than the amount of PV power generated until 1 s. The battery discharged and supplied the load demanded in the few instances of delays in PV power generation. When the PV cells resumed supplying power, the battery began charging itself (Figure 4.7b).

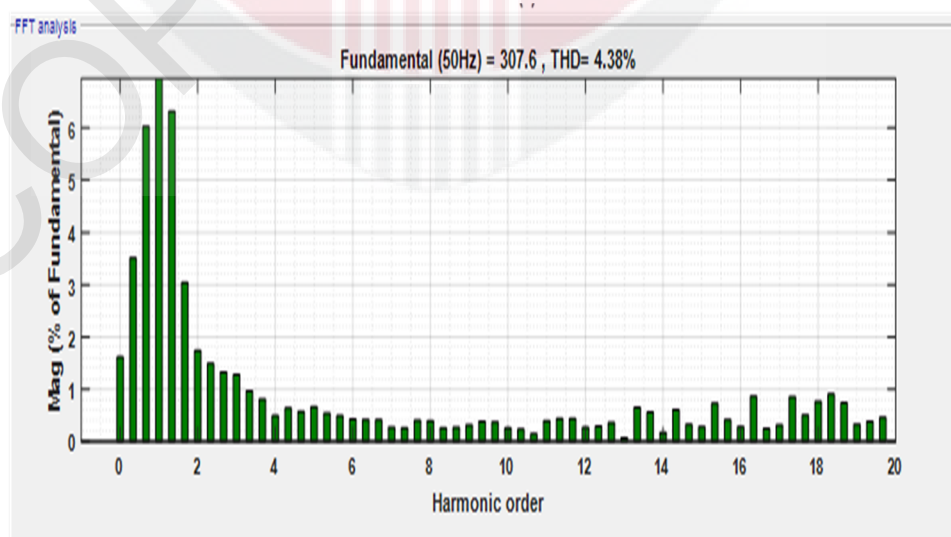


Figure 4.7a: The total harmonic distortion THD of voltage

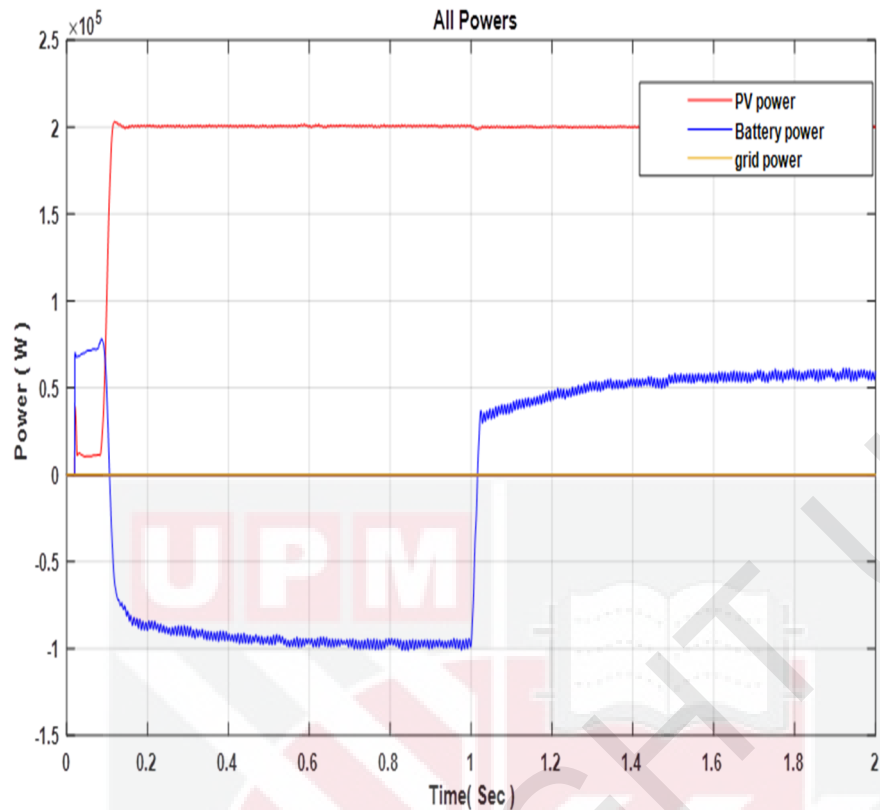


Figure 4.7b: The power generated by of the PV system battery power and total power of hybrid

4.4.4 Mode 4

The conditions were the same as that of the previous mode except that the irradiance was decreased to 500 W/m^2 and the PV cells generated a constant 100 kW of power. Figure 4.8 depicts the batteries, PV cells', and hybrid system's power generation. As the amount of PV power generated was equal to the load demanded, the battery was in an idle state. Between 1 to 2 s, the amount of PV power generated was less than the load demanded. As such, the battery was neither charging or discharging between 0 to 1 s as the amount of PV power generated was equal to the load demanded. However, between 1 to 2 s, the load demanded exceeded the amount of PV power generated. As

such, the battery discharged power to make up for the difference and supply the balance load. The battery can continue doing this so long as its reserves are not completely depleted. This enables hybrid systems to provide the load demanded independent of the grid and even when the PV cells fail to produce sufficient power to meet the load demanded, by placing the battery in the discharged state.

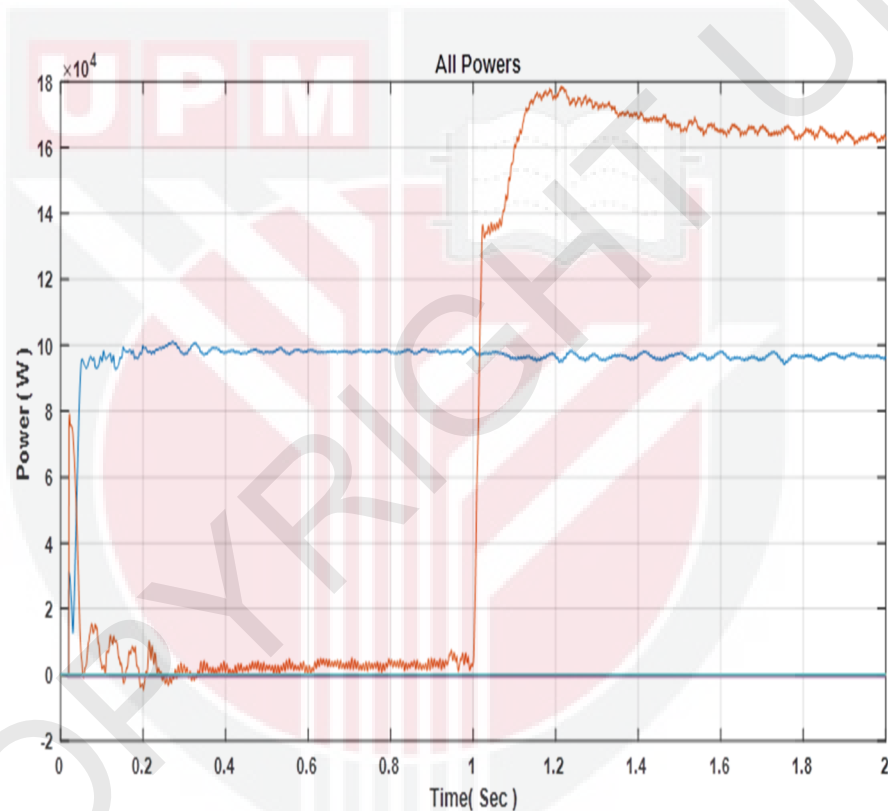


Figure 4.8: Power generated, power of Battery and grid power

4.4.5 Mode 5

In this mode, the load demanded was assumed to be constant and closed to 100 kW while the irradiance supplied at 25°C decreased from 1000 to 500 W/m^2 in 1 s. Figure 4.9a shows the PV-generated power profile curve for the

whole period. The decrease in irradiance decreased the amount of PV power generated from 200 to 100kW in 1 s and the battery discharged to supply the load demanded after 1 s.

In this mode: Between 0 to 1 s, the amount of PV power generated exceeded the load demanded. As such, the battery was in a charging state. If the battery's SOC remains within its specified operating limit and there is an excess of power from the PV cells, the PV system works. The excess PV power generated is utilized to charge the battery and ensure that it remains within the desired SOC range.

Between 1 to 2 s, the amount of PV power generated was equal to the load demanded. As such, the PV operated at its MPP and the battery was in an idle state as the load demanded was equal to the amount of PV power generated, which prevents the battery from charging or discharging. Figure 4.9b depicts the THD of the 3Ph voltage and current waveforms. As seen, at 0.6 s, the three cycles at a frequency of 50Hz caused a THD of 4.16% 0.8 s caused a THD of 4.56%

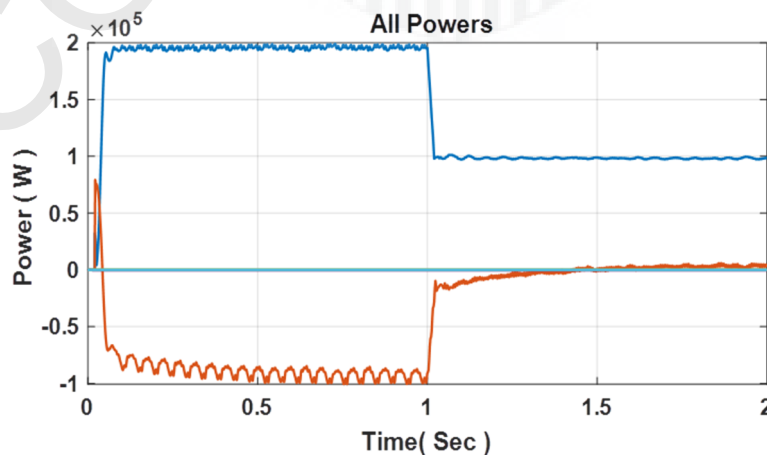


Figure 4.9a: PV power and Battery power

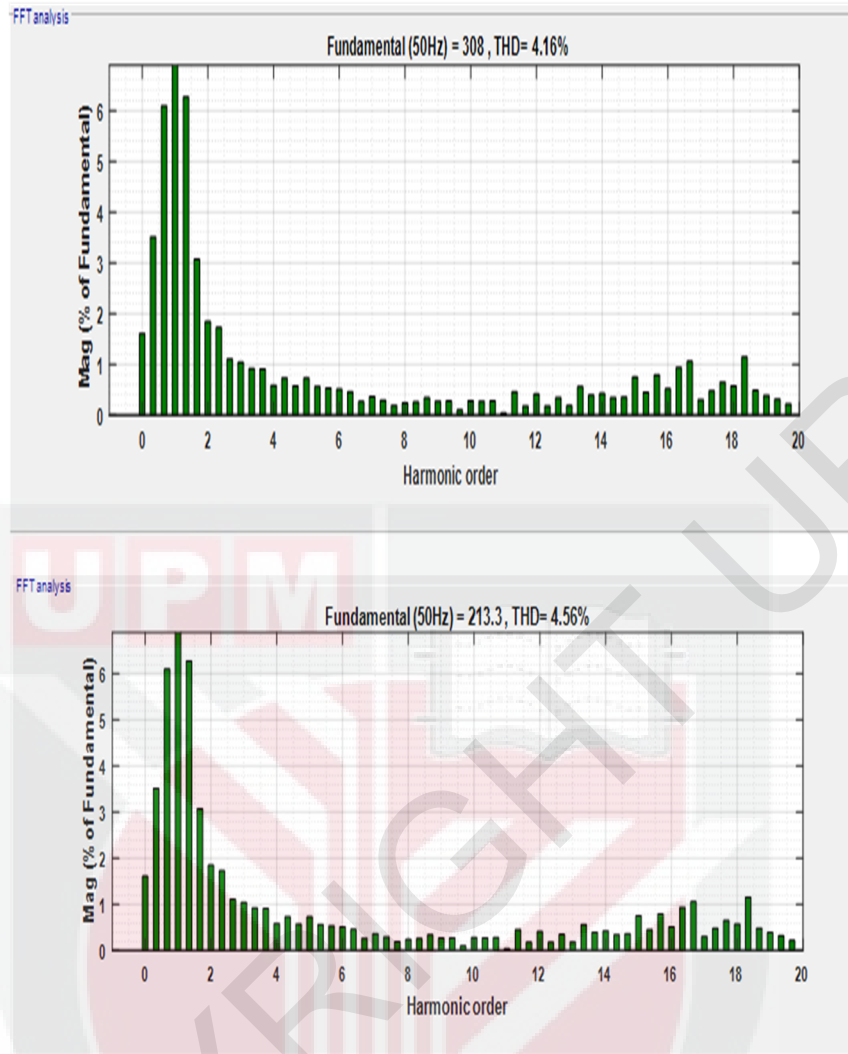


Figure 4.9b: Harmonics of Three Phase Voltage and Current

4.4.6 Mode 6

In this mode, the load was assumed to be constant and close to 250 kW while the irradiance supplied at 25°C changed from 1000 to 500 W/m² in 1 s. Figure 4.10a shows the PV-generated power profile curve for the whole period. The decrease in irradiance decreased the amount of PV power generated from 200 to 100kW in 1 s and the battery discharged to supply the load demanded after 1 s.

In this mode: Between 0 to 1 s, the amount of PV power generated was less than the load demanded. As such, the battery was in a discharging state. Between 1 to 2 s, the amount of PV power generated was less than the load demanded, with the load increasing faster than the PV cells can generate power. Therefore, hybrid systems offer crucial load independence from the grid as the battery will make up the difference, so long as it is not completely depleted, if the PV cells are unable to generate sufficient power to meet the load demanded. Figures 4.10b the voltage and current results and the THD with an LC filter.

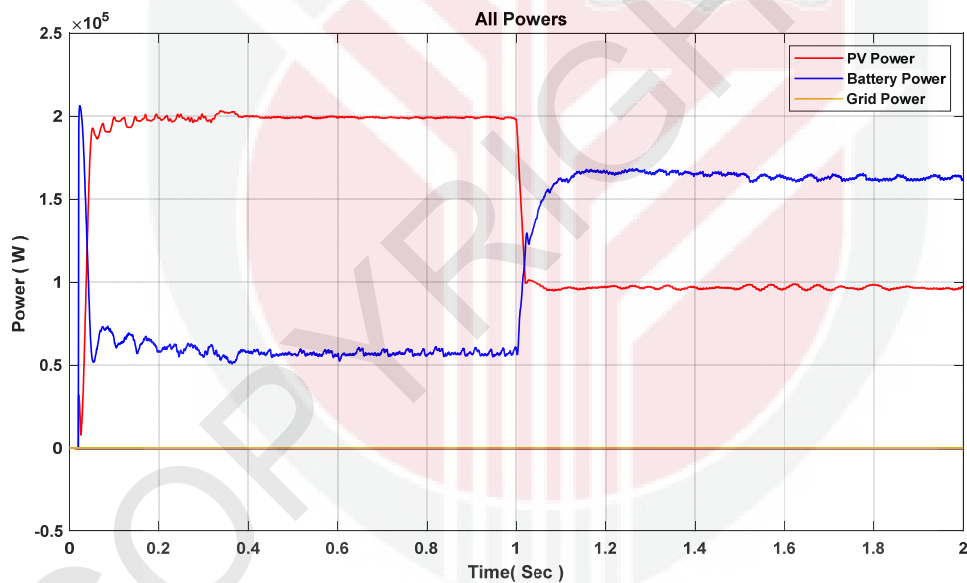
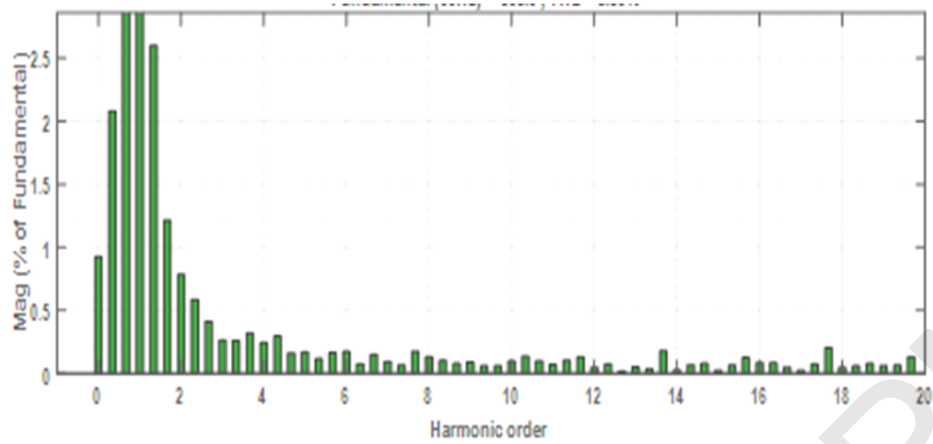
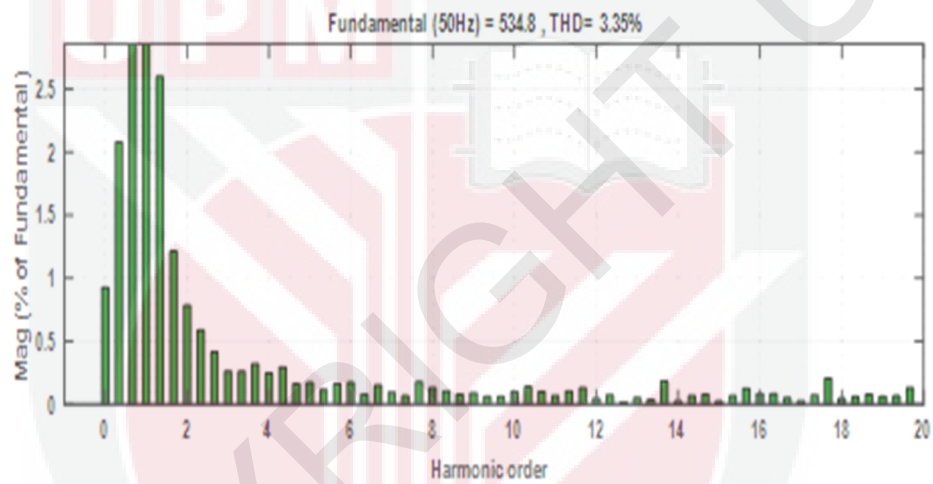


Figure 4.10a: Shows the power generated by of the PV system battery power and total power of hybrid



THD of three phase Voltage.



THD of three phase currents

Figure 4.10b: Harmonics of Three Phase Voltage and Current

4.5 Discussions

This study explores the dynamic behavior of photovoltaic (PV) systems in grid-tied configurations under various operating conditions. It investigates six distinct modes, each characterized by different load demands, PV generation profiles, and battery utilization. Furthermore, the analysis delves into power balance and quality, ensuring that the grid-tied system operates efficiently .

Both modes 1 and 2 experienced changes in PV-generated power from 200 kW to 100 kW in 1 second. In mode 1, the load demanded was 100 kW while in Mode 2 it was 250 kW. Battery power was used to compensate for PV delay and ensure that the load was continuously supplied. In Mode 2, the battery discharged to make up the power shortage during the PV delay. Its role also differed based on the load and PV characteristics of the two modes.

Both modes 3 and 4 experienced changes in load demanded from 100 kW to 250 kW in 1 second. Mode 3 experienced a constant irradiance of 1000 W/m² while it was reduced to 500 W/m² in Mode 4. The battery charged in Mode 3 when the amount of PV power generated exceeded the load demanded. This ensures a consistent supply of power. Meanwhile, in Mode 4, the battery remained idle as the amount of PV power generated was equal to the load demanded and only discharged when load demanded exceeded the amount of PV power generated. In modes 5 and 6 experienced constant load demands of 100 to 250 kW, respectively, with the amount of PV power generated changing from 200 to 100 kW in 1 s. Mode 5 utilized the battery to ensure continuous power supply when the amount of PV power generated exceeded the load demanded. In Mode 6, the battery discharged to make up the difference in power shortage when the amount of PV power generated was less than the load demanded. Therefore, the role of the battery switched from supplying power to covering power shortages according to the PV output.

Table 4.3 lists the differences between the discussed modes

Table 4.3: Comparison between modes 1-6

Model	Load Demand	PV Profile	Battery Utilization
1	100 kW	Rapid Shift 200 kW to 100 kW	Compensate for PV delays, maintain power supply
2	250 kW	Rapid Shift 200 kW to 100 kW	Discharge to bridge power deficit during PV delays
3	250 kW	Load Shift 100 kW to 250 kW	Charge when PV > Demand, maintain consistent supply
4	250 kW	Load Shift 100 kW to 250 kW	Idle when PV = Demand, discharge when Demand > PV
5	100-250 kW	Rapid Shift 200 kW to 100 kW	Engage battery for uninterrupted supply when PV > Demand
6	100-250 kW	Rapid Shift 200 kW to 100 kW	Discharge to compensate for power shortages when PV < Demand

In Off-the-Grid Self-Consumption (OGSC), the battery stores the excess PV power for later use to maximize energy use and minimize waste. It differs from the other modes as the battery behaves according to changes in the load demanded and the amount of PV power generated.

As the charging and discharging patterns of the battery changed according to the load demanded, the amount of PV power generated, and the conditions of the modes, it evidently played a critical role in maintaining a stable power supply in most of the modes. Its operation also changed depending on the PV delay as well as variations in the loads demanded and irradiance supplied.

Power balance between inverter generation, ES, and the voltage and current of the loads was achieved in all the modes. The THDs were within acceptable ranges as well; namely, 3.7% to 4.56%, which ensured that the power quality was maintained even under changing conditions.

The different modes were chosen to simulate realistic disturbances and operating conditions commonly faced in grid-tied PV systems. These scenarios address issues like changes in solar irradiance, load demand, and PV power generation delays, ensuring the energy management system can handle various challenges.

Modes 1 and 2: Simulate rapid drops in PV power (200 kW to 100 kW in 1 second), representing conditions like passing clouds. Mode 1 involves low load demand (100 kW), while Mode 2 evaluates high load demand (250 kW), with the battery compensating for PV delays.

Modes 3 and 4: Focus on changes in load demand (100 kW to 250 kW) under constant (1000 W/m²) or reduced (500 W/m²) solar irradiance. Mode 3 tests battery charging when PV power exceeds load, while Mode 4 examines battery behavior when PV matches or falls below the load.

Modes 5 and 6: Represent rapid PV power drops (200 kW to 100 kW) with constant load demands of 100 kW and 250 kW. These modes evaluate the battery's ability to store excess power or compensate for shortages.

Off-the-Grid Self-Consumption (OGSC): Tests the system's ability to work independently, with the battery storing extra energy during high PV generation and discharging during low PV generation.

The cost-effectiveness analysis including system costs like the PV system costs, battery costs, power electronics, grid connections, energy saving and revenue with the operational benefits like battery utilization, and improved power quality are addressed effectively in the next chapter.

4.6 Summary

Growing energy demands are expected to render existing energy resources insufficient. Solar energy faces challenges in terms of providing continuous and reliable power supply to consumers. However, it has become increasingly important to implement renewable energy (RE) and energy management (EM) systems to increase the supply of power, improve efficiency, and maintain the stability of energy systems. As such, this present study integrated energy storage (ES) devices; namely, batteries and direct current DC to DC converters; into energy systems that support battery operation and effectively manage power flow, especially during peak load demands. The proposed system also addresses low solar irradiation and sudden load change scenarios by enabling the battery to operate in a discharge state to supply power to the load. Conversely, when the demand matches or exceeds the available solar energy, the battery is charged using solar power. The proposed system highlights the significance of RE systems and EM strategies in meeting growing energy demands and ensuring a reliable supply of power during solar variability and fluctuating loads. A MATLAB® Simulink model was used to evaluate the integration of a 200kW photovoltaic (PV) array with a 380 V grid and 150 kW batteries. The loads, consisting of a 100 kW and a 150kW unit,

were parallel connected. The results indicated that boost and three-phase (3Ph) inverters can be used to successfully integrate PV systems to the power grid to supply alternating current (AC) power. The inclusion of a battery also addressed power shortages during periods of insufficient power generation and to store surplus power.



CHAPTER 5

SMART MICROGRID WITH OPTIMIZATION APPROACHES

5.1 Introduction

In today's world, energy is one of the primary and significant problems the world needs to overcome. Energy problems include generation, transmission, and receiving problems, but the most important is excess and maintaining electricity production and distribution demand. Research shows that 15% of the people around the globe have no electricity usage due to any access or are away from the grid stations and live in off-grid areas. The only solution for the off-grid community to provide electricity is installing renewable systems in those areas [202]. Environmental activists encourage people and authorities to install renewable systems like PV, Wind, and Biomass. According to estimated research, in 2035, renewable energy will be counted as one-third of the total energy in the world. To achieve long-term expectations from the system, it is necessary to carefully isolate and predict the solar system of the region where it is installed and keep the door open to expand the system further when the demand increases [203]. The engineer also plays a vital role in making these systems more efficient by improving the power demand and quality and maintaining the system grid stability for unpredictable solar irradiation and sudden climate weather conditions [204]. Renewable becomes more stable when a backup system is installed, which works when sudden climate change occurs and at nighttime when no solar power is available [205].

The use of ESSs also increased pollution emissions. The idea of a smart grid was introduced due to renewable energy and storage issues. An intelligent system in the shape of a smart grid was developed, which provided energy to loads by performing a bi-way communication between them through an advanced measuring infrastructure (AMI) [206]. Different renewable sources, i.e., Diesel generators, MT, etc., are used by smart grids to provide electrical energy to different types of load [207]. The energy requirement of the consumers is made possible by the exchange of energy between utility and smart grid due to uncertainties in renewable sources [208]. Obtaining the energy with minimum operating cost cannot only be solved by modeling the source side. Different DSM strategies can be used to deal with it. A vast amount of contribution has been made to energy management in smart grids by optimizing its source side as well as consumption side research. The reduction of operating costs and pollution emissions, the MOPSO algorithm is used, whose optimal solution uses fuzzy-based logic [209]; however, they have not considered peak average ratio (PAR) to reduce peaks in the system. Modeling uncertainty in renewable energy sources and reducing cost and emission in [210] by MOPSO algorithm. [211] introduced an efficient energy management system that successfully reduced the cost of storage systems under DSM strategy by using Branch and Reduce Optimization Navigator (BARON); however, carbon emission due to EES was ignored. Demand was managed by real-time pricing aided by an inclined block rate. Also, power scheduling is performed by normalizing its function using the Genetic algorithm [212]. Dual composition is used to model constraints in a real-time proposed system that performs a two-way communication [212] for optimal scheduling.

In [213], the cost associated with energy consumption is reduced by using an artificial bee colony (ABC) algorithm and a quasi-static technique that also improves the load factor. Non-dominated genetic sorting algorithm II (NSGA-II) is used to reduce the microgrid's operating cost [214], increasing the system's efficiency by using PVs, batteries, and utility grid as the energy inputs. SQP algorithm is used in [215] to increase customer comfort by reducing customer bills and PAR with the B technique. This algorithm solves the above equation as a mixed integer linear programming (MILP) problem [216]. It introduces the concept of DC microgrids, which has reduced the system's cost and increased its availability [217]. Two scenarios describe results obtained from the Multi-Objective Genetic Algorithm (MOGA). Operating cost and pollution emissions are minimized using the MOPSO algorithm, whose results are distributed to 3 scenarios [218]. Cost, emission, and customer satisfaction were modeled as the three objectives in [219] using a non-dominated genetic sorting algorithm III (NSGA-II) algorithm. At the same time, the load factor has not been improved. In [220], DSM Load curtailment and shifting strategies are used to reduce operating costs and pollution. ϵ -constraint approach is used to solve Mixed Integer Non-linear Programming (MILNP) and obtain Pareto fronts. The comparison is drawn for different techniques to reduce consumption and operating costs in an intelligent grid. [221] also described different algorithms, i.e., MOPSO and GA. PSO, MILP, etc., for obtaining objectives. In [222], the total cost of the smart grid is reduced by using the MAPPO algorithm. Real-time pricing (RTP) and load schedules were used as the DSM method's optimal functioning. [223] described different DSM strategies for an intelligent microgrid to work for demand response. Case

studies showed that peak clipping, valley filling, and load shifting were experimented with to operate microgrids [224]. Minimizing operational costs and energy consumption are the important issues considered in smart grids. [225] uses artificial intelligence (AI) techniques for different management applications, i.e., integrating renewable sources, Demand side management, ESS summation, and energy management smart grid. The peak-to-average ratio is minimized by reducing the peak load for residential consumers using load shifting as DSM strategy, and results were formulated for both cases with and without DSM strategy [226]. [227] proposed an energy management system (EMS) for an intelligent building that increases customer comfort by managing the system's cost and energy consumption, which also increases the overall security. A fair pricing scheme is introduced to help reduce low-energy consumers' bills by introducing a fair pricing scheme as in [228] that helps him calculate the energy cost of both high-energy consumers and low-energy consumers and charge them accordingly [229] and reduces computational costs for managing energy consumption in smart building (SB) using genetic algorithm (GA) with DSM strategies. The smart grid architecture model (SGAM) is presented in [230] and uses powerful tactics for modeling the condition of a microgrid on the generation and management sides. In [231], different algorithms are compared for demand-side management strategies to reduce operating costs and energy consumption in a smart grid. Cost and PAR are minimized for load in a residential area, and an optimal scheduling model is proposed for EVs in smart grids by MILP, whose results are optimized under the proposed model [232-233] uses Grey wolf optimization for optimal energy management in PHEVs, and Monte Carlo simulations model intermittent

behavior of renewable sources. Table 5.1 summarizes the findings from the survey above.

Table 5.1: Summarizes of literature review

Ref	Method used	Comments
[209]	Fuzzy-based.	The researcher have not considered peak average ratio (PAR) to reduce peaks in the system.
[210]	MOPSO algorithm.	Considering the pollution function as the main objective, but the operational costs was increased.
[211]	Branch and Reduce Optimization Navigator (BARON).	Carbon emission due to EES was ignored.
[212]	Dual composition.	Considering the cost, technical issues as the main objective, Carbon emission was ignored.
[213]	Artificial bee colony (ABC).	Considering the cost, technical issues as the main objective, Carbon emission was ignored.
[214]	Non-dominated genetic sorting algorithm II (NSGA-II).	Focusing on the consumer's bill and the consumers are also able to sell power to the main grid, but Carbon emission was ignored.
[215]	SQP algorithm.	Focusing on the consumer's bill and the consumers are also able to sell power to the main grid, but Carbon emission was ignored.
[216]	Mixed integer linear programming (MILP).	Focusing on increase the availability and reduce network costs, but Carbon emissions was ignored.
[217]	Multi-Objective Genetic Algorithm (MOGA).	Focusing on the home appliances scheduling problem that incorporate realistic aspects and was ignored User Comfort, Electricity cost.
[218]	MOPSO algorithm.	Focusing on two objectives that are operation cost and emission's propagation and was ignored User Comfort.
[219]	Non-dominated genetic sorting algorithm II (NSGA-II) algorithm.	The load factor has not been improved.
220	Mixed Integer Non-linear Programming (MILNP).	User Comfort was not taken into consideration.
222	MAPPO algorithm.	Reducing the total cost of the smart grid, but was not considering the other parameters.
226	DSM strategy.	Focusing on the daily consumption patterns, but was not considered the other parameters.
227	Energy management system (EMS)	Focusing on home management and privacy issues and was ignored the cost.
228	A fair pricing scheme.	Focusing on reducing the cost and was ignored emissions and user Comfort.
229	Genetic algorithm (GA).	Focusing on reducing the cost of the consumer regardless of the impact on consumer comfort.
230	The smart grid architecture model (SGAM).	Focusing on challenges cybersecurity aspects related with impact on consumer comfort. The cost and emission's propagation were ignored.
231	Different algorithms are compared for demand-side management strategies.	A number of algorithms have been used as optimization problems, which it leads to difficulty in application, difficulty in regular maintenance, and complexity during work.
232	Mixed integer linear programming.	Focusing on reduces the energy cost of the residential household, while reducing costs without making a comparison with consumer convenience.
233	Grey wolf optimization.	Focusing on User Comfort and was ignored the cost and Peak to Average Ratio

It is clearly understood from the above research that many numbers of models have been proposed that were efficient in reducing cost and energy consumption in intelligent grids, but still, substantial research gaps in proposed models are left in terms of several technical and physical factors that are: Different models have reduced operating and emissions but ignored energy consumption and consumer comfort, which produced inconvenience on the customer side. Load curtailment and Load shifting are used as demand response programs that have also caused discomfort to customers.

This study represents a scheduled way to minimize operating costs and energy consumption in an intelligent microgrid consisting of WTs, PVs, MTs, and ESSs. The proposed model supplies energy to residential types of consumers (RC). Non-dominated genetic sorting algorithm II (NSGA-II) is adopted to find the Pareto fronts of the optimization problem, and the real solution is selected by the decision-making method. The rest of the paper's organization is: Section 2 introduces the concept of a smart grid. The system model is explained in Section 3. Section 4 deals with the proposed methodology and its related approaches for the optimization problem. In Section 5, simulations and results are discussed. Finally, a conclusion is drawn in Section 6.

5.2 Overview of Smart Microgrid

A smart microgrid is a technical device that provides electrical energy to loads using intelligent energy meters, which perform a bi-way communication between the system and the utility grid. Daily load demand from the customer

is received by the smart meter in the installed advanced metering infrastructure (AMI) in a typical micro smart grid. The smart meter also receives electricity prices a day ahead of the utility. After receiving both price and demand, it devises a plan to supply optimal energy to load connected, observing all technical, economic, and environmental situations. Figure 5.1 shows an overview of a smart grid in which photovoltaic cells (PVs) and wind turbines (WTs) are used as renewable energy resources, Micro Gas Turbines (MGTs) are used as distributed energy sources (DESS), Electrical energy storage systems (ESSs) in the form of batteries are used as storage elements, and utility grid (UG) is used to exchange power with the system when required. Three classes of consumers, including Residential Consumers (RCs), Commercial Consumers (CCs), and Industrial Consumers (ICs), are used as loads.

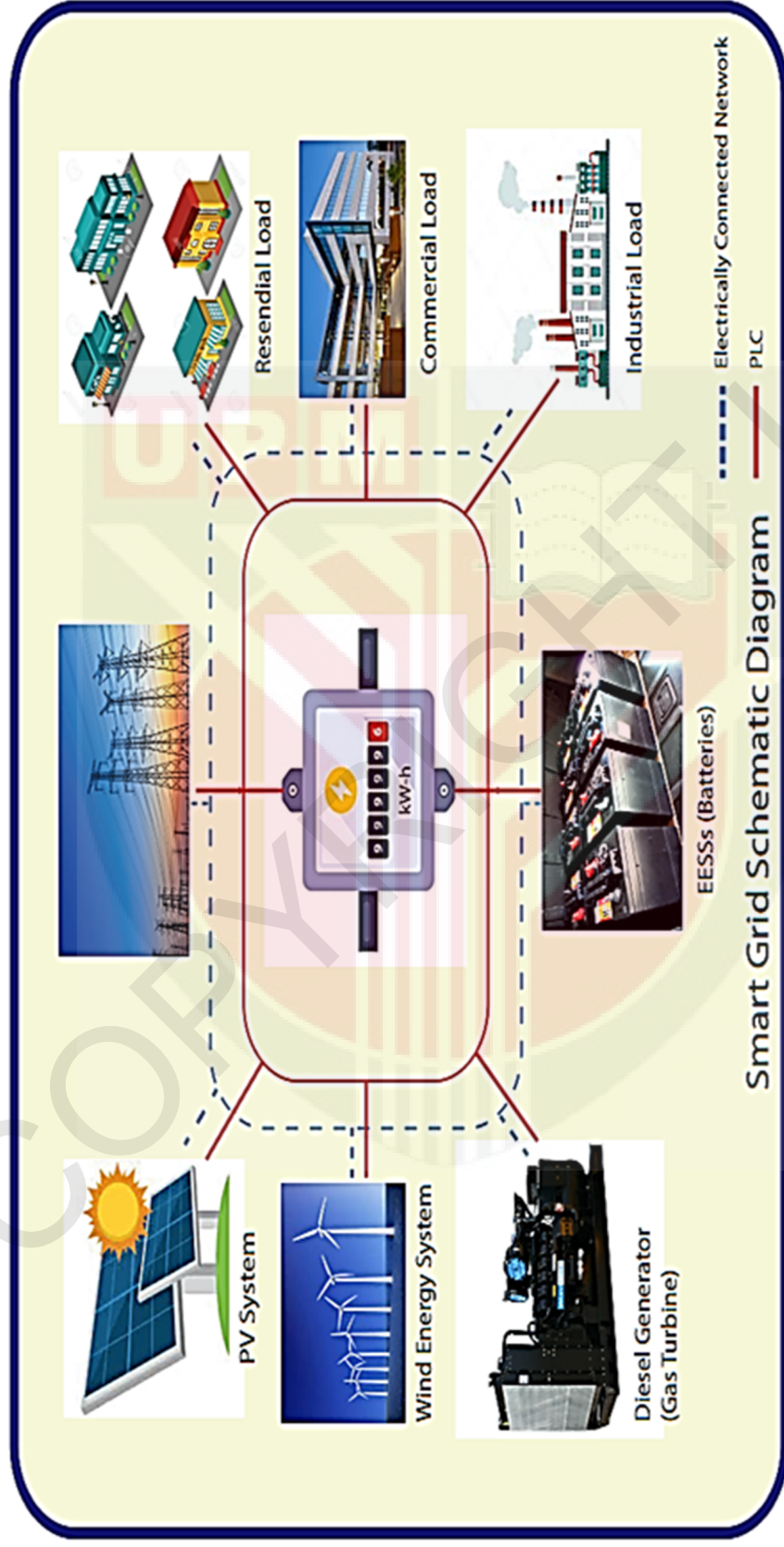


Figure 5.1: Smart Microgrid

5.3 System Model

A. Supplied Power Resources

Supplied Power resources are the energy sources that transmit the generated energy to the total number of loads connected with the proposed model. The number of power-provided sources in our proposed model is of two types with known and unknown resources. Our proposed model, as described in 2 Micro Turbines (MTs), constitutes known resources, whereas PV and wind turbines (WTs) explain the unknown resources. Batteries are used as Electrical energy storage systems (ESSs) in the model, along with the power resources. The exchange of electricity is made possible by using a utility grid (UG) between the customer and the energy distributor in the proposed model.

B. Load types

The type of load fed by our model consists of different home appliances, i.e. electric bulbs, fans, water motors, washing machines, etc., with a maximum load range of 4-35 kW, falling into the residential consumer category. Uncertainties are associated with renewable energy resources due to their erratic behavior i.e. solar source (PV) and wind depend on availability. Both renewable energy resources crucially depend on atmospheric conditions and climate which makes them vulnerable to obtaining their 24-hour day-ahead forecast. Different types of stochastic and probabilistic techniques containing fuzzy-based logic, beta PDF and CDFs, Maximum likelihood and Bayesian methods, and Monte Carlo (MC) simulations are used to model the intermittent

behavior of PV and wind [234]. Our proposed model uses the probabilistic method to overcome the uncertain behavior of renewable sources. Solar and wind uncertainty is tackled using solar radiance, wind speed, and ambient temperature, as discussed in subsections.

C. PV Modeling

The photoelectric effect is used as a base for solar power generation by converting the light from the sun to electrical energy. The light rays in the form of solar radiation from the sun are utilized and absorbed by the material and converted to electrical particles that constitute the DC form of electricity. Beta PDF and linear power are used to model the uncertainty by the use of ambient temperature and solar radiance (si) in 1 and 2. [219, 235].

$$L(si) = \begin{cases} \frac{\lambda(\sigma+\phi)si^{(\sigma-1)}(1-si)^{(\phi-1)}}{\lambda(\sigma)\lambda(\phi)} & 0 \leq si \leq 1, \sigma \geq 0, \phi \geq 0 \\ 0 & \end{cases} \quad (5.1)$$

$$N(x) = TH_a + \frac{si}{si^{def}} \times (T_N - 20), t \in (1, \dots, 24) \quad (5.2)$$

Where T_e is the ambient temperature, si is the solar irradiance, and T_N is the nominating cell temperature. σ and ϕ are the parametric value of beta PDF given as in 3 and 4;

$$\sigma = \alpha \left(\frac{\alpha(1+\alpha)}{\varphi^2} - 1 \right) \quad (5.3)$$

$$\phi = (1 - \alpha) \left(\frac{\alpha(1+\alpha)}{\varphi^2} - 1 \right) \quad (5.4)$$

Solar power can be determined by equation 5 using the values obtained from the above functions.

$$SP_s = S_s^{def} \times \frac{si}{si^{def}} \times (1 + \xi \times (N(x) - N(x)^{def}) \times M_{sc} \times \theta_{sc}) \quad (5.5)$$

D. Modeling of Wind

A wind turbine generator (WTG) is used to produce wind power. The mechanical energy of wind is converted to electrical energy by WTG. The use of wind power is increasing exponentially; however, wind power generated is also associated with different uncertain and unknown elements that make it vulnerable to predicting its factual day forecast. The wind's direction, speed, and wind speed characteristic curve are the elements that affect the generated wind power. Waybill PDF utilizes wind speed as the modeling element to control the uncertain behavior of wind as given in equation 6 [219].

$$X_v(S_v) = 1 - \exp\left(-\left(\frac{S_v}{\beta_s}\right)^2\right) \quad (5.6)$$

β_s is the value assumed of the scalar parameter of wind speed. It is given by equation 7.

$$\beta_s = \frac{2}{\sqrt{\gamma}} S_r \quad (5.7)$$

While S_r is the measured speed of wind for modelling the Wei-bull PDF given in equation 8.

$$S_r = \beta_s \zeta \left(1 + \frac{1}{2}\right) \quad (5.8)$$

Wind power output is calculated by equation 9 [232].

$$E_{WTurbine} = \begin{cases} 0 & S_s w < S_{st} \\ E_w \left(\frac{S_s w - S_{st}}{S_w - S_{st}} \right) & S_{st} \leq S_s w < S_w \\ E_w & S_w \leq S_s w < S_{sf} \\ 0 & S_s w \geq S_{sf} \end{cases} \quad (5.9)$$

Where E_w , $S_s w$, S_{st} , S_w and S_{sf} are the rated WT power, speed of the wind, cut-in speed of the wind, rated speed of the wind, and cut-out speed of the wind respectively.

5.4 Objective Functions

The main objective of our model is to simulate a smart microgrid to reduce operational expenses and energy usage. Bi-objective functions are utilized to optimize the smart grid in the proposed model, which is described as follows;

1. Operating cost, the first objective function

This function minimizes the cost associated with the operation of the smart grid, known as the operational cost of the smart grid as given in equation 10:

$$\min OB_1 = \sum_{c=1}^C \mu_c \sum_{t=1}^T (\sum_{g=1}^G PRICE_{MT}(c, t, g) + \sum_{e=1}^E PRICE_{Battery}(c, t, e) + PRICE_{Utility}(c, t)) \quad (5.10)$$

2. Energy Consumption, the second objective function

The energy utilized by the smart grid under study is given by equation 11:

$$\min OB_2 = \sum_{h=1}^H ES_{MG}(h) \times TimeS_{MG}(h) \quad (5.11)$$

5.5 Smart Grid Constraints Performance and Metrics

Some limits must be observed to operate the microgrid effectively, known as constraints. Constraints impose bounds on the smart grid that affect the overall efficiency. Technical conditions for renewable sources and power balance constraints constitute the general constraints for the smart grid. Smart Grid performance metrics [236, 237] and constraints are utilized in our model which is described in the subsection:

1. Power balance

This constraint is used to model the generated power and load required in our model. According to this constraint, the power provided to the model must be equal to the power utilized by consumers as in equation 12.

$$\sum_{c=1}^C \mu_c \sum_{t=1}^T ((\sum_{g=1}^G P_{MT}(c, t, g)) + (\sum_{sc=1}^{SC} P_{sc}(c, t, sc)) (\sum_{tv=1}^T VP_tv(c, t, TV)) + \sum_{s=1}^S P_{battery}(c, t, s) + P_{GRID}^{Bought}(c, t)) = \sum_{c=1}^C \mu_c \sum_{t=1}^T T(P_{RESLOAD}(c, t) + P_{COMLOAD}(c, t) + P_{INDLOAD}(c, t) + P_{GRID}^{Sell}(c, t)) \quad (5.12)$$

2. Electricity cost

The rate structure is one based on real-time pricing (RTP), with tariffs changing throughout the day, every day, to reflect the actual cost of energy. There would

be no demand costs with RTP, just energy prices that may change on an hourly basis.

3. The Performance Assessment Ratio (PAR)

Represents the proportion of the highest energy consumption level to the average energy consumption level over a specific timeframe. To decrease PAR and prevent peak power plant operations, utility providers encourage customers to shift their energy consumption from on-peak to off-peak timeslots. This PAR reduction is beneficial for both utility companies and customers due to two main reasons: first, it smoothens out the load curve and reduces peaks in the demand load curve, and second, it lowers the energy costs for consumers. The PAR can be computed by dividing the highest energy consumption level by the average energy consumption level during the designated period.

$$PAR = \frac{\max(E_{tot}(t))}{\frac{1}{T} \sum_{t=1}^T E_{tot}(t)} \quad (5.13)$$

4. Carbon emissions

It represents the CO₂ emissions in kg/kWh as in equation 14:

$$CO_2 = \frac{EP_{avg}}{\mu \times \gamma} \quad (5.14)$$

Where EP_{avg} indicates the average monthly energy bill and reflects the price per kWh. μ refers to the average price per kWh which is set to 0.2\$, while γ represents the electricity emissions factor which is almost 1.37.

5. User Comfort

This research investigates user comfort by assessing the duration of time consumers must wait for an activity after their energy consumption shifts from on-peak to off-peak timeslots. As consumers transfer their loads to off-peak hours, they may experience some level of discomfort. The analysis highlights a trade-off between the cost of energy and waiting time, wherein reducing energy costs may increase waiting time, and vice versa. The research emphasizes the importance of minimizing the waiting time for consumers, and identifies it as a key factor in evaluating user comfort concerning load switching between on-peak and off-peak timeslots, user comfort is

$$waiting(Delay) = \frac{\sum_{t=1}^T |(T_{unsch}(t) - T_{sch}(t))|}{\sum_{t=1}^T T_{sch}(t)} \quad (5.15)$$

The User Comfort (UC) is calculated in terms of waiting time/delay that an appliance faces due to scheduling and un scheduling periods and the status of an appliance.

6. Storage System E_{Smin}

This section will go through the suggested energy storage systems and their formulae. Because ESS has specific limits, such as charging, the lowest and maximum charging levels are represented by E_{Smin} and E_{Smax} , respectively. The state of charge (SOC) is thought to be between 20% and 80% of its maximal value. The stored energy of ESS is denoted by:

$$SE(t) = SE(t - 1) + \tau \cdot \eta^{ESS} \cdot EE^{char}(t) - \frac{\tau \cdot EE^{discharge}(t)}{\eta^{ESS}} \quad (5.16)$$

where SE indicates energy stored and measured in (kWh) at time t , η^{ESS} implies ESS efficiency, τ defines the period in hours, EE^{char} represents power provided by the solar and wind systems to batteries, and $EE^{dischar}$ means power supplied from batteries to load. The following constraints have been imposed to keep charging/discharging within limits and to prevent deep discharge/overcharge.

$$EE^{char} \leq EE_{max}^{char}, EE^{dischar} \leq EE_{min}^{dischar}, \text{ and } SE \leq SE_{max}^{char} \quad (5.17)$$

We will detail the approaches we suggested in our study in this part. To mimic optimization challenges, a non-dominated genetic sorting algorithm (NSGA-II) is utilized. The decision-making technique was used to choose the best choice from among the non-dominated alternatives. We will also go through the approaches that have been used in the past. Three alternative scenarios demonstrating the optimal value of operating cost and energy usage were presented for the proposed algorithm's outcome analysis. The NSGA-II algorithm with renewable energy resources without RES was the first scenario, while the same method with RES only is the second scenario and optimum scheduling of RES and ESS was the last scenario to reduce expenditures and energy usage.

5.6 Proposed Algorithm

A. NSGA-II

In our proposed model to obtain Pareto fronts, we have used non-dominating sorting genetic algorithm II (NSGA-II). Using the concept of crowding distance

and non-dominated sorting, an optimal solution from the obtained Pareto fronts is generated by NSGA-II . The overall algorithm is illustrated in Figure 5.2.

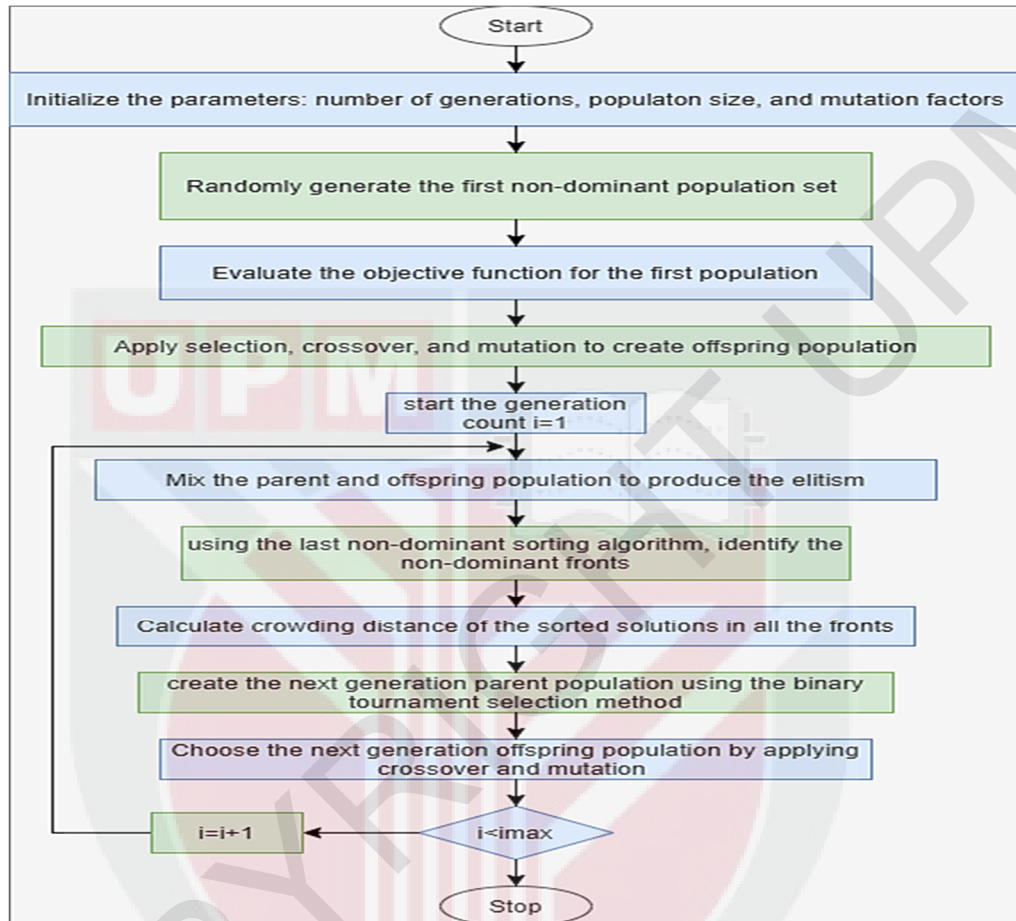


Figure 5.2: NSGA-II algorithm Steps

B. BPSO Algorithm

The Binary particle swarm optimization (BPSO) algorithm is another approach for identifying the best solutions within a given search area. While it is typically used in a continuous area, it can be adapted for use in a discrete domain, which is known as BPSO. The four primary determinants of BPSO are the particle's initial position, starting velocity, own best position, and global best position. BPSO begins by creating a search space and randomly distributing a

population throughout the space. In each step of the algorithm, the particle speeds are updated using Equation (18),

$$\sum_{t=1}^{C24} \sum_{i=1}^I \sum_{t=1}^{C24} \sum_{i=1}^I U_1^{t+1} = \sum_{t=1}^{C24} \sum_{i=1}^I UV_1^t(j) + Z1K1(Xibest, i(j)) + Z2K2(Xigest, i(j) - X_{i1}^t(j)) \quad (5.18)$$

Where U is the inertia factor, U_j^t is current velocity. U_i^{t+1} is the velocity of a particle random numbers are $k1$ and $k2$, while $z1$ is the local pull and $z2$ is the global pull. X_i^t is the particle's current position, $Xigest$ is the local and $Xibest$ is the global best position. Equation (19) is used to map the velocities of particles between 0 and 1.

$$sim(U_i^{t+1}(j)) = \frac{1}{1 + \exp(-U_i^{t+1}(j))} \quad (5.19)$$

C. BFO Algorithm

Bacterial foraging optimization (BFO) is a program that takes inspiration from natural processes. This algorithm has become popular among researchers due to its success in solving practical problems. In the natural world, bacteria swim towards the best sources of nutrients and optimize their energy, and the BFO algorithm models this process by considering several solutions, or "nutrients". BFO follows a four-step process that is similar to the WDO algorithm: reproduction, movement, elimination-dispersal, and chemo taxis. BFO uses specific criteria to guide its search process. Under the chemo taxis step, the system initializes the parameters and examines the initial positions of the particles, before calculating new positions of the bacteria in the solution

matrix. The swimming cycle is started in the second phase to determine the appliances' present best state. Following this action, the reproduction cycle iterates, selecting only the fittest options to create the new population. The final step is to remove the least fitting solutions and replace them with fresh random samples that have a reduced likelihood. This is a crucial stage because it eliminates the least fit options and reduces the likelihood of recurrence. The overall proposed model of the Microgrid operation system is represented in Figure 5.3.



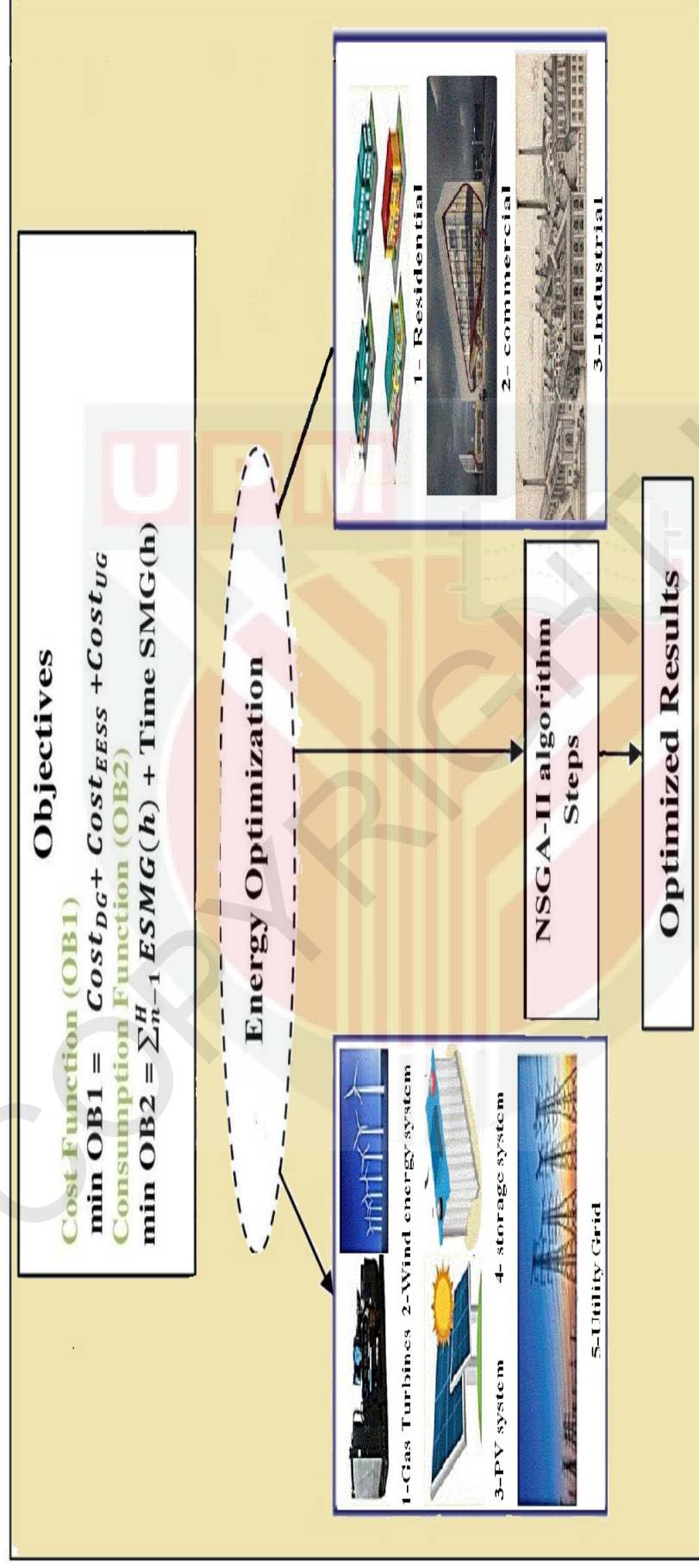


Figure 5.3: The proposed model of the Microgrid operation

5.7 Simulations and Result Analysis

In this part, we provided the simulation results of the suggested NSGA-II approach, along with comparisons to the other two meta-heuristics methods (PSO, and BFA). This system evaluates the integration of RESs, ESS, and the performance of the NSGA-II algorithm in three situations. The first scenario includes neither RES nor ESS, whereas the second includes just RES and the third includes both RES and ESS where the first objective function, is the system's operational cost, and the second objective function, energy consumption in a smart grid with ESSs, is investigated. A user with 6 passive appliances and an ESS is regarded as a source to implement the proposed NSGA-II. To support the load of premises we have made the power supply of the electric utility companies (EUCs) accessible 24 hours a day. To fulfill the needs of residential customers, the suggested model includes MTs, PVs, WT, and batteries. The suggested model is simulated using the MATLAB 2021b software version, and the simulation time is varied depending on the case under study. The day-ahead 24-hour values of wind speed and solar irradiance are shown in Figure 5.4. Figures (5.5-5.8) illustrate the eruptive grid signals (forecast temperature).

Purchased energy cost (RTP), battery charging levels, and overall load demands) utilized in the proposed study. PV system power production is mostly determined by solar irradiation and ambient temperature. As shown in Figure 5.9, we examined 90% of the total RE in any scheduling time window. In addition, of the 90% of RE utilized for charging the ESS, 30% is consumed

in each time slot. Figure 5.10 displays the NSGA-II algorithm solutions for this situation, with iteration 110 picked as the best response by the decision-making process since it is the closest to the ideal point.

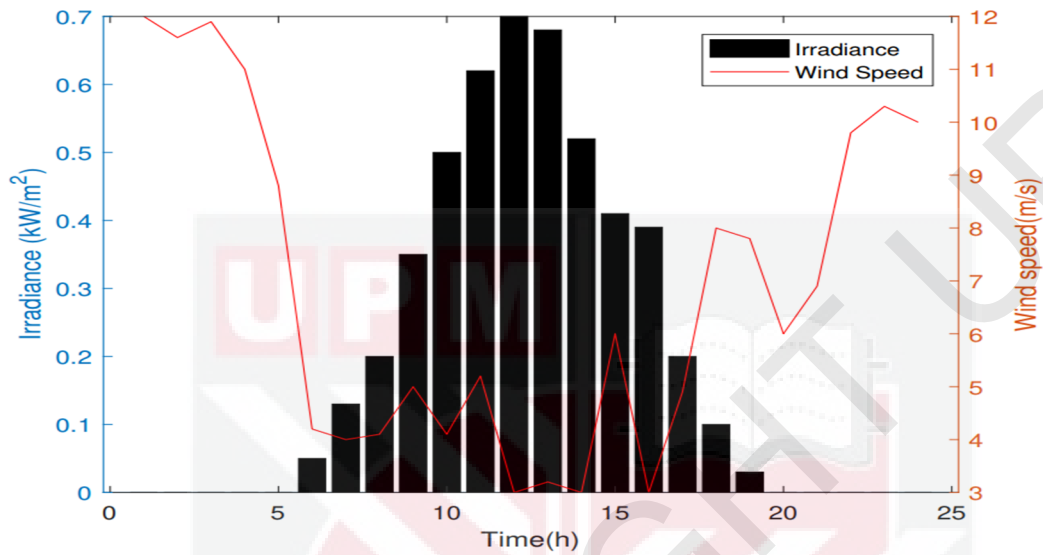


Figure 5.4: Solar intensity and speed of wind

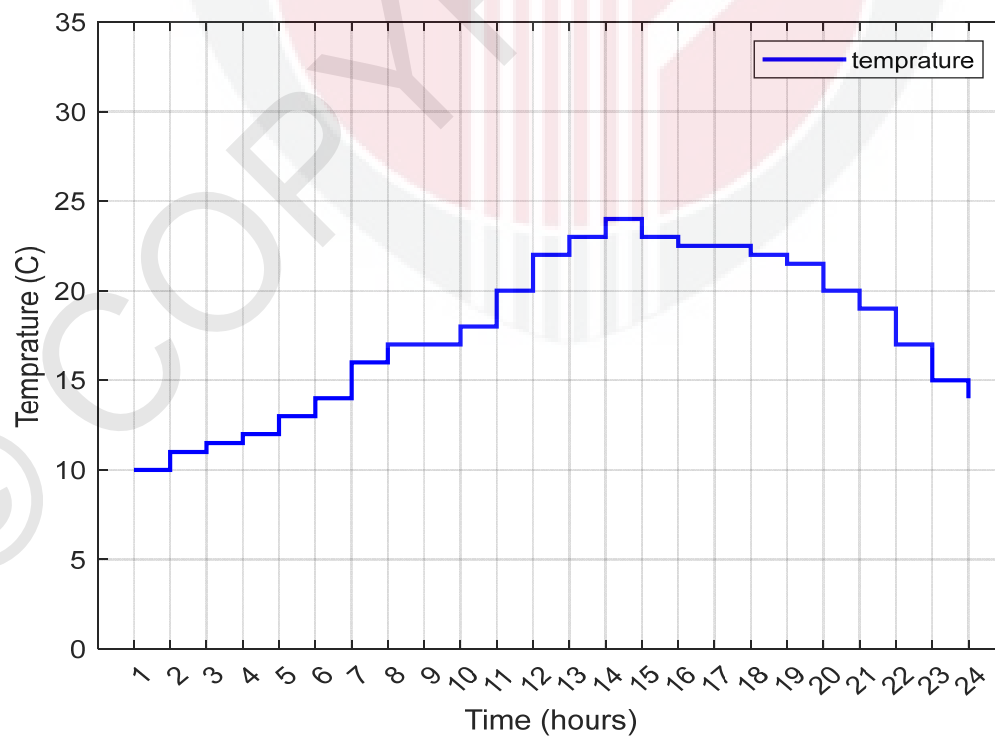


Figure 5.5: Daily forecast temperatures

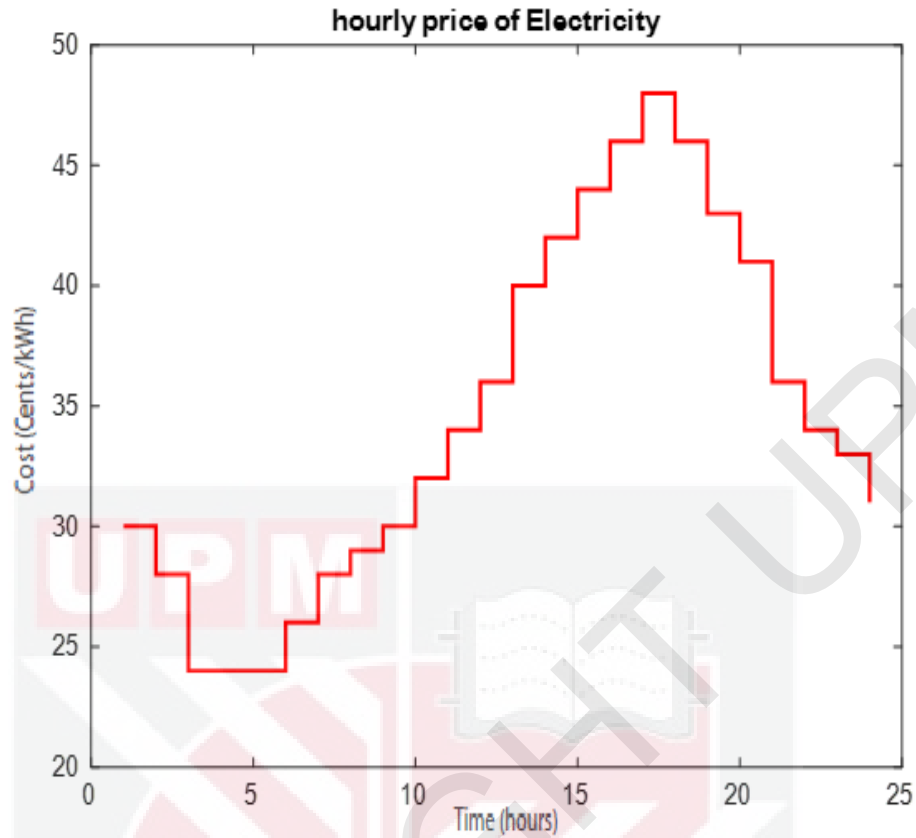


Figure 5.6: Purchased energy cost

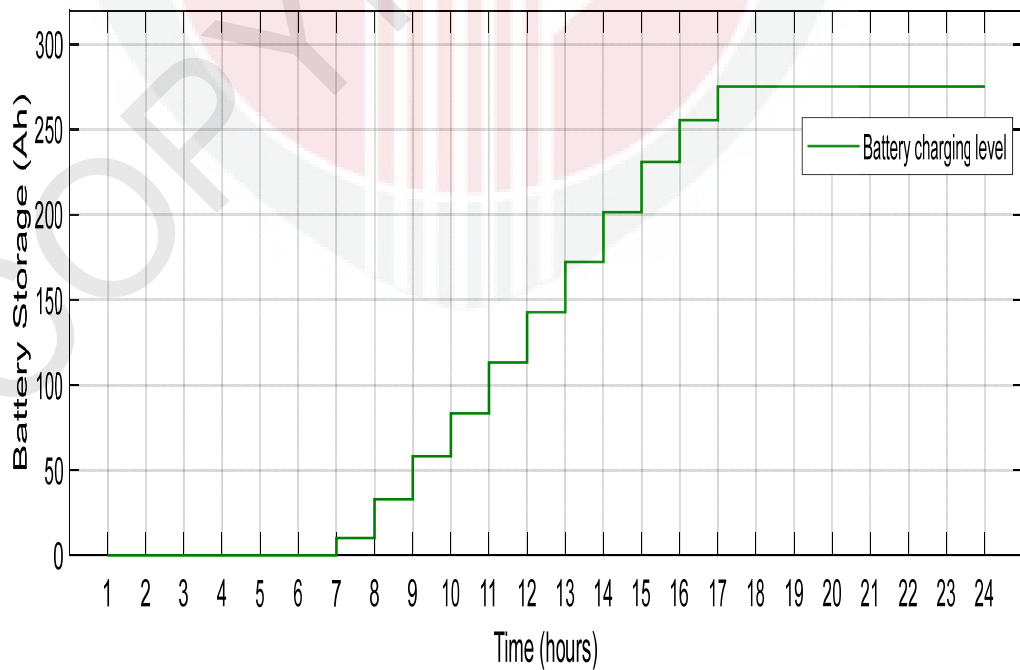


Figure 5.7: Daily battery storage

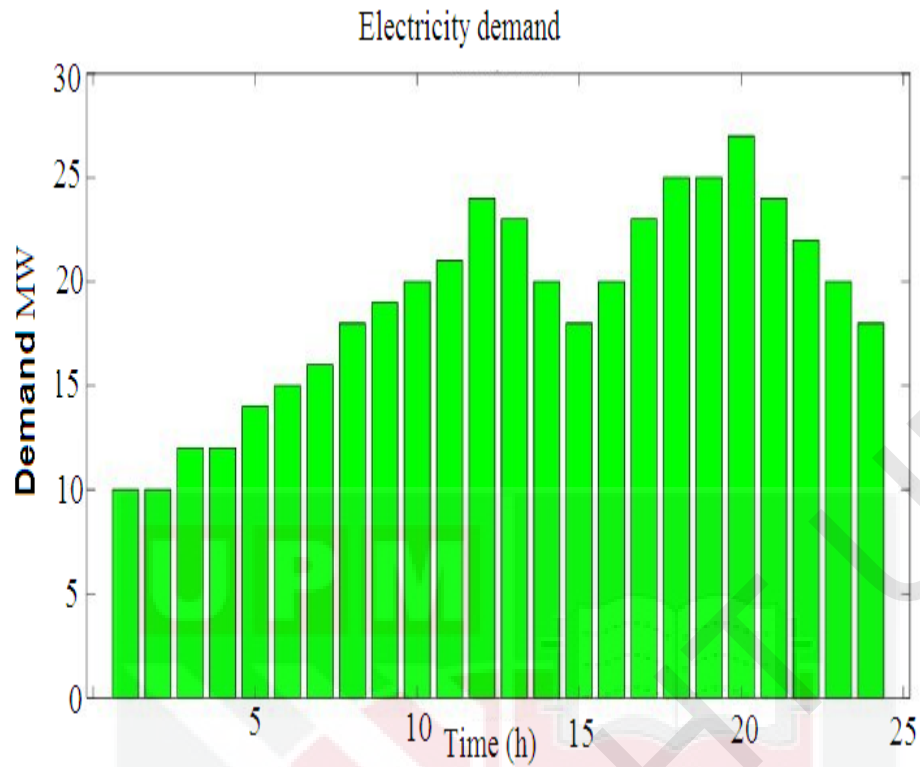


Figure 5.8: Overall load demand

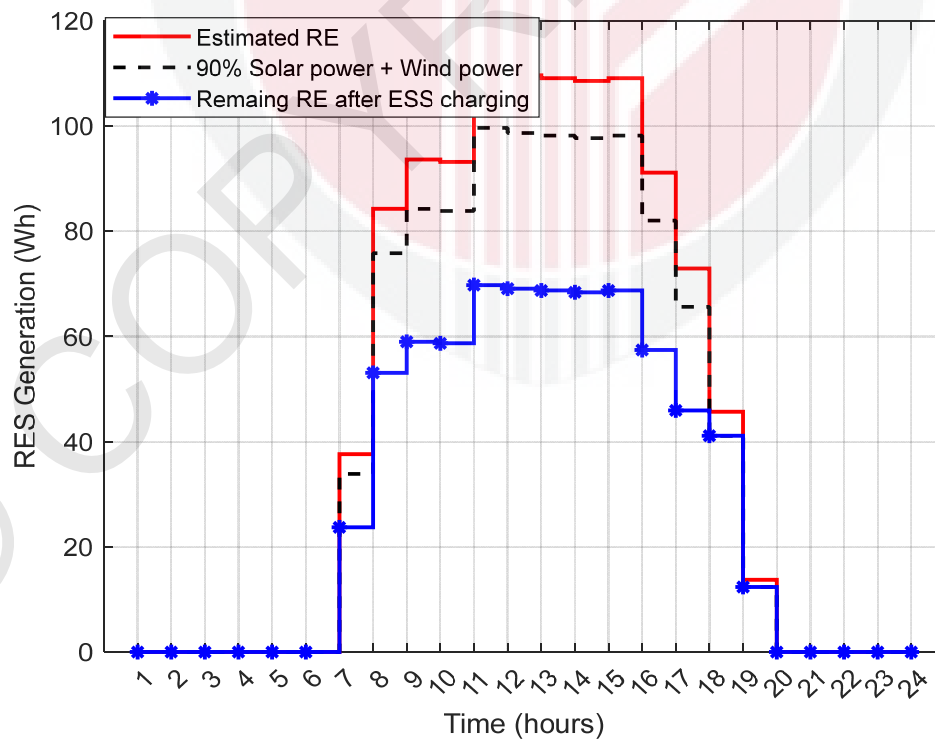


Figure 5.9: The expected RE and ESS charging level

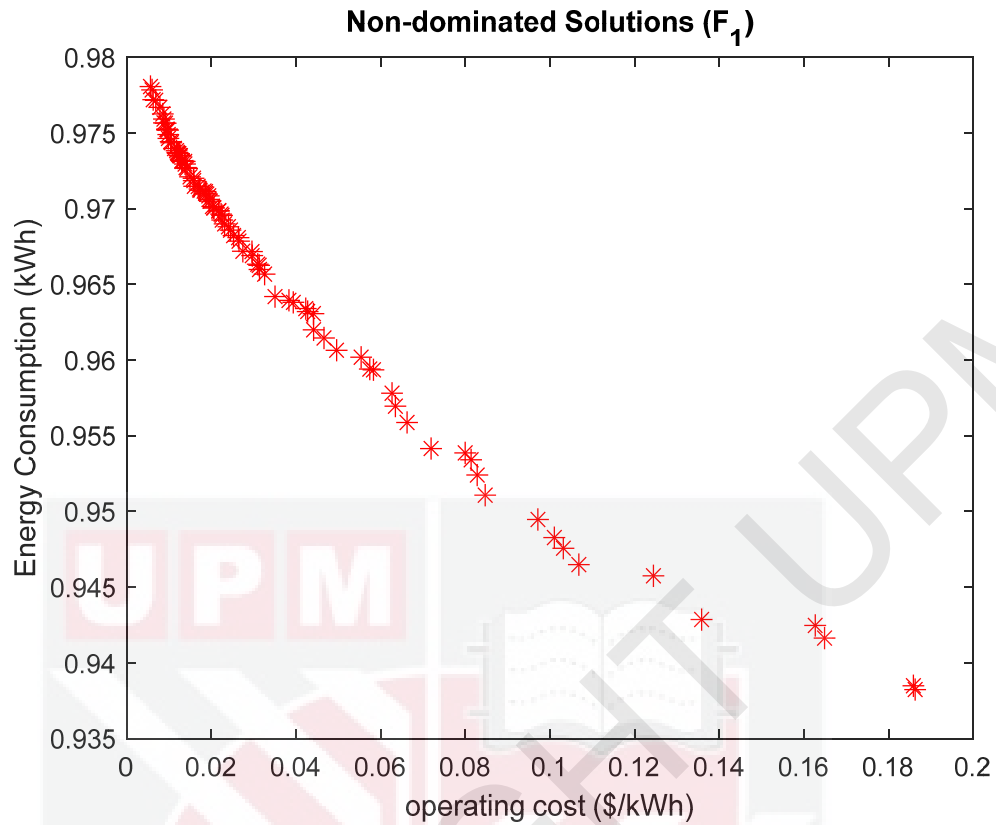


Figure 5.10: Scenario 1 by NSGA-II

At a certain time and by utilizing only the NSGA-II, it can reduce the energy consumption from 0.976KWh to 0.937kWh with 0.1\$/kW average operating cost.

5.8 Scenario 1

We will not employ RES and ESS in this case; instead, we will schedule the appliances using the scheduling algorithms. As a consequence, the cost, PAR, carbon emissions, and UC are calculated below

A. Electricity cost

Figure 5.11 illustrates the power cost of planned and unscheduled loads in the absence of RES and ESS. In time slot 9, the maximum cost of the unscheduled is 70 cents. The highest cost of power in PSO is 66 cents in time slots 19, 21, and 23. In BFA, the maximum cost of power in time slot 9 is 58 cents. In the instance of NSGA-II, the time slot 19 is 56 cents. In terms of electricity bill minimization, the suggested NSGA-II algorithm outperforms previous heuristic methods. The total cost of power in unplanned load is 740 cents, whereas the costs of BFA, PSO, and NSGA-II are 705, 683, and 672 cents, respectively. Overall, power costs demonstrate that BFA, PSO, and NSGA each save 4.7%, 7.7%, and 9.18%, respectively. Nevertheless, when total cost reduction is involved, the NSGA-II method offers the best results when compared with other algorithms in this circumstance. Table 5.2 shows the cost comparison for Scenario 1.

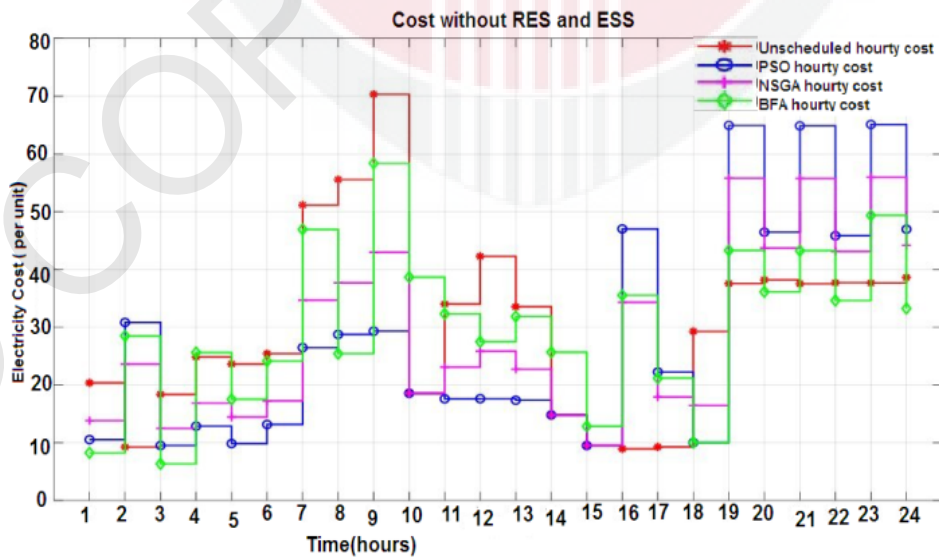


Figure 5.11: Cost reduction for scenario 1

Table 5.2: Comparison of scenario 1 cost

Algorithm	Unscheduled	PSO	BFA	NSGA-II
Cost	740	705	683	672
Reduction (%)	-	4.7	7.7	9.2

B. PAR

Figure 5.12 illustrates the PAR of the unscheduled and scheduled load. Results show that PAR for the unscheduled is 2.62 while PAR for the scheduled algorithms is: 2.34 by PSO, 2.26 by BFA, and 2.12 by NSGA respectively. As a result, the percentage reduction for the algorithms is 10% for the PSO, 13.1% for the BFA, and 18.4% for the NSGA-II. The comparison of PAR in scenario 1 is shown in Table5. 3.

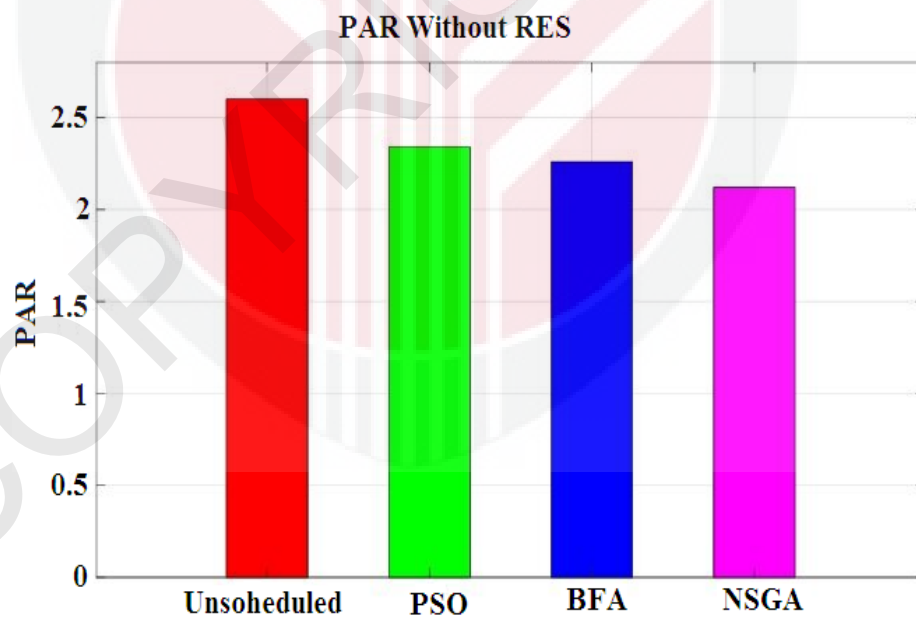
**Figure 5.12: PAR reduction in scenario 1**

Table 5.3: Comparison of scenario 1 PAR

Algorithm	Unscheduled	PSO	BFA	NSGA-II
PAR	2.6	2.34	2.26	2.12
Reduction (%)	-	10.0	13.1	18.4

C. Carbon emissions

Figure 5.13 demonstrates the comparable carbon emissions of planned and unscheduled loads without RES and ESS. The results reveal that carbon emissions from heuristic methods are lower than those from unplanned loads. Maximum carbon emissions in unplanned time slot 21 are 162 pounds. In the case of BFA, it is 156 pounds in time slot 21, whereas it is 152 pounds in time slot 21 for PSO. It is 150 pounds in time slot 21 according to NSGA-II schedule. In unplanned load, the total carbon emissions are 3206 pounds. It is 2904, 2890, and 2861 pounds for BFA, PSO, and NSGA-II, respectively. As a consequence, overall carbon emissions in BFA are decreased by 9.41%, in PSO by 9.85%, and in NSGA-II by 10.7%. However, in this circumstance, the NSGA-II algorithm produces the greatest results in terms of lowering carbon emissions. Table 5.4 compares carbon emissions in Scenario 1.

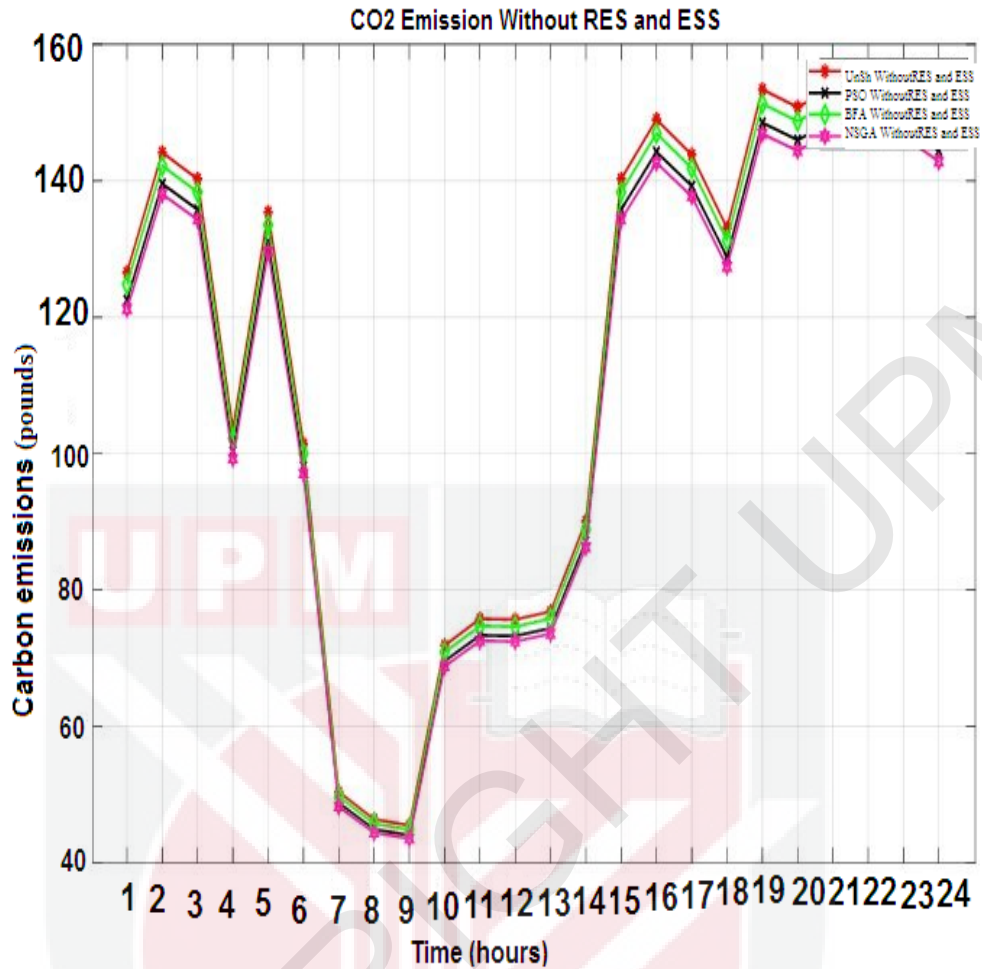


Figure 5.13: Carbon emissions reduction in scenario 1

Table 5.4: Comparison of scenario 1 carbon emission

Algorithm	Unscheduled	PSO	BFA	NSGA-II
Co2	3206	2904	2890	2861
Reduction (%)	-	9.41	9.85	10.7

5.9 Scenario 2

In this particular case, the incorporation of exclusively Renewable Energy Sources (RES) without Energy Storage Systems (ESS) into the residential vicinity is assessed based on the factors of electricity costs, Peak-to-Average Ratio (PAR), and carbon dioxide emissions

A. Electricity cost

Figure 5.14 illustrates the electricity expenses incurred by both scheduled and unscheduled loads using only Renewable Energy Sources (RES). Table 5.5 displays the evaluated costs and their comparison within scenario 2.

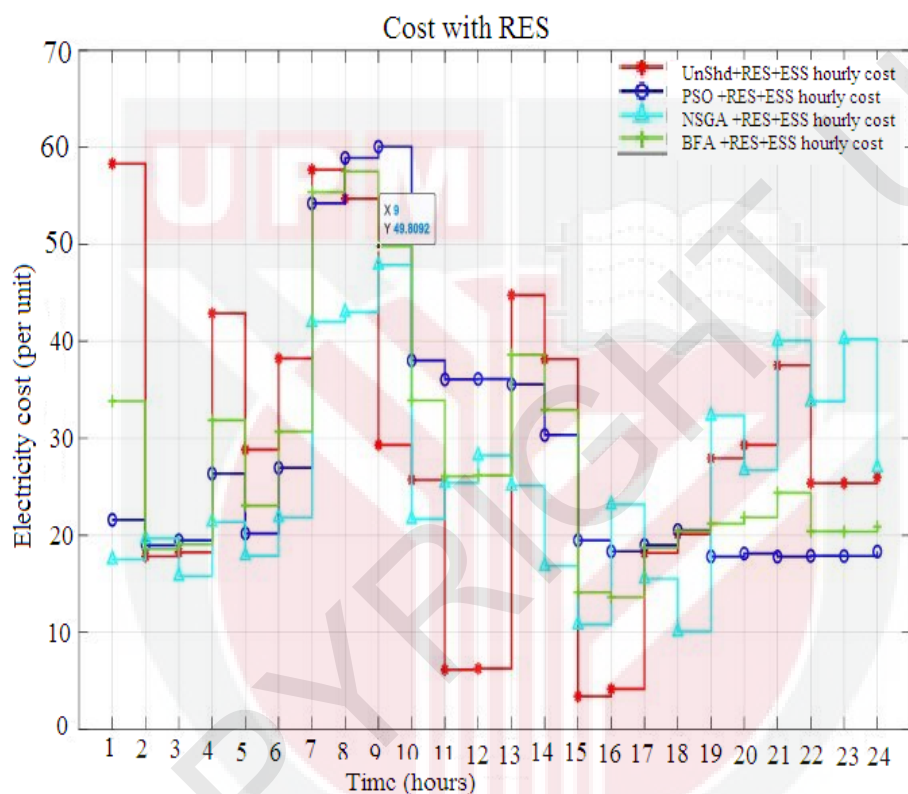


Figure 5.14: Cost reduction for Scenario 2

Table 5.5: Comparison of scenario 2 cost

Algorithm	Unscheduled	PSO	BFA	NSGA-II
Cost	692	659	636	620
Reduction (%)	-	5.2	8.1	10.4

B. PAR

Figure 5.15 illustrates the peak-to-average ratio (PAR) of unscheduled and scheduled loads, and the comparison of PAR in scenario 2 is presented in Table 5.6.

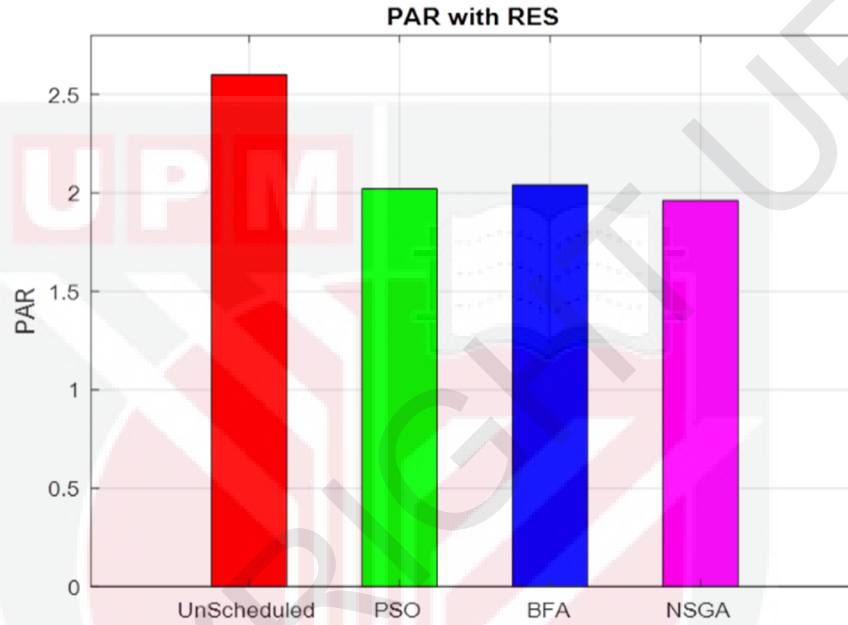


Figure 5.15: PAR reduction in scenario 2

Table 5.6: Comparison of scenario 2 PAR

Algorithm	Unscheduled	PSO	BFA	NSGA-II
PAR	2.6	2.02	2.04	1.96
Reduction (%)	-	22.3	21.5	24.6

C. Carbon emissions

Figure 5.16 depicts the carbon emissions resulting from scheduled and unscheduled loads when only RES is integrated. The corresponding comparison of carbon emissions in scenario 2 is presented in Table 5.7.

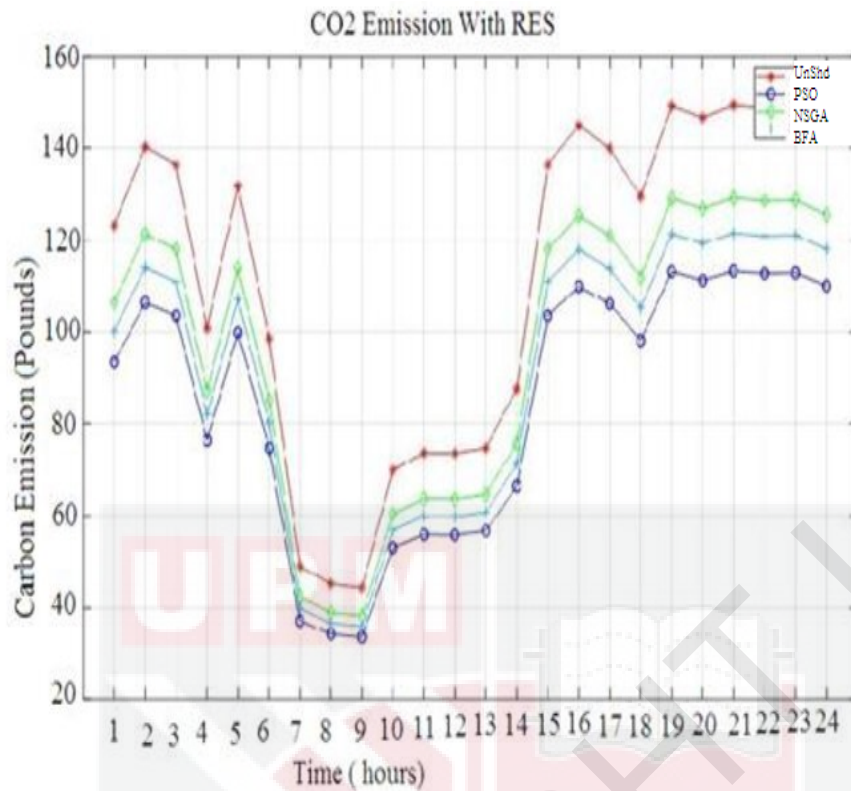


Figure 5.16: Carbon emissions reduction in Scenario 2

Table 5.7: Comparison of scenario 2 carbon emissions

Algorithm	Unscheduled	PSO	BFA	NSGA-II
PAR	2717	2247	2400	2303
Reduction (%)	-	17.3	11.6	15.2

5.10 Scenario 3

In this particular case, the combination of renewable energy sources (RES) and the energy storage systems (ESS) in a local area are assessed based on four factors: electricity bill, PAR, carbon emissions, and UC.

A. Electricity cost

To evaluate the impact of RES and ESS integration on electricity costs, Figure 5.17 displays the comparison of scheduled and unscheduled load costs with RES alone. The assessed costs and their comparison for scenario 3 are also presented in Table 5.5. and 5.8.

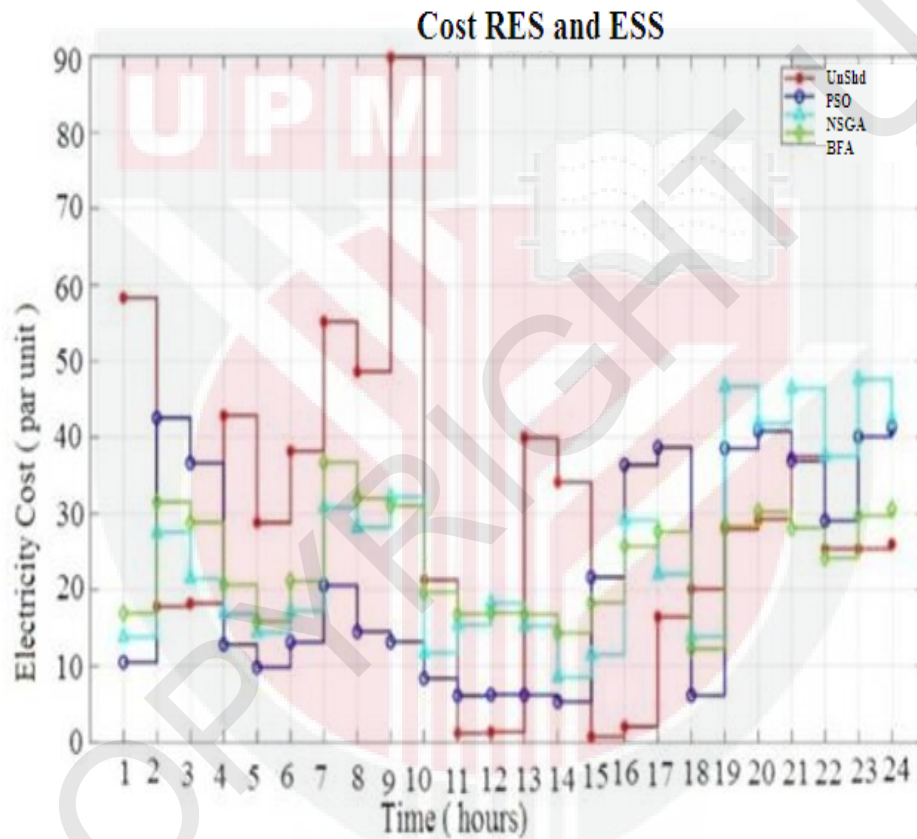


Figure 5.17: Cost reduction for scenario 3

Table 5.8: Comparison of scenario 3 cost

Algorithm	Unscheduled	PSO	BFA	NSGA-II
Cost	710	633	588	582
Reduction (%)	-	10.8	17.1	19.0

B. PAR

The PAR comparison of scheduled and unscheduled load is illustrated in Figure 5.18. Additionally, Table 8 presents the PAR evaluation and comparison of scenario 3 which integrates both RES and ESS into the local area.

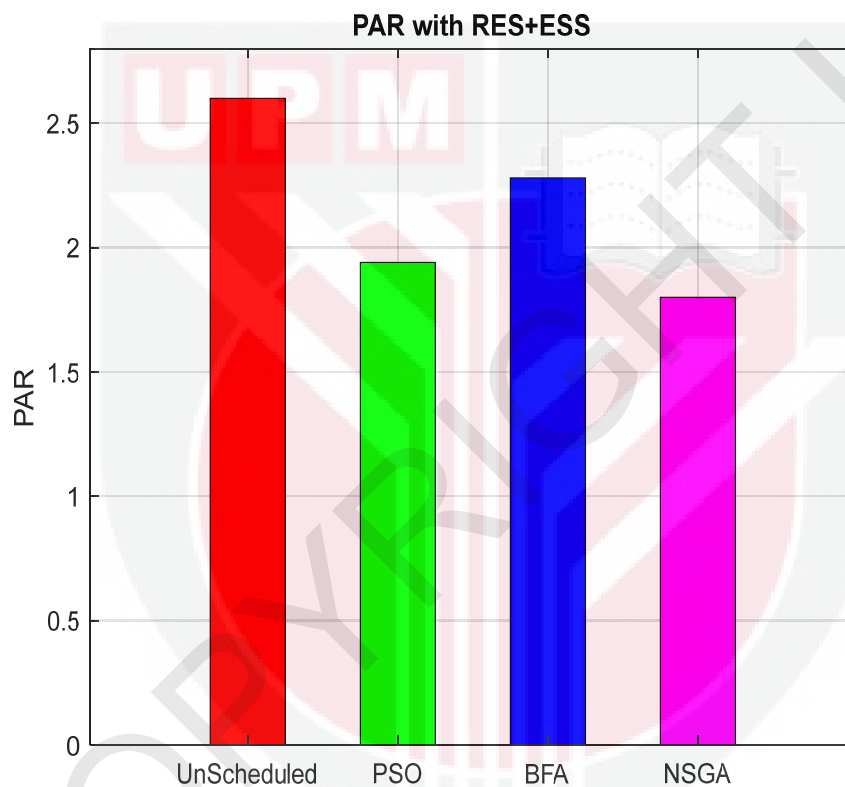


Figure 5.18: PAR reduction in scenario 3

Table 5.9: Comparison of scenario 3 PAR

Algorithm	Unscheduled	PSO	BFA	NSGA-II
PAR	2.6	1.91	2.28	1.8
Reduction (%)	-	26.5	12.3	30.7

C. Carbon emissions

Figure 5.19 depicts the carbon emissions associated with scheduled and unscheduled loads when integrating RES and ESS in the local area. The comparison of carbon emissions in scenario 2 is tabulated in Table 5.10.

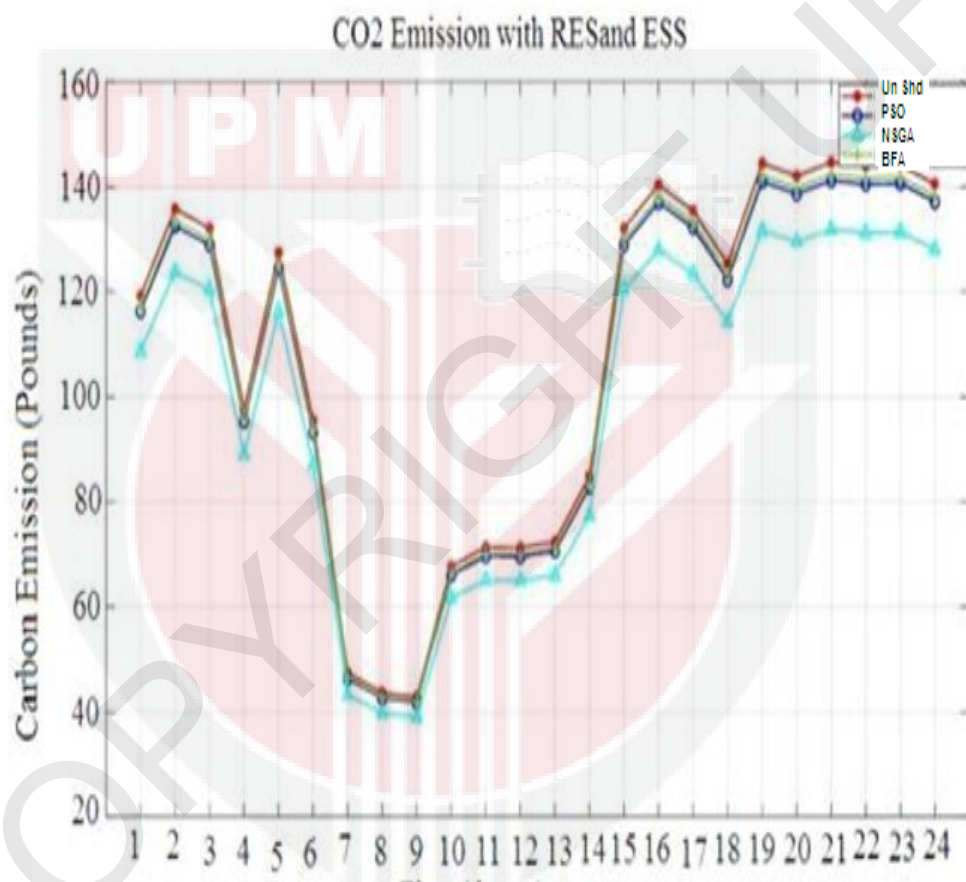


Figure 5.19: Carbon emissions reduction in scenario 3

Table 5.10: Comparison of scenario 3 carbon emissions

Algorithm	Unscheduled	PSO	BFA	NSGA-II
Co2	2612	2412	2389	2043
Reduction (%)	-	7.6	8.5	21.7

D. User Comfort

User Comfort is manipulated in terms of waiting time in this paper. Waiting time is the amount of time a user waits before turning on an appliance. For a reduced power cost, users must use their appliances according to the desired timetable. If a user is more concerned with saving money, he will have to sacrifice his comfort. Figures 5.20, 5.21, and 5.22 show the average waiting time for the PSO, BFA, and NSGA- II algorithms, respectively. The results reveal that NSGA- II has shorter waiting time than other algorithms. In certain instances, the PSO and BFA have short waiting periods; however the NSGA- II algorithm has the shortest waiting time in practically all situations.

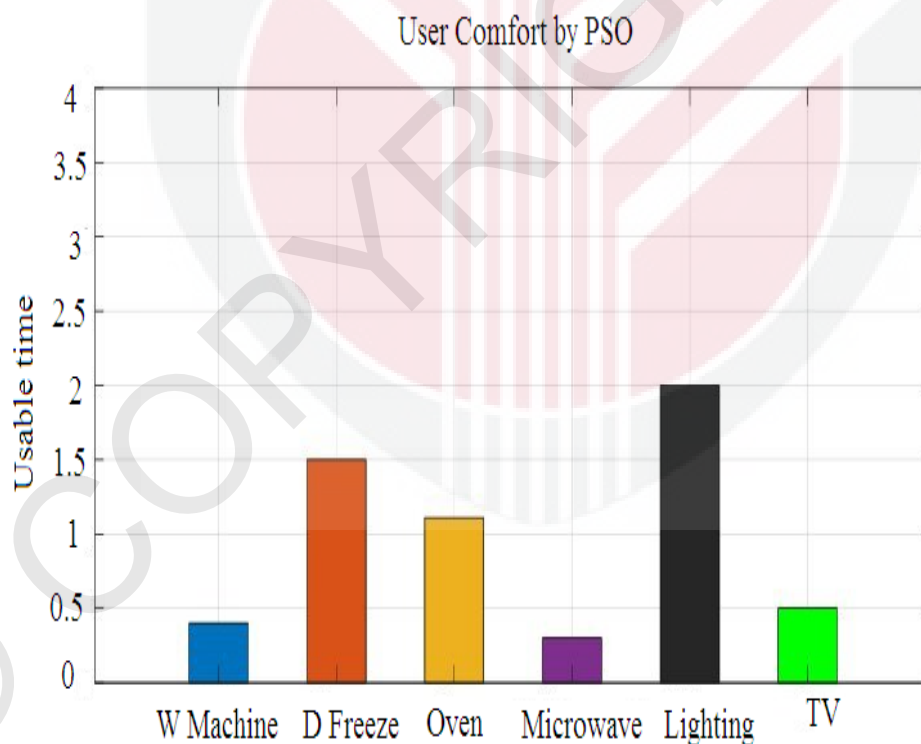


Figure 5.20: UC by PSO

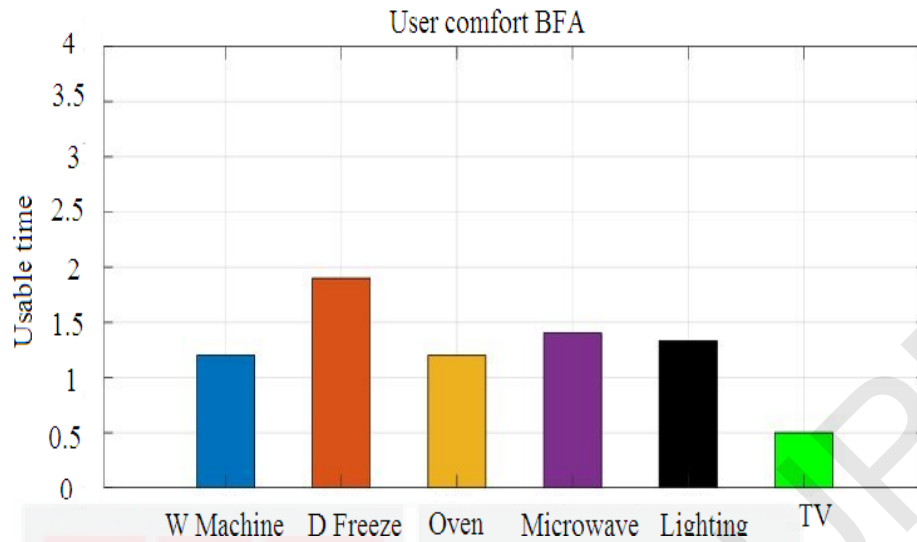


Figure 5.21: UC by BFA

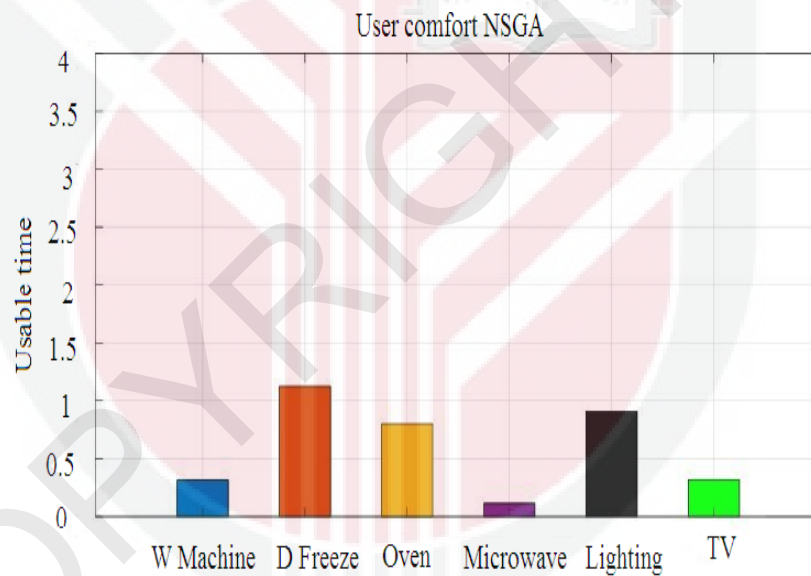


Figure 5.22: UC by NSGA-II

5.11 Comparaison Study

As shown in Table 5.11 and in scenario involving both renewable energy sources (RES) and energy storage systems (ESS), the NSGA- II algorithm consistently outperforms PSO and BFA, providing optimal solutions with

significant cost, PAR, and CO₂ reductions. The choice of algorithm depends on specific priorities, such as cost minimization, environmental impact reduction, or peak-to-average ratio improvement.

Scenario-1: (without RES and ESS)

NSGA-II demonstrates the highest cost reduction of 9.2%, with notable reductions in PAR (18.4%) and CO₂ emissions (10.7%).

PSO and BFA also exhibit substantial improvements over the unscheduled scenario.

Scenario-2: (with RES and without ESS)

NSGA-II continues to outperform other algorithms, achieving a 10.4% cost reduction and significant improvements in PAR and CO₂ reduction.

BFA and PSO show competitive results, with BFA providing the highest CO₂ reduction (21.5%).

Scenario-3: (with both RES and ESS)

NSGA-II maintains its superior performance, achieving the highest cost reduction (19.0%), PAR reduction (30.7%), and CO₂ reduction (21.7%). BFA follows closely, demonstrating substantial improvements in all metrics. PSO exhibits competitive results, especially in cost and PAR reduction.

Table 5.11: Comparison of all metric parameters

Algorithm	Cost	Red. (%)	PAR	Red. (%)	CO2	Red. (%)	Scenario
UnSch.	740	-	2.6	-	3206	-	Scenario-1 (without RES and ESS)
PSO	705	4.7	2.34	10	2904	9.41	
BFA	683	7.7	2.26	13.1	2890	9.85	
NSGA-II	672	9.2	2.12	18.4	2861	10.7	
UnSch.	692	-	2.6	-	2717	-	Scenario-2 (with RES and without ESS)
PSO	659	5.2	2.02	22.3	2247	17.3	
BFA	636	8.1	2.04	21.5	2400	11.6	
NSGA-II	620	10.4	1.96	24.6	2303	15.2	
UnSch,	710	-	2.6	-	2612	-	Scenario-3 (with both RES and ESS)
PSO	633	10.8	1.91	26.5	2412	7.6	
BFA	588	17.1	2.28	12.3	2389	8.5	
NSGA-II	582	19.0	1.8	30.7	2043	21.7	

5.12 Summary

This chapter introduces an optimal bi-objective optimization methodology customized for microgrid systems, encompassing economic, technological, and environmental considerations. The framework portrays the objectives of an intelligent microgrid, aiming to minimize operational costs, CO2 emissions, peak-to-average ratio (PAR), and energy consumption while concurrently enhancing user comfort (UC). A scheduled power allocation strategy is formulated to efficiently cater to the energy needs of residential loads. The stochastic nature of wind and solar resources is characterized by modeling wind speed and solar radiation intensity using a beta probability density function (PDF). The non-dominated sorting genetic algorithm II (NSGA-II) is employed to address optimization challenges. A decision-making process is implemented to select the optimal solution from the non-dominated alternatives. The study presents three scenarios illustrating the optimal operational values for various parameters and energy consumption, providing a comprehensive analysis of the proposed algorithm's efficacy. The

Leveraging the NSGA-II algorithm, coupled with renewable energy resources and optimal energy storage system scheduling, yielded significant reductions in overall expenses, PAR, CO₂ emissions, user discomfort, and energy consumption. MATLAB simulations were conducted to substantiate the efficacy of our proposed approach. The obtained results underscore the effectiveness and productivity of our devised NSGA-II-based approach. Notably, the proposed algorithm demonstrated a substantial reduction in electricity costs by 19.0%, peak-to-average ratio (PAR) by 30.7%, and carbon emissions by 21.7% in scenario-3, as evidenced by a comparative analysis with the unscheduled case.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusions

The following issues can be addressed, and several recommendations can be proposed for future work, including:

1. Under grid connected operating conditions, the dynamic performances of the three inverter PI, SMC, and MPC control techniques are nearly identical, but the dynamic performances of the classical PI control technique are slightly better and smoother than the other two inverter control techniques.
2. All the three control approaches satisfied the unity power factor criteria. The resultant rise and settling time of the sliding mode is lower than that of PI and MPC types. In addition, the resulting output power levels from the sliding mode inverter control approach are higher than those produced through the PI and MPC method. Also, the DC link voltage values in MPC are constant and match the intended voltage levels.
3. The steady state results achieved from the PI, Sliding, and MPC with their LCL filters are sufficient to cover the grid and connected load requirements with unity power factor.
4. All responses of the PI method are soft with simple design, little distortion and ripple. The sliding mode inverter control approach produces greater output power levels than the PI and MPC systems. The DC link voltage measurements from MPC are similarly consistent and correspond to the anticipated voltage levels.
5. The proposed EM system assessed the performance of a hybrid battery-PV grid connected system under various power distortions, such as sudden changes in load demanded and rapid fluctuations in irradiation supplied. MATLAB Simulink was used to simulate a 200 kW PV array connected to a 380 V grid and a battery with a 150 kW capacity. The loads were distributed within power ratings of 100 to 250 kW. The first strategy involved using the MPPT algorithm to control the boost-based UD DC-to-DC converter circuit while other strategies used PWM for the BD DC-to-DC converter of the ES system and the 3Ph inverter. The results demonstrated that boost and 3Ph inverters can be used to successfully integrate PV systems to a grid by supplying the AC load.

6. A battery was also incorporated into the system to overcome power shortages when insufficient power is generated to store excess power. Although this present study provides valuable insights into the behaviors and performance of the hybrid battery-PV systems that are connected to the power grid under different power distortion scenarios,
7. The final part of this research has presented an optimized model for the effective management of energy in a smart grid, integrating renewable energy resources (RERs) such as PV arrays, Micro Turbines (MTs), electrical energy storage systems (ESSs), and a Utility grid (UG). The inherent unpredictability of renewable resources was characterized using the beta Probability Density Function (PDF). The primary objectives of the study were to minimize the operational costs and energy consumption within a smart grid, as outlined in three distinct scenarios.
8. Following the optimization of objective functions by the Non-dominated Sorting Genetic Algorithm (NSGA-II) algorithm, the decision-making process facilitated the selection of the most optimal solution. Incorporating renewable energy resources and the optimal scheduling of ESSs, the NSGA-II algorithm was employed to achieve cost and energy consumption reductions in the specified scenario. Specifically, for NSGA-II, the operational cost was recorded at 0.15 \$/kW, with an energy consumption of 0.939 kWh. The outcomes of the study demonstrate the superior performance of the proposed algorithm compared to benchmark algorithms, showcasing reductions in energy cost, carbon emissions, and peak-to-average ratio (PAR). For instance, in scenario-2, the electricity bill witnessed a decrease of 16.4%, PAR reduced by 24.6%, and carbon emissions reduced by 15.2%. Through comprehensive simulation and results analysis, it can be concluded that the proposed model holds significant merit in optimizing operational costs and enhancing energy efficiency within an intelligent grid.

6.2 Suggestions for future work

There are several aspects for future research to improve:

1. Using advanced control algorithms: like exploring sophisticated control algorithms, such as model predictive control (MPC) and artificial intelligence-based techniques to optimize the system operation, as well as improve its response speed, accuracy, and efficiency.
2. Conducting scalability analysis: the system scalability may be assessed by investigating its performance using PV cells and batteries of different capacities, as well as various load demand profiles to determine its adaptability and suitability for assorted scales and configurations.
3. Integrating additional RE sources: the study could be expanded to incorporate other RE sources, such as wind or hydroelectric power to

create a multi-source hybrid system. This would facilitate a comprehensive analysis of the performance of the proposed system, as well as its ability to integrate multiple RE technologies.

4. Assessing the economic viability: an economic analysis could be conducted to evaluate the cost-effectiveness and financial feasibility of a hybrid system. The analysis should also take into consideration the cost of installation and maintenance, as well as explore potential revenue streams, such as feed-in tariffs or demand response programmers.



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LIST OF PUBLICATIONS

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