OPTIMIZATION OF TECHNO-ECONOMIC PARAMETERS AND DYNAMIC MODELING OF A PHOTOVOLTAIC-BATTERY-FUEL CELL HYBRID ENERGY SYSTEM USING HOMER PRO AND MATLAB/SIMULINK

A Project report is submitted in partial fulfillment of the requirements for the award of Degree of Bachelor of Science in Electrical and Electronic Engineering.

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DECLARATION

I hereby declare that this project "**Optimization of techno-economic parameters and dynamic modeling of a photovoltaic-battery-fuel cell hybrid energy system using HOMER Pro and MATLAB/Simulink**" represents my own work which has been done in the laboratories of the Department of Electrical and Electronic Engineering under the Faculty of Engineering of Daffodil International University in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering, and has not been previously included in a thesis or dissertation submitted to this or any other institution for a degree, diploma or other qualifications. I have attempted to identify all the risks related to this research that may arise in conducting this research, obtained the relevant ethical and/or safety approval (where applicable), and acknowledged my obligations and the rights of the participants.

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APPROVAL

The thesis entitled **“Optimization of techno-economic parameters and dynamic modeling of a photovoltaic-battery-fuel cell hybrid energy system using HOMER Pro and MATLAB/Simulink”** submitted by **Mahafujul Haq Riad (221-33-1728), Md Azizul Hakim Mouaz (221-33-1707) & Kazi Tuhin Hossain (221-33-1755)** has been done under my supervision and accepted as satisfactory in partial fulfillment of the requirements for the degree of **Bachelor of Science in Electrical and Electronic Engineering** in **November, 2025.**

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Dedicated

To

Our Parents & Teachers

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LIST OF ABBREVIATIONS

PV	Photovoltaic
MPPT	Maximum Power Point Traking
FC	Fuel Cell
BESS	Battery Energy Storage System
DG	Distributed Generation
COE	Cost of Energy
NPC	Net Present Cost
LCOE	Levelized Cost of Energy
GHG	Greenhouse Gas
DC-DC	Bidirectional DC-DC Converter
DC-AC	Inverter (DC to AC Conversion)
PLL	Phase-Locked Loop
dq0	Direct Quadrature Zero Transformation
PWM	Pulse Width Modulation
LCL	Inductor Capacitor Inductor Filter
MATLAB/Simulink	Dynamic System Modeling and Simulation Software
HOMER Pro	Hybrid Optimization Model for Electric Renewables
Ada-Grad	Adaptive Gradient Algorithm
PQ	Power Quality
AMI	Advanced Metering Infrastructure
O&M	Operation and Maintenance
SOC	State of Charge

LIST OF SYMBOLS

Symbol	*Name of the symbol*
kWp	Kilowatt-peak (rated PV power)
kW	Kilowatt
kWh	Kilowatt-hour
H_2	Hydrogen
O_2	Oxygen
CO_2	Carbon Dioxide
A	Ampere
V	Volt

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ABSTRACT

This paper presents a simulation-based analysis and design of a Grid-Tied Hybrid Power System with Photovoltaic (PV) modules, Fuel Cells (FCs), and Battery Energy Storage Systems (BESS) for clean and reliable electricity generation. The method of this work is based on the integration of economic optimization using HOMER Pro with dynamic simulation of performance in MATLAB/Simulink. The first stage HOMER Pro was used to determine the least cost system design based on set parameters such as solar irradiance, component costs, load profiles, and fuel cost, resulting in an optimized configuration consisting of a 1300 kWp PV array, a 300 kW fuel cell, 119 batteries (4.8 kWh each), and a 450 kW inverter. In the second stage, full dynamic modeling was carried out to simulate system performance under varying solar radiation, load cycling, and grid outages. These can be summarized that the proposed HES can provide a continuous power supply, a constant DC bus voltage, and efficient energy management through the intelligent control of bidirectional converters and inverters. The system shows a low Net Present Cost (NPC), a competitive Levelized Cost of Energy (LCOE), and an increased grid robustness, which makes it a clean, technically reliable, and economically attractive option for the integration of clean energy. This paper contributes to the HRES design by coupling economic optimization and technical simulation to enhance performance, flexibility, and sustainability.

Keywords:

1. ***Grid-tied hybrid system***
2. ***Photovoltaic (PV) system***
3. ***Fuel Cell (FC)***
4. ***Battery energy storage system (BESS)***
5. ***HOMER Pro software***
6. ***MATLAB/Simulink software environment***
7. ***Renewable Energy Optimization***

CHAPTER 1
INTRODUCTION

1.1 Introduction

Renewable energy relies on energy flows from natural events that are continuously replenished [1], such as solar, wind, hydro , and biomass, are environmentally sustainable substitutes for fossil fuels. Rapid advances in renewable technology, in particular in photovoltaic (PV) and fuel-cell (FC) technology, are leading to significant changes in the global energy system [2]. The growth in clean energy demand stems from both the need to halt environmental destruction and to enhance energy security by decreasing dependence on finite materials [3].

Global cooperation, like the Paris Agreement, has resulted in more government and industry pledges to reduce carbon emissions and build renewable energy infrastructure [4]. The distributed generation (DG) technology facilitated by microgrid, such as PV, fuel cells, batteries, and power electronics, is being regarded as the future of sustainable energy [5]. Energy sources utilization may be maximized in grid-tied hybrid energy systems (e.g. solar PV-battery-fuel cell), and they are gaining more and more attention among researchers [6], to enhance efficiency, and to ensure a stable energy supply under different environmental conditions.

1.2 Problem Statement and Proposed Solution

While there have been substantial developments in integrating renewables, a few issues persist in hybrid energy systems [7]. The majority of the models do not consider economic and technical aspects simultaneously, which leads to costly or ineffective results. In addition, the dynamic modeling of the PV battery fuel cell interaction under different loads and environmental conditions has not been adequately studied. The seamless switching between grid-connected and islanded modes still presents a technical obstacle, and long-term battery aging, as well as the lack of standardization, further impede mass application [8].

To overcome these drawbacks, this paper introduces a grid-connected hybrid power plant model based on solar PV arrays, fuel cells, and battery energy storage systems (BESS). The system takes advantage of the synergies of each PV array for renewable generation, batteries for high-speed response storage, and fuel cells for extended backup in long solar low periods. Sophisticated control schemes and bi-directional converters are employed to guarantee flexible energy management, smooth operation of the system in grid-connected and island modes, and improved grid stability.

1.3 Objectives

The objective of this work is to develop, analyze, and validate a hybrid renewable energy system connected to the grid that improves the efficiency, the cost, the reliability, and the environmental friendliness. The specific objectives are:

1. To design a hybrid system of PV, batteries, and fuel cells for a steady and uninterrupted power supply.
2. To conduct economic optimization using Homer Pro to identify the most cost-effective system architecture based on Net Present Cost (NPC) and Levelized Cost of Energy (LCOE).

3. Dynamic modeling and simulation with MATLAB/Simulink to study the system stability, control strategies, and performance of the system under different operating conditions were adopted.

4. To assess the possibility of seamless operation in both grid-tied and islanded modes for improved resilience and reliability.

5. To provide a scalable and sustainable solution to satisfy growing energy needs worldwide and to lessen the dependence on fossil fuels.

6. Promote the application of novel and energy-conserving technologies compatible with global machinery to achieve net-zero carbon emissions in the industry and energy sectors.

1.4 Brief Methodology

The study adopts a hybrid technique of economic analysis and dynamic simulation in two phases.

1. Economic Modeling (Homer Pro):
   - Input Parameters: The inputs are solar irradiance data, load profiles, component costs, fuel prices, to name a few.
   - The software did the trade-off analysis on hybrid system configuration by NPC, LCOE, and reliability.
   - The optimum system configuration found was a 1300 kWp PV array, 450 kW inverter, 300 kW fuel cell, and 119 batteries (4.8 kWh each).
2. Dynamic Modeling (MATLAB/Simulink):
   - Based on results obtained from Homer Pro, a comprehensive model was designed to model PV production, battery charge/discharge cycles, fuel cell running, DC-DC bidirectional converter function, and inverter synchronization.
   - Several operating conditions, such as grid outages, varying load requirements, and intermittent solar, were evaluated.
   - The results proved a high operational stability with low carbon emission, favorable LCOE, and cost-effectiveness of the system.

1.5 Implementation Schedule / Gantt Chart

Table 1.1. Implementation Schedule

Task	Duration	Start	End
Literature Review	2	Week 1	Week 2
Exploring Software	1	Week 3	Week 3
Design Economic Model	3	Week 4	Week 6
Design Dynamic Model	5	Week 7	Week 10
System Testing and Optimization	2	Week 11	Week 12
Final Report Writing	4	Week 13	Week 16

This Gantt chart gives a structured direction in order for us to finish our project within the time frame of around 16 weeks, as it is clearly seen that is enough time to complete each phase, but also allows me to add some alterations if it is necessary.

1.6 Structure of the Report

Chapter 1: Introduction

The chapter makes available a comprehensive background and context of the study, which introduces the thesis. The background clearly defines the objectives of the study and the problem under investigation. Also, the chapter describes the implementation of the project, specifying the steps and strategies employed in the procedure.

Chapter 2: Literature Review

The review of literature deals with the study of existing research on the thesis topic. By comparing previous studies with the current study, it identifies holes in the literature. This contrast is based on, among others, good practice and methods that have influenced the approach to the study and the new contributions in the present research.

Chapter 3: Design Procedure

This chapter presents the two-stage optimization and simulation approach for designing the grid-connected hybrid power system. Then, a 1300 kWp PV array, 450 kW inverter, a 300 kW fuel cell, and 119 batteries (each battery has 4.8 kWh) were selected as the optimal design configuration based on economic analysis in the first step using Homer Pro among different combinations according to solar irradiance, load profiles, and component costs. To enable the investigation of system efficiency under different scenarios, including grid outages, load changes, and solar variability, the best system architecture was implemented in MATLAB/Simulink in step two. This combined approach ensured the technical reliability and economic feasibility of the proposed hybrid system.

Chapter 4: Result Analysis

In this chapter, the performance evaluation and simulation results of the proposed grid-connected PV-FC-BESS hybrid system are presented, which was modeled in MATLAB/Simulink. The system was tested under different solar irradiation conditions to assess its capabilities in managing the power flow between the grid and microgrid, providing a constant DC bus voltage, and assuring an uninterrupted power output. The study of the system's general performance and the dynamic behavior of its subsystems verified an effective coordination and control of the systems and the reliability of the whole power supply, showing the applicability of the model to practical use.

Chapter 5: Project Management

This chapter is focused on the management part of the thesis project. It describes the planning and implementation of the project management plan, including devel- oping a schedule, monitoring costs, assigning resources, and monitoring milestones of the project. It further considers what has been learned from managing the project management process, and discernments into managing management.

Chapter 6: Impact Assessment of the Project

The cost-benefit analysis of the proposed Hybrid Power plant is included in this chapter, focusing on economic, social, Environmental, and ethical impacts. Economically, the system ensures savings in the long run for a good LCOE and NPC, reduces the operating cost, and reduces the dependence on fuel. In society, it also enhances energy reliability, promotes regional development, and creates opportunities in renewable energy. The project aligns with net-zero emission goals and the UN Sustainable Development Goals globally by promoting clean, sustainable electricity production. From the point of view of ethics, it promotes sustainability and social responsibility, and from the environmental point of view, it mitigates carbon emissions and resource consumption. In summary, the project represents an ethical, eco-friendly, and financially sound approach to energy, and hence, this scheme can be considered as a stepping stone to a sustainable energy future.

Chapter 7: Conclusion

The primary findings and contributions are summarized in the final chapter. It provides recommendations for possible system improvements and further research directions based on the acquired knowledge in the study. The chapter closes with comments which underline the significance of the work and the impact on the discipline, as well as consider the wider effects and applications of the research.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The reviews on RES show a trend of the world toward hybrid systems of PV, batteries, and fuel cells. These systems compensate for the intermittent nature of solar energy, and they offer dependable, scalable, and green solutions. Investigation has been made on economic optimization tools, dynamic simulation platforms, and control strategies. Yet the majority are still limited by a low degree of coupling between economic and technical aspects, who often don't consider dynamism and real-life variations, or who take into account life-cycle effects such as battery degradation.

2.2 Related Research/ Works

1. Hybrid Systems with PV, Batteries, and Fuel Cells [9]:
Investigations have shown that the combined systems of PV, batteries, and fuel cells provide high energy reliability, efficiency, and environmental performance in applications at the house, building, and community levels.

2. Batteries for Storage and Cost Reduction [10], [11]:
Studies suggest that lithium-ion batteries enable peak shaving, load shifting, and electricity cost reduction by storing excess solar energy for utilization during the period of high tariffs.

3. Fuel Cells as Auxiliary Power Sources [12], [13], [10]:
Hydrogen fuel cells have been employed as auxiliary units to ensure a stable backup in the event of long solar interruptions. Some products also feature electrolyzers to produce hydrogen on-site.

4. Advanced Control Strategies [10],[14], [15], [16]:
Adaptive techniques that include AdaGrad and flatness-based control have been utilized to enhance power quality, voltage regulation, and dynamic balancing in hybrid systems.

5. Grid-Tied and Islanded Operation [13],[10] [34];
Several works focus on hybrid systems that can operate in grid-connected and off-grid modes with a smooth transition to provide a continuous power supply in the event of power interruptions.

6. Economic and Environmental Optimization [17], [18]:
The results of the HOMER Pro simulation results demonstrate that the tailored HRES system achieves minimal cost of energy (COE) and carbon dioxide (CO_2) emissions.

7. Importance of Proper System Sizing [19]:
Oversizing increases the capital cost while under-sizing causes loads to be unmet, according to literature, which points to the importance of forecasting accurately and optimizing the design.

2.3 Compare and Contrast

Related literature, though interesting, is limited by partial optimization on technical or economic objectives and/or single- or two-period analysis. Few works model the PV, batteries, and fuel cells as they vary at different environmental and load conditions. In addition, seamless switching between grid-connected and islanded mode, long-term battery aging, and universal design standards are still missing.

The proposed system goes beyond these constraints by considering the holistic perspective. It uses Homer Pro to optimize the cost, MATLAB/Simulink to model the dynamics, and is reliable from the technical and economic perspectives. The concept (1300 kWp PV, 300 kW fuel cell, 119 batteries, and 450 kW inverter) has been developed to combine efficiency, reliability, and low cost. With the development of bidirectional converters and smart control, flexible energy management and system sustainability are guaranteed during grid failures; the solution is complete and more scalable when compared to the traditional hybrid solutions.

2.4 Summary

Hybrid renewable energy systems have recently been considered as a viable option to meet the ever-growing need for clean and reliable energy [20]. The reviewed results have shown the effectiveness of these power sources management methodologies, but also highlighted that some challenges are still open in energy, modeling, and control strategies optimization.

With this background, the paper is aimed at illustrating the full hybrid power plant model, combining cost affordability and technical robustness. The system is evaluated for cost effectiveness, autonomy, and environmental safety by using the optimal tool HOMER Pro and the simulation tool MATLAB/Simulink. Its modular, scalable, and flexible design enables it to run in both grid-connected and island modes, making it particularly suitable for mission-critical facilities and remote communities. Finally, this paper successfully addresses the major shortcomings of existing studies and clearly indicates the opportunity for a potent low-carbon energy future.

CHAPTER 3
DESIGN PROCEDURE

3.1 Introduction

In the present work, a two-level method integrating optimization and simulation is applied. Initially, an economic analysis was designed using Homer Pro. By providing input of items like solar irradiance, load profiles, cost of components, cost of fuels, among others, the software makes it possible to design and simulate several hybrid system configurations. Homer Pro simulates for an optimal system design over a range of Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and other financial metrics. The "most feasible" design was then found to be the optimal design, which includes 1300 kWp of solar PV array, 450 kW inverter, 300 kW fuel cell, and 119 batteries at 4.8 kWh each.

The methodology was divided into two stages. Details for the system were taken from Homer Pro, and a dynamic model was constructed in MATLAB/Simulink in the second step. At this point, priority was given to developing full-scale simulations of individual subsystems (photovoltaic generation, fuel cell operation, battery charging and discharging, dc-dc bidirectional converter operation, and inverter control for synchronizing the grid). In addition, dynamic events such as sudden grid outages, progressive load increases, and fluctuating solar irradiance were simulated to test the stability and reliability of the system. This combined approach ensures economic and technical performance considerations are optimized and provides a holistic approach to hybrid power system design.

3.2 System Design and Components

3.2.1 System optimization using HOMER Pro:

The battery and fuel cell system grid-connected hybrid power system is designed in this paper by using HOMER simulation software. The main objective was to evaluate and compare the cost of the different types of systems. There are certain data to be provided for the HOMER software to perform optimization and simulations properly, including electrical load demand, component specifications, fuel prices, and direct resources [21]. Based on this information, HOMER creates various system designs and evaluates their technical and economic characteristics [22]. The following sections present a description of input parameters and the data needed for simulation to analyze and select a cost-effective model.

3.2.1.1 Load Profile

A correct dimensioning and optimization of the hybrid system would be highly dependent on these load profiles [23]. The average daily energy demand used for the design of a hybrid power system is 4570 kWh. This value represents the scaled annual average daily load, which is an important input to the HOMER simulation. The daily average load curve is illustrated in Figure 3.1, in which the hours from 14 to 17 are the peak load periods. This period of peak demand is the most important time for sizing components in order to attain the needed capacity and size of the system. The maximum load during this period was measured at 413.87 kW. To determine accurately the peak load, a system must withstand the highest demand without breakdown or shortage of power. In addition to the daily load patterns, Figure 3.2 presents monthly average loads that offer a season-by-month trend of energy demand.

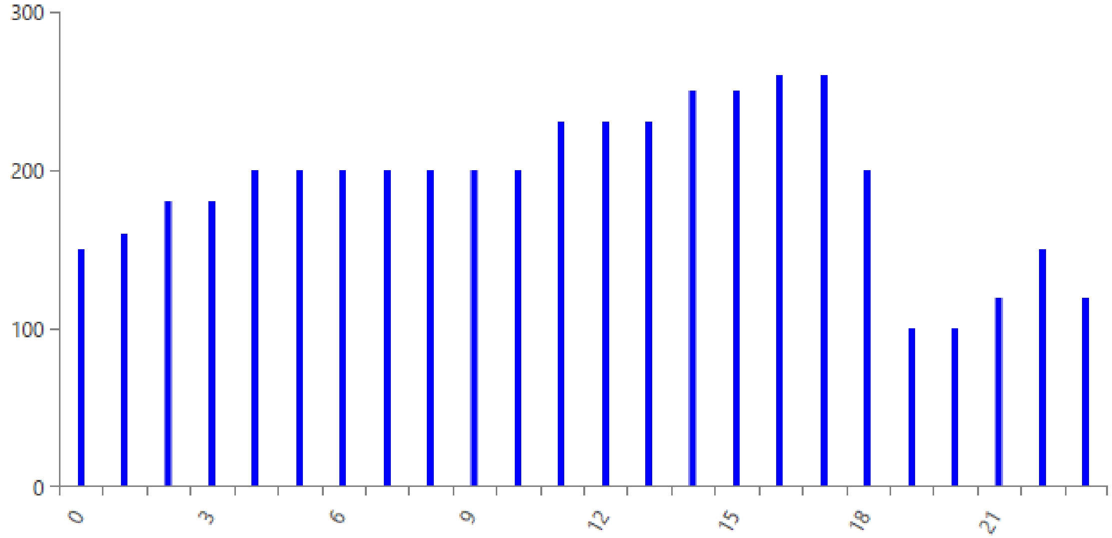

Figure 3.1. Daily load profile

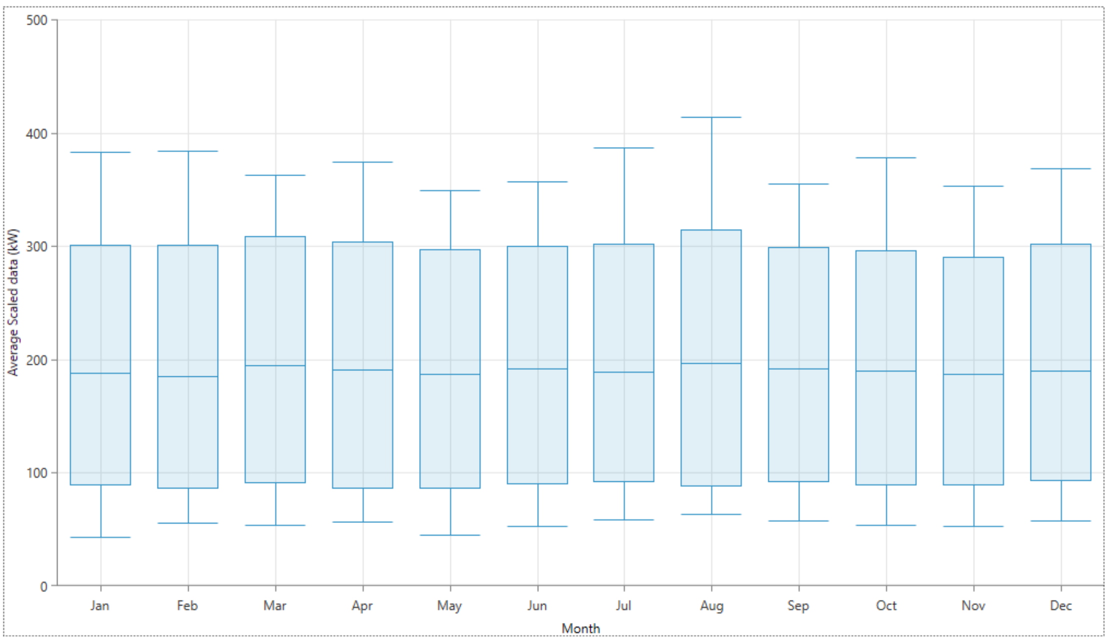

Figure 3.2. Monthly average load for a complete year

3.2.1.2 Solar Radiation Data

The data of solar radiation used in this study are extracted from the NASA Surface Meteorology and Solar Energy database. This type of data is necessary to make a precise simulation of the solar potential with the HOMER software [24]. Average monthly solar radiation (Figure 3.3) at different locations has been illustrated. The study focuses on the Dhaka district near Savar, which has a geographical position at 23°52.6 °N latitude and 90°19.2'E longitude. According to NASA data, the average daily solar radiation in this region is 4.65 kWh/m²/day. This value is crucial for evaluating feasibility and determining the optimal size of photovoltaic (PV) components used in the system.

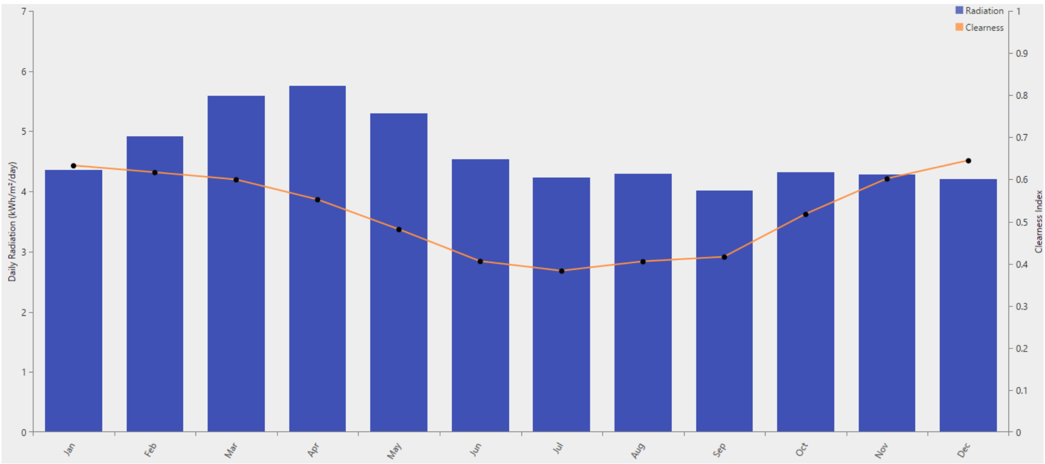

Figure 3.3. Solar Radiation Data

3.2.1.3 Simulation Model in Homer Pro

The hybrid power system simulation component models are chosen from different reliable sources to achieve realistic modeling. Figure 3.4 shows the grid-connected hybrid system modeled in HOMER, which consists of PV arrays, a converter, batteries, a fuel cell, a load, and is also to be connected to the grid. HOMER software models this configuration according to the location and load profile that is introduced [25]. The model takes into account various cost parameters such as installation cost, operation and maintenance (O & M) cost, replacement cost, interest rate, and life cycle energy costs. These inputs enable HOMER to test the system performance and hence find the optimal, cost-efficient configuration for the chosen site.

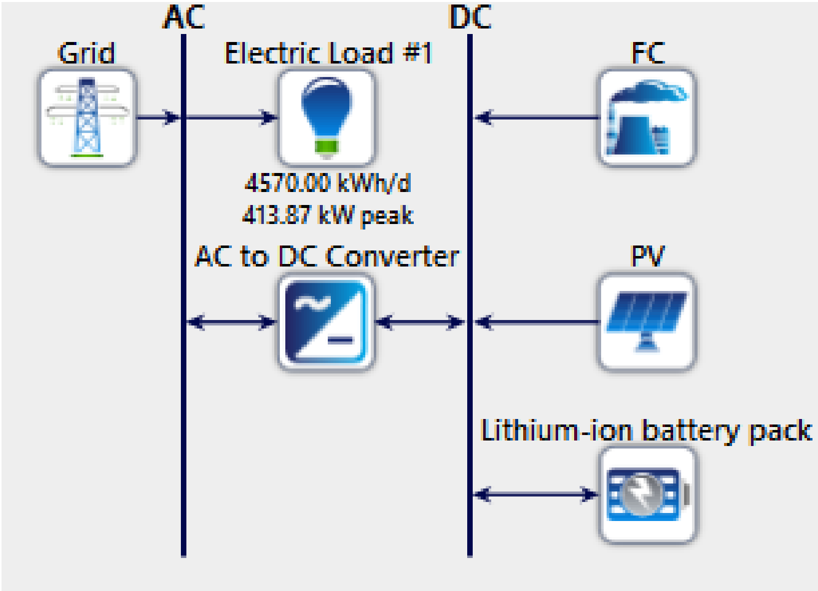

Figure 3.4. Simulation Model

3.2.1.4 PV Array

The LONGI LR5-72HPH photovoltaic (PV) module manufactured by Longi is recognized for its high performance with an efficiency of about 21.1% and a long operation life duration up to 25 years. The specific PV model was chosen for the hybrid system simulation due to its reliable performance [26]. The investment cost for the PV arrays was considered to be $163.71 per kW, and the annual O&M was assumed to be $1/ 1.$/kW.

3.2.1.5 Power Converter

SUN-50K-SG01HP3-EU-BM4 converter by Deye gets up to 97.60% efficiency, and its lifespan is 15 years. For this study, the capital cost for a 1 kW converter is taken as $35.30ens, and its replacement cost is also $35.30. Also, it can be seen that the AOM cost is 2$/kW/year; hence, it is a cost-effective and performance system for the hybrid system.

3.2.1.6 Battery Bank

In this part, a designed battery bank with a capacity of 4.8 kWh is investigated to be integrated into a hybrid power system. Negligible energy was wasted during the charge and discharge processes, with overall battery bank operating efficiency in the vicinity of 98%. Batteries are built with prismatic cells and come with an integrated Battery Management System (BMS), which ensures long battery life and maximum performance. The capital and replacement costs for the battery bank are taken to be $344.25/kW, respectively. In addition, both the operating and maintenance (O&M) cost is estimated at $28.69 per kW annually.

3.2.1.7 Fuel Cell

Given that no specific fuel cell model is available in HOMER Pro, the fuel cell was modeled as a Generic Genset (connected to the DC bus of HOMER) with control over operational hours and efficiency. It permits accurate simulations in software. The fuel cell's capital cost was based on the $30 per kW installed and replaced for $28 per kW. The O&M cost was likely in the vicinity of $0.0025 per year.

3.2.1.8 Grid

In the proposed work, a grid was introduced as a cogeneration system component. Its main function is to guarantee that electric power is available all the time and at a desirable quality level by assisting the system in cases when renewable energy sources (RES) like solar and fuel cells cannot satisfy total load demand [27]. In the case of power deficiency, the system stability is maintained through the contribution of Managed power (deficit) by the grid. On the other side, if the renewable energy system provided more power than what was needed for the load at that moment, there would be a surplus being injected into the grid. The extra power sent back to the grid is restricted to 100 KW, allowing for efficient energy management and avoiding wastage. By integrating the grid in this way, the overall system becomes more robust and adaptable to maintain power availability and affordability while leveraging renewable resources when they are abundant.

3.2.1.9 HOMER Pro Software

In the USA, the National Renewable Energy Laboratory (NREL) has developed a well-known software package for designing and analyzing hybrid systems called HOMER [22], which is widely used. In the present study, HOMER is employed by entering the necessary parameters, including electric load consumption, solar radiation, wind speed, and details of the system components, as well as their costs.

3.2.1.10 Cost Analysis Procedure by HOMER

1. Net Present Cost (NPC): NPC is indicative of the total life-cycle cost of installation and operation of the system [28]. This is determined using the formula:

   $$NPC = \frac{TAC}{CRF(i, R_{prj})}$$

   Where TAC is the total annualized cost ($), CRF is the capital recovery factor, i is the real interest rate per year (%), and Rprj is the project life (years)

2. Total annualized cost: It is the sum of all the annualized costs of system’s element n, i.e., Capital cost (CC), O&M (Operation and Maintenance) cost (OMC), replacement cost, Fuel Cost, etc.
3.

4. Capital Recovery Factor (CRF): It is a factor for evaluating the present value of equivalent annual payments [28]. It is calculated by:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Where i means annual real interest rate and n is the number of years (project lifetime).

5. Annual Real Interest Rate (i): This is derived from the nominal interest rate and inflation rate [28], calculated as:

$$i = \frac{i' - F}{1+F}\text{i}$$

Where i means real interest rate, i' means nominal interest rate, and F means annual inflation rate.

6. Cost of Energy (COE): COE represents the average cost per kilowatt-hour (kWh) of useful electrical energy produced by the system [28]. It is calculated as:

$$COE = \frac{TAC}{L_{prim,AC} + L_{prim,DC}}$$

Where, $L_{prim,AC}$ is the AC primary load and $L_{prim,DC}$ is the DC primary load

3.2.1.11 Optimization Results

"Figure 3.5 presents the results of optimizing a grid-connected hybrid power system that combines a photovoltaic (PV) array, fuel cell, and battery storage. As shown in Figure 3.5, this system, when connected to the grid, achieved a minimum Cost of Energy (COE) of $0.0521. In this refined scenario, the share of renewable energy in the total energy supply reached 57.9%, which demonstrates a substantial reform towards green power production. The hybrid system to be studied consists of a 1300 kW PV array, a 300 kW fuel cell, and a 450 kW AC to DC converter. It also has 119 batteries with a storage of 4.8kWh each. That way, energy is produced, transformed, and stored efficiently to supply different demand profiles. The Net Present Cost (NPC) associated with this configuration is considered to be $ 1.21 M, which presents a cost-effective and dependable energy option. Referring to Figure 3.6, the overall yearly electricity generation of the hybrid system is 2,615,947 kWh. Of this, 1,668,040 kWh is served by the load, and 251,800 kWh is sold to the grid. This excess can be used to improve grid support and potentially be monetized through feed-in tariffs and net metering. Moreover, Figure 3.6 illustrates %u2013 the average monthly electricity generation from various components in the hybrid system. This subdivision points to seasonal change in generation (driven by the PV mainly) and reinforces the importance of combining several sources and storage to maintain balanced performance through the year."

Architecture						Cost				System	
PV (kW)	FC (kW)	Lithium-ion battery pack	Grid (kW)	AC to DC Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (kg/yr)
1,300	300	119	999,999	450	LF	$1.29M	$0.0521	$78,502	$278,674	57.9	7,212

Figure 3.5. Simulation Results

Production	kWh/yr	%
LONGI LR5-72HPH	1,808,190	69.1
Fuel Cell	115,718	4.42
Grid Purchases	692,039	26.5
Total	2,615,947	100

Consumption	kWh/yr	%
AC Primary Load	1,668,040	86.9
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	251,800	13.1
Total	1,919,840	100

Quantity	kWh/yr	%
Excess Electricity	663,598	25.4
Unmet Electric Load	10.1	0.000600
Capacity Shortage	351	0.0210

Quantity	Value	Units
Renewable Fraction	57.9	%
Max. Renew. Penetration	619	%

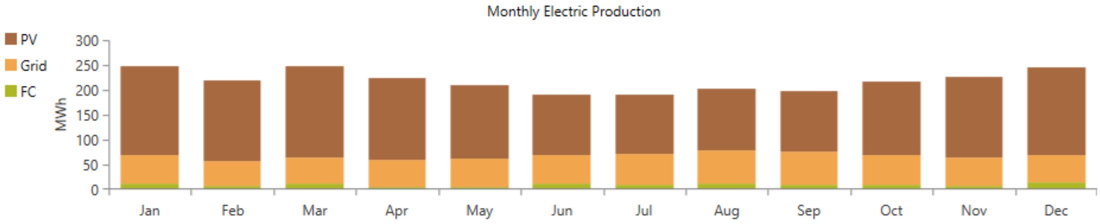

Figure 3.6. Energy Summary and Monthly Electric Production

3.2.2 System Design in MATLAB/Simulink:

The Hybrid Renewable Energy System is modeled and simulated in the MATLAB/ Simulink environment according to the proposed configuration of HOMER Pro software. HOMER Pro, a top-rated software for microgrid design and optimization, can be used to identify the optimal system configuration (i.e., most cost-effective and technically viable). The system components and their sizes (i.e., PV arrays, energy storage, backup generation units) are obtained from the optimization of HOMER Pro. The implementation is developed in MATLAB/Simulink, the most popular tool for modelling, simulating, and analyzing dynamic systems [29]. Simulink, an add-on for MATLAB, provides a graphical environment for designing system-level models from block diagrams [30]. It is quite effective in simulating power systems due to its large libraries (e.g., Simscape and SimPowerSystems), which have pre-designed components for electric, mechanical, and thermal systems [30]. This makes it an interesting tool for high-fidelity simulations of complex hybrid energy systems.

The sub-systems of the hybrid system are represented as separate subsystem blocks in the Simulink model, which help in achieving a modular and clear design. The overall system architecture is shown in Figure 3.7, including the integration of different energy sources and storage technologies. The concept incorporates a 1300 kWp photovoltaic (PV) farm as the dominant renewables system. It facilitates energy storage of 4,8 kWh per battery and allows load balancing and supply in hours where solar generation is low. A 300 kW fuel cell is included to provide support when the system is called upon during peak times or when renewable energy resources are not available at a minimum level.

A hybrid inverter is used to perform power conversion and control operations. Likewise, it facilitates the exchange of electricity between a PV array, batteries, load, and grid. Additionally, the system has a flexible load profile, and it is grid-connected to enable reversible power flow at any time. Due to its modular architecture in Simulink, each module of the system was tested by itself or as part of a complete MEG-SMD system. In general, the MATLAB/Simulink platform defines a reliable process where validating the operational characteristics of energy flow and stability operations in a hybrid energy system is done before practical implementation.

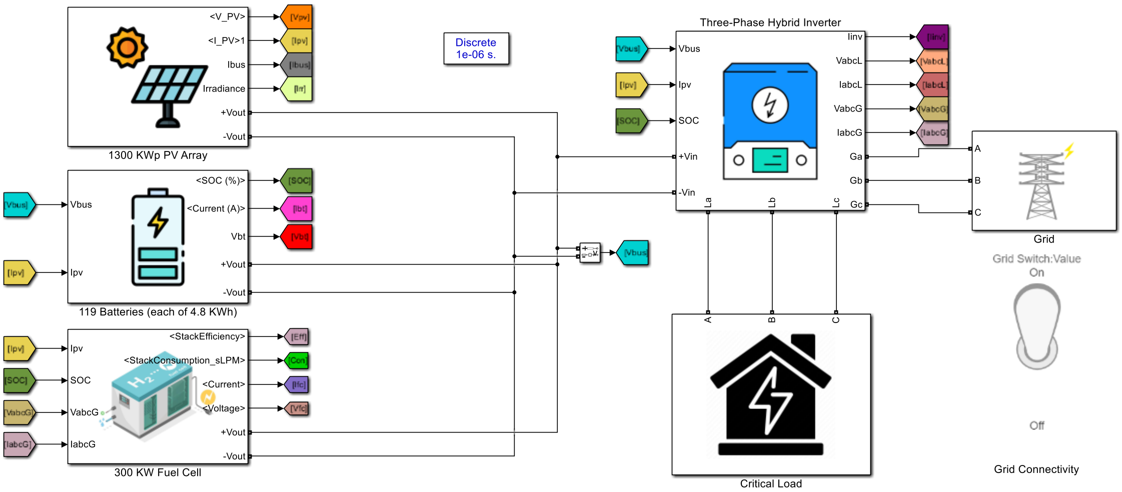

Figure 3.7. System Model

3.2.2.1 Subsystem for PV Array

The subsystem consists of the PV array, a boost DC-DC converter, and the Perturb and Observe (P&O) MPPT algorithm to extract maximum energy at different irradiance levels. In MATLAB/Simulink, this architecture is realized for modeling and simulation. The control algorithm aims at the maximum power-point tracking of the PV system, and it adapts to solar irradiation variation in real-time.

The PV array is connected to the DC bus through a boost converter, as shown in Figure 3.8. It is the role of the converter to boost the voltage from the PV array to a level that matches the condition needed by the DC link or subsequent stage in power flow. The boost controller gate signal is provided by a specific control unit including the incremental conductance MPPT algorithm. This algorithm is contained in a MATLAB Function block called MPPT_Control, and adapts in real-time to the conditions in which the PV array operates.

The P&O algorithm is one of the most popular MPPT methods, mainly because it is simple and easy to implement [31].It operates by injecting a disturbance in the working point of the PV array and measuring its variation on the output power. If this power is raised, the disguise passes on in the event of being a greater value than before, and if a smaller one, it makes stuff go backwards. This iteration allows the algorithm to track the MPP of the PV array in any condition [31]. The flow of the algorithm is illustrated in Figure 3.10, depicting the loop used by the control system to select the optimal duty cycle for the boost converter.

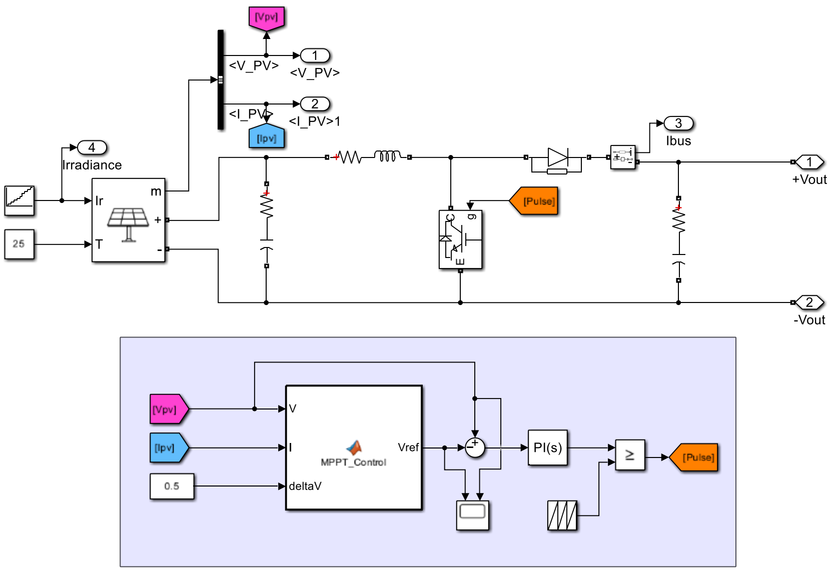

Figure 3.8. PV Array & MPPT Control

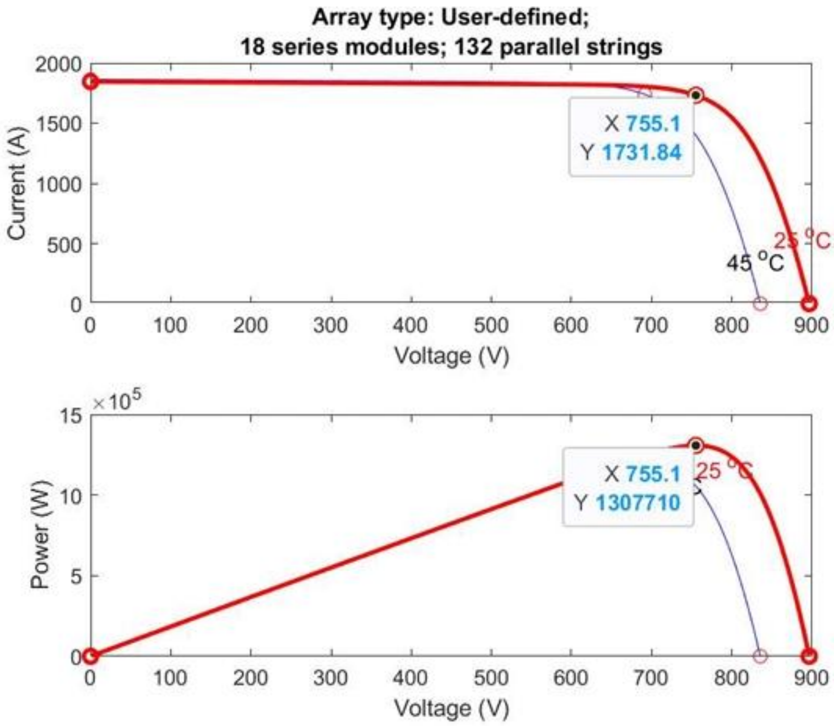

Figure 3.9. IV and PV curves of PV Array

Variable atmospheric solar luminous intensity conditions are simulated into the model with a Stair block in Simulink, permitting practical testing and performance analysis of the MPPT controller. The PV array can be tested for insensitivity and speed using variable solar irradiances. The electrical characteristics of the PV array for these conditions are shown in Figure 3.9 (IV) and (PV) curves. The PV curve explains that the maximum power output of the system is about 1300 kW. This value is consistent with the theoretical value calculated by HOMER Pro software, which verifies the rationality of the MPPT strategy and PV subsystem design. The joint consideration of hardware modelling and algorithmic control demonstrates the importance of intelligent energy harvesting for solar power systems. An efficient voltage control is achieved using a boost converter, and the PV module works at its maximum power point (MPP), which is achieved using a P&O MPPT algorithm shown in Figure 3.10 [31]. Such a system is required in grid-tied and standalone renewable energy systems, where the maximum power production from PV panels is crucial. Furthermore, the use of MATLAB/Simulink permits easy insertion of other MPPT techniques or further implementation for providing energy storage and load management into the system.

The proposed sub-system can harvest the maximum power from the PV panel under varying irradiance conditions when operated in conjunction with a boost converter P&O MPPT algorithm. Simulation results verify that the system performance can be well preserved.

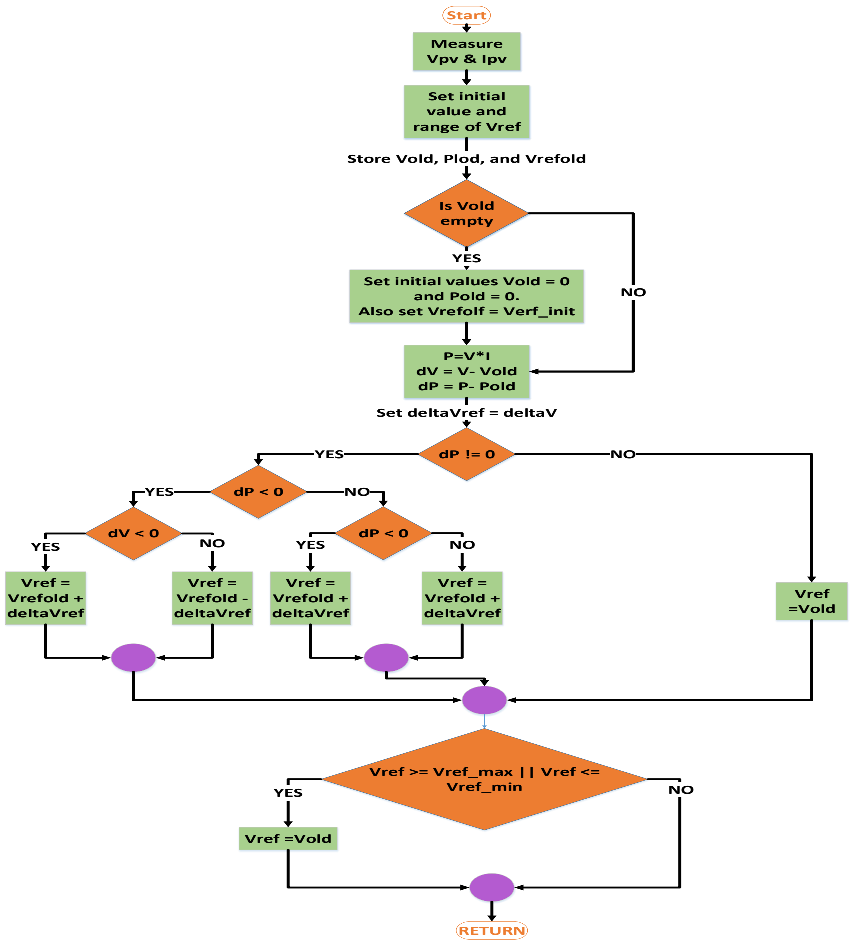

Figure 3.10. Flowchart for P&O MPPT Algorithm

3.2.2.2 Subsystem for Battery Pack

The energy storage and control sub-system includes batteries, a bi-directional Buck-Boost converter, and its control circuit to manage the operation of the DC-DC converter. According to this configuration, the battery bank is fully charged and discharged in a controlled manner.

The battery bank is interfaced with the DC bus, as depicted in Figure 3.11, with a bidirectional Buck-Boost converter. This converter plays a significant role in regulating the energy transfer between the battery and the DC bus [32]. It is formed by four semiconductor switches, such that the system can work in a buck and boost manner between the relative battery voltage and the DC bus voltage. One advantage of the bidirectional Buck-Boost converter is that it can operate over a wide range of power conversion and has better-controlled energy flow, which makes it a reliable system in general [33].

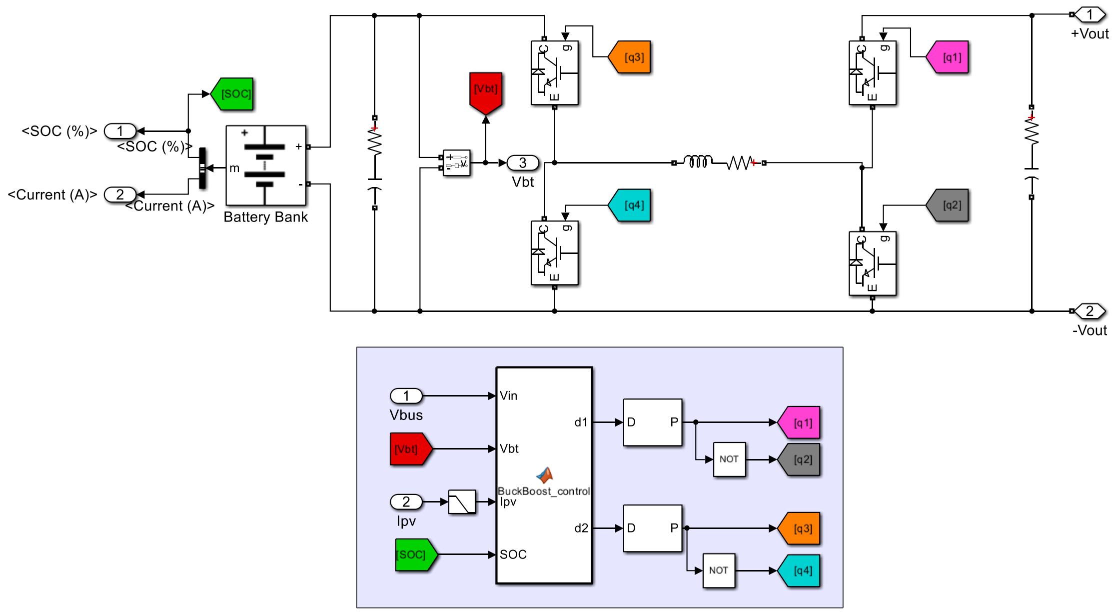

Figure 3.11. Energy Storage and Control

The converter is a dynamic counterpart addressing the voltage difference between the battery and DC bus. When the voltage of the battery bank is lower than that of the DC bus, two modes are divided: Buck mode in charging and Boost mode in discharging. This is shown in Figure 3.12 and Figure 3.13 with the current flow direction, and the states of the switches as a function of each case. In a buck charging mode, power is drawn from the bus to the battery in a step-down manner. On the other hand, in boost mode discharging, energy goes from the battery to the DC link through step-up conversion.

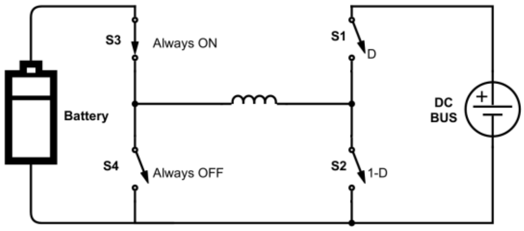

Figure 3.12. BUCK Charging Mode

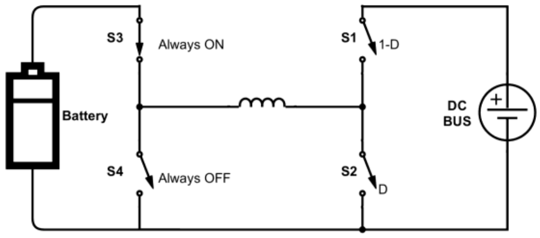

Figure 3.13. BOOST Discharging Mode

Similarly, if the battery bank voltage exceeds that of the DC bus voltage, a bi-directional converter operates in parallel dual-mode. The system is, as shown in Figure 3.14 and Figure 3.15, recyclable for both boosting and bucking operation, where energy conduction directionality is created again according to the control logic. Such energy control offers versatility to the systems in accordance with various working situations and maintains an optimal charge or discharge of the battery, regardless of voltage variations, in a more beneficial manner.

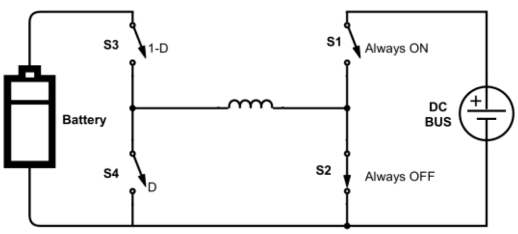

Figure 3.14. BOOST Charging Mode

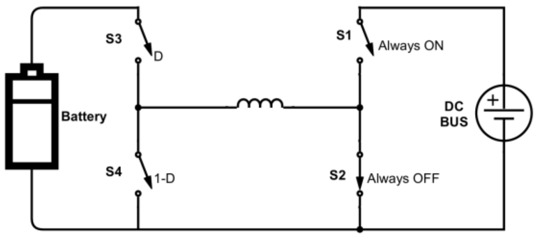

Figure 3.15. Buck Discharging Mode

When the battery bank voltage matches the DC bus voltage, which always happens in practice, the converter is functioning as a synchronous buck-boost. In this way, energy is transmitted with practically no voltage variation, so that the system operates efficiently during charging and discharging. These modes are shown in Figure 3.16 and Figure 3.17, revealing the capability of the converter to deal with equilibrium conditions of the system.

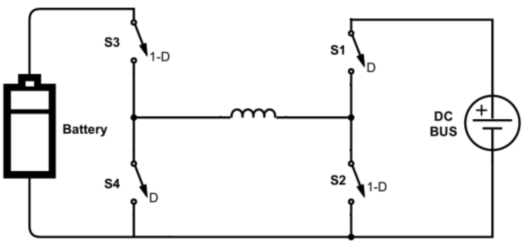

Figure 3.16. BUCK-BOOST Charging Mode

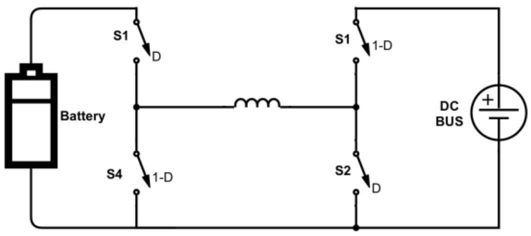

Figure 3.17. Buck-BOOST Discharging Mode

The bidirectional Buck-Boost converter's controller is a crucial component for the system. The flowchart shown in Figure 3.18 controls the operating mode of the converter. Such a control strategy is developed in the MATLAB function to match the functional block shown in Figure 3.11. The flow chart explicitly defines the situations to convert from charging and discharging modes as per system factors, mainly including the PV current value and the battery SOC.

According to the control scheme in Figure 3.18, two conditions would force the converter into charging mode: either when the PV current goes over 300A or once the battery SOC falls below 20%. These situations are examples of an excess of solar energy for storage or when the battery has to be charged in order to keep it in good operating condition. In contrast, the discharging mode comes for the converter when the PV current is less than 300A and the battery SOC is greater than 20%. This condition guarantees that the battery discharging is turned on only in states of low solar input and the battery has sufficient charge to fulfill load demands.

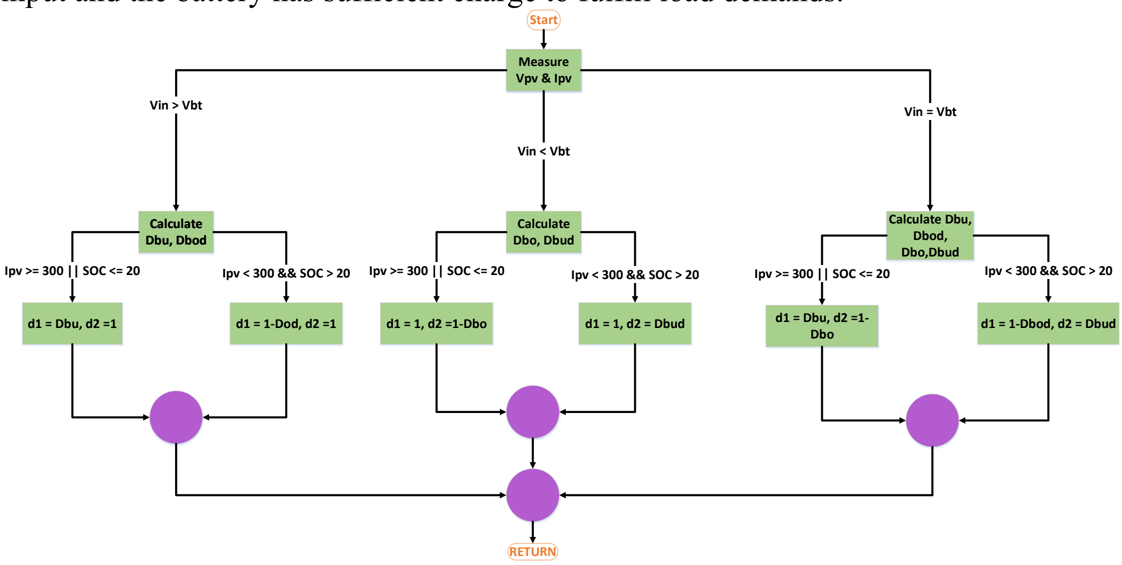

Figure 3.18. Control Flowchart for Bidirectional Converter

An advantage of the control scheme is that it provides a very simple and effective way for signal generation. The control circuit described in the flowchart and programmed for MATLAB generates only two different values of duty cycle. For each operational mode is associated a duty cycle which reduces the recharging or the discharging, thus controlling the conversion switch. The duty cycles are then further processed to generate the four control pulses required for operation of the four semiconductor switches in the bidirectional converter.

Using NOT logic gates, as shown in Figure 3.11, two control pulses can also be obtained from each duty cycle. This approach greatly simplifies the computational load and complexity of the control circuitry while still achieving efficient, robust operation. Based on the inversion by logic gate type signal, the switching of switches is properly conducted so as not to overlap for safe operation without short-circuiting.

In conclusion, the proposed bidirectional Buck-Boost converter battery management system presents a flexible and robust solution for energy storage systems in DC-microgrid or renewable resources. Keeping stepped up, stepped down, and step-up/step-down, it provides efficient bi-directional power flow for buck, boost, or buck-boost mode of operation determined by the voltage reference level. The MATLAB-controlled algorithm improves system intelligence and modifies the converters' operation on the fly, which is determined by PV current and battery SOC. The control signal generation logic, which is simple and involves only two pulses and logical complementation, adds to the system efficiency, robustness, and implementability.

3.2.2.3 Subsystem for Fuel Cell Stack

This section explains how a fuel cell (FC) stack is incorporated into the suggested hybrid power system along with the complementary control mechanisms. The FC is linked with the DC bus by a BOOST converter and two IGBT switches in Figure 3.19. This configuration allows the energy cell to flexibly regulate its power support to the system in response to varying operating circumstances.

A Stateflow chart is implemented to generate the pulse-width modulated (PWM) signals necessary to switch the BOOST converter. Power from the fuel cell is regulated by controlling (e.g., adjusting) the output voltage of the BOOST converter to regulate power output from the fuel cell by varying the duty cycle of PWM signals. This voltage regulation is required in order to ensure stable operation of the DC bus and to meet system power demands adequately.

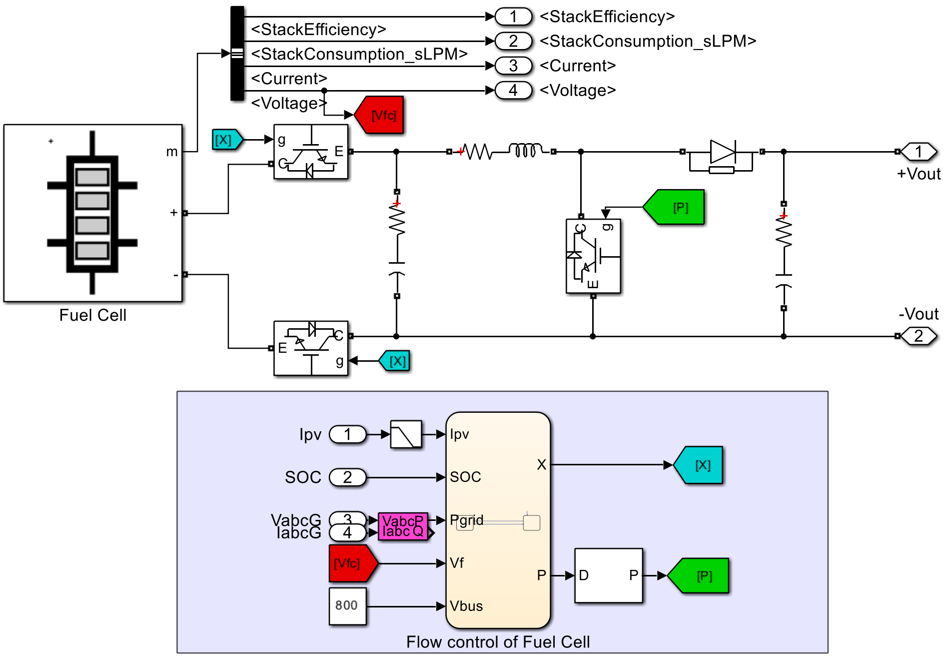

Figure 3.19. Fuel Cell Stack & Its Control Mechanism

It also includes a state-based logic controller for the commutation of the IGBTs, which is implemented in this Stateflow chart. Figure 3.20 is the state transition diagram, which shows how to determine when to connect or disconnect the fuel cell stack current. This control methodology increases the system flexibility with respect to varying scenarios and considers critical system parameters such as PV current and grid availability.

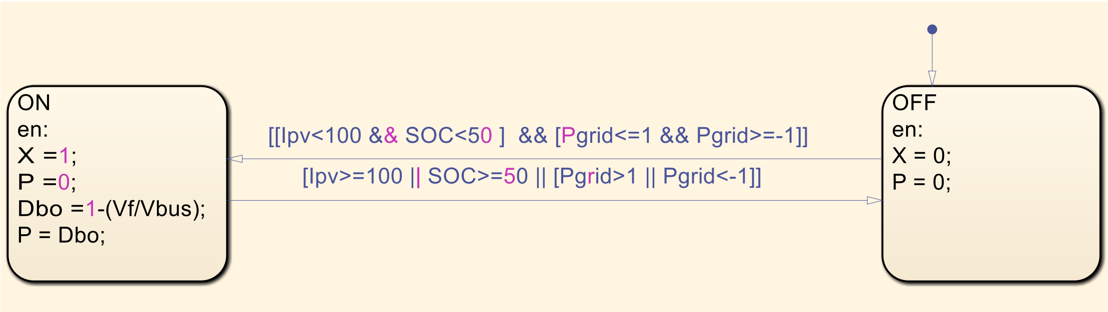

Figure 3.20. Flow Control of Fuel Cell

The Fuel cell turns on and begins feeding current to the system if its control logic is set to a PV current under 100A, an SOC of less than 50% for the battery pack, and the absence of a grid. These situations both symbolize a lack of renewable energy output and are not supported by the battery, and the fuel cell should be used to make up any power deficiencies.
If the photovoltaic current is greater than 100A, the fuel cell is turned off and deactivated; alternatively, when the battery SOC is greater than 50% or if the grid is present. So, the system will prefer renewable sources and grid power over fuel use and make the best overall use of energy.

In addition to improved utilization of a variety of energy sources, the life of the fuel cell is prolonged by operating the fuel cell as required. The MATLAB-based control functions and the Stateflow logic are embedded directly in Simulink to result in a real-time adaptive control functioning under different conditions of operation, all while maintaining stability and efficient performance of the system.

3.2.2.4 Subsystem for Hybrid Inverter

This subsystem is based on a three-phase hybrid inverter with an LCL filter and a grid-forming control system, which can operate properly in both grid-connected and islanded modes. This configuration facilitates the transition from grid-connected to islanded operation, as illustrated in Figure 3.21, providing a stable power supply at all times [34]. The main power electronics component used in this configuration is a three-phase, six-switch inverter, whose structure is shown in Figure 3.22. Six gate pulses, the control signals for this inverter, are produced by a specialized control subsystem, which is similarly seen in Figure 3.21. The inverter's output must be modulated by this control subsystem to allow for a smooth transition between grid-connected and islanded operation [34].

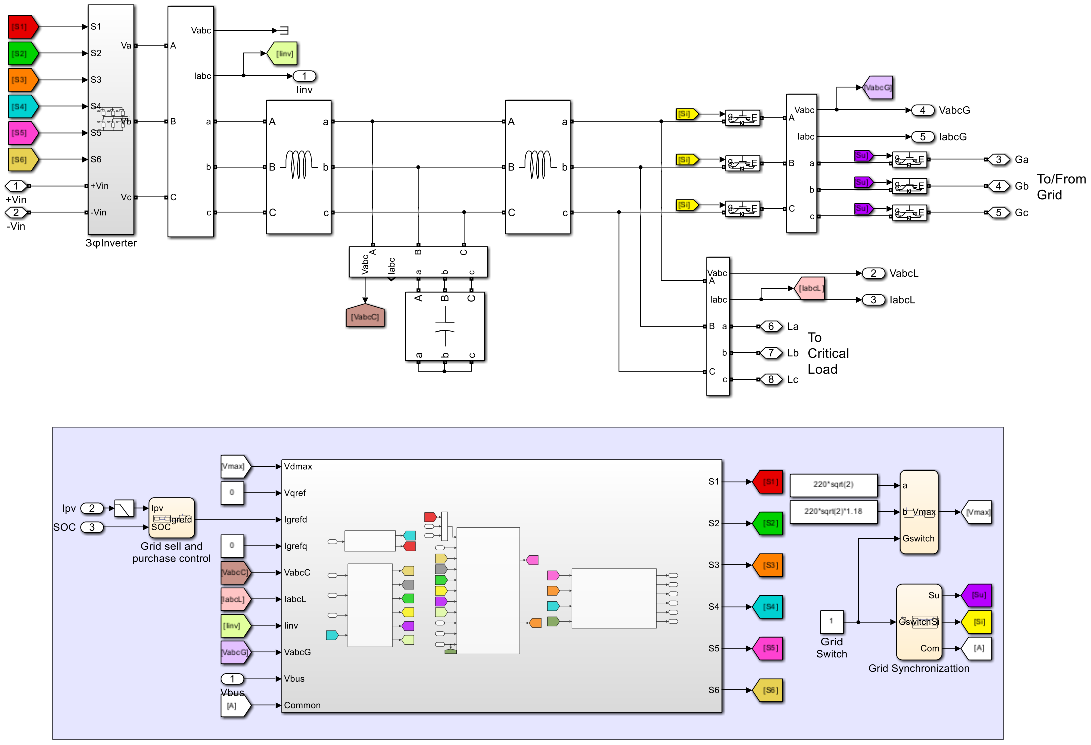

Figure 3.21. Hybrid Inverter with Control Block

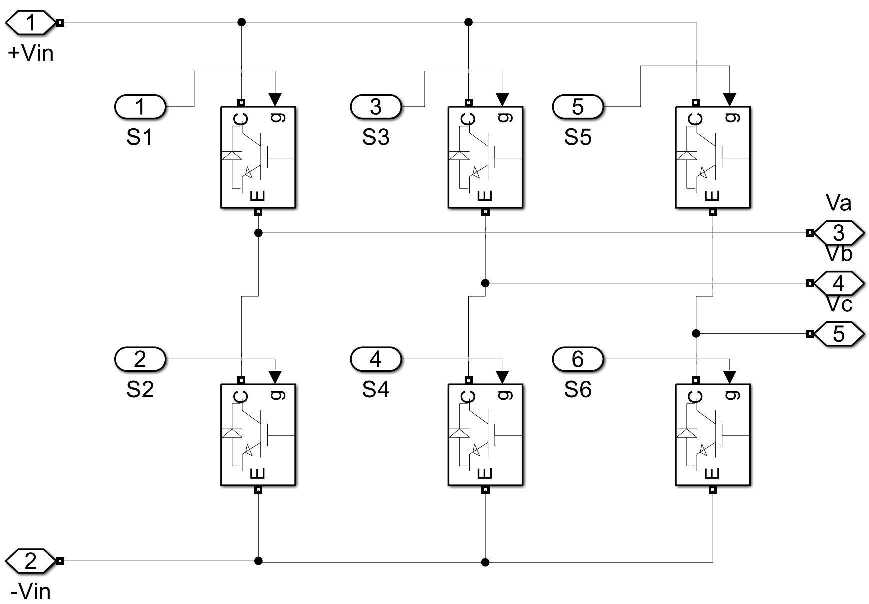

Figure 3.22. Three-Phase Inverter Circuit

The section of the inverter control subsystem is arranged in four main blocks from the point of view of functionalities. These are the abc to dq0 transformation block, the phase-locked loop (PLL), a current reference generator with an inductor current feedback loop, and finally a pulse width modulation (PWM) signal generator. All of these building blocks have a functional role in the control scheme and can be seen visually in Figure 3.23.

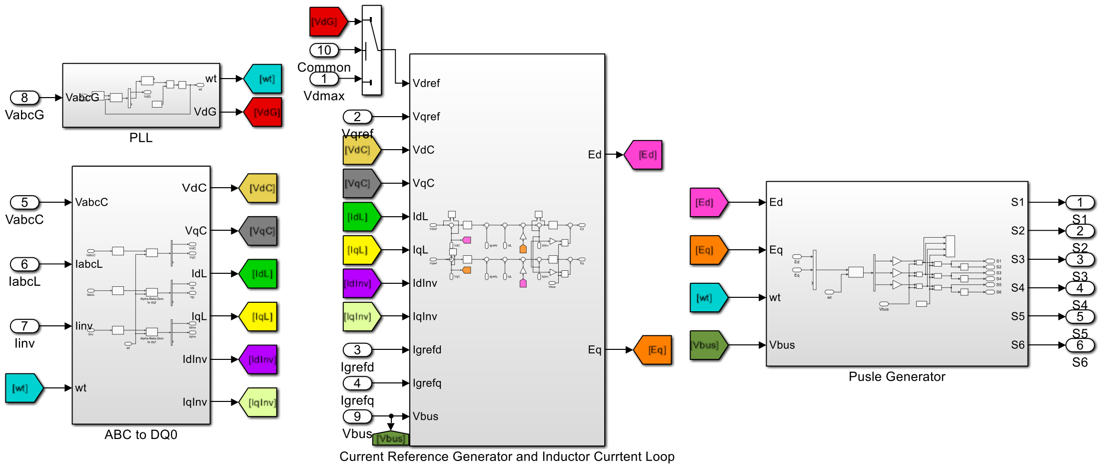

Figure 3.23. Control Subsystem for Hybrid Inverter

The abc to dq0 transformation is a part of the first level of the control sequence. It receives signals from the voltage of the filter capacitor, the load current, and the inverter current. At first, these three-phase signals (in the abc frame) are transformed to the stationary reference frame (αβ) through the Clarke transform. Then, the αβ vectors are transformed into the dq0 rotating reference frame by the Park transform. This two-stage transformation process, as illustrated in Figure 3.24, is introduced to facilitate the dynamic control of the AC variables by converting them into quasi-DC values in the dqo frame. This representation enables more efficient and responsive inverter control algorithms.

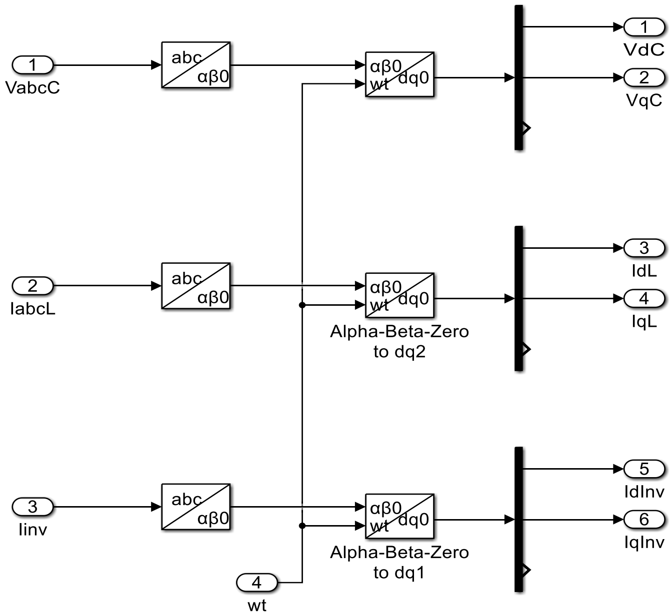

Figure 3.24. ABC to dq0 Converter Subsystem

The control system must maintain rotation phase synchronization with the utility grid for the DQ and/or Park transformation execution to be valid [35]. Such synchronization is being realized through the Phase-Locked Loop (PLL), which is illustrated in Figure 3.25. The PLL tracks the phase angle of the grid voltage in real time and orients the dq0 transformation [36]. Accurate phase tracking keeps the reference frame aligned with the rotating vector of the grid, which is needed for power quality and system stability during grid-connected operation.

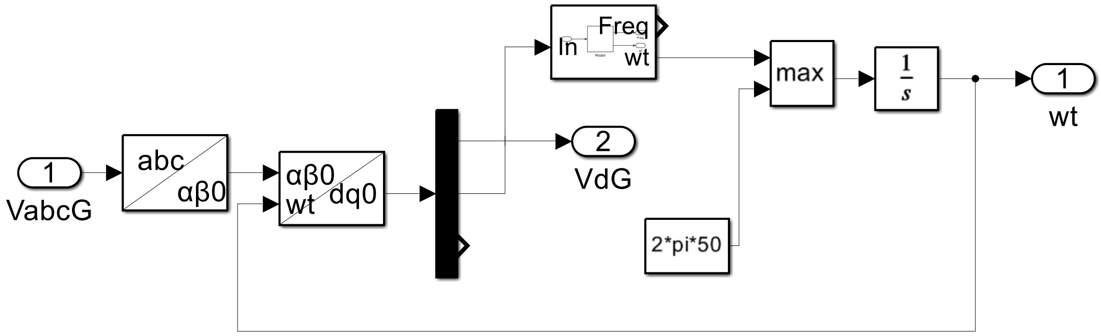

Figure 3.25. PLL Subsystem

After the conversion to the dq0 domain is complete, the signals are sent to a current reference generator subsystem that includes an inductor current control loop. This subsystem is crucial in producing reference voltages for the inverter, as can be seen in Figure 3.26. These reference voltages are functions of the difference between the actually measured currents (and/or any other parameters of operation desired) and predetermined set points, so that a control system modifies in real time the inverter output to meet power demand in real time. That means a proportional-integral (PI) control method is introduced in the inductor current loop, which can further enhance current tracking performance, eliminate steady-state error significantly, and bring higher overall control quality.

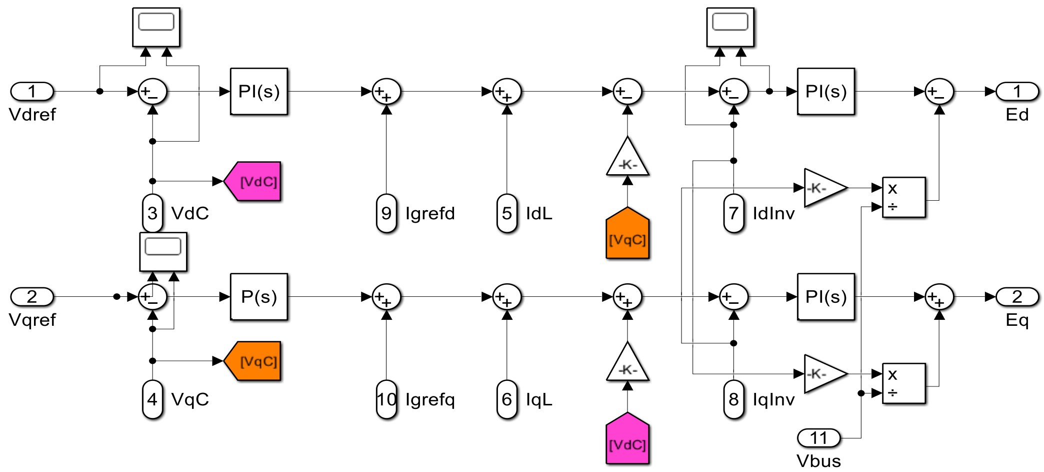

Figure 3.26. Current Reference Generator Subsystem with Inductor Current Control Loop

The reference voltages derived from the current controller serve as inputs to the PWM generation subsystem and are subsequently converted back to the abc domain via inverse Park and Clarke transformations. These abc-domain voltages are then used as inputs to the PWM generator, which is shown in Figure 3.27. Within this block, voltages are converted into gate pulse signals by means of common PWM algorithms that may be Sinusoidal PWM (SPWM) or Space Vector Modulation (SVM), among others. These gate pulses are precisely timed and modulated to control the switching of the three-phase inverter, thereby ensuring that the inverter output conforms to the desired voltage and frequency specifications. This entire control chain allows the inverter to function optimally in both grid-tied and islanded modes, responding dynamically to load changes and grid conditions.

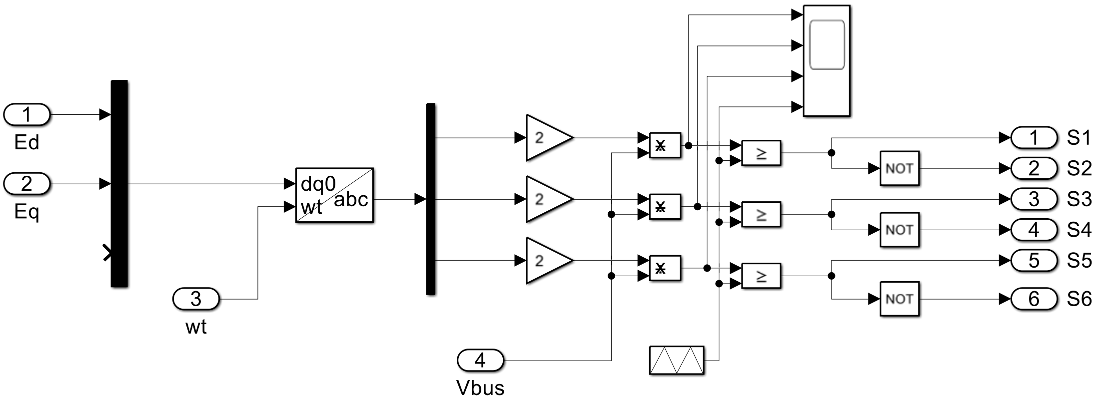

Figure 3.27. PWM Generator Subsystem

In addition to the basic control elements, a logical system based on a system of state flow charts is used in order to study the transfer from the sale operation mode to purchase from the grid. This state logic is also contained in the general control system of Figure 3.21, and is explained further in Figure 3.28. The flow chart of the state is an algebraic formulation of a group of decision-making rules by using real-time values for photovoltaic (PV) current and battery SOC. The control logic distinguishes between operating modes by monitoring whether the PV current is within a specific range and whether the battery SOC falls within predefined thresholds.

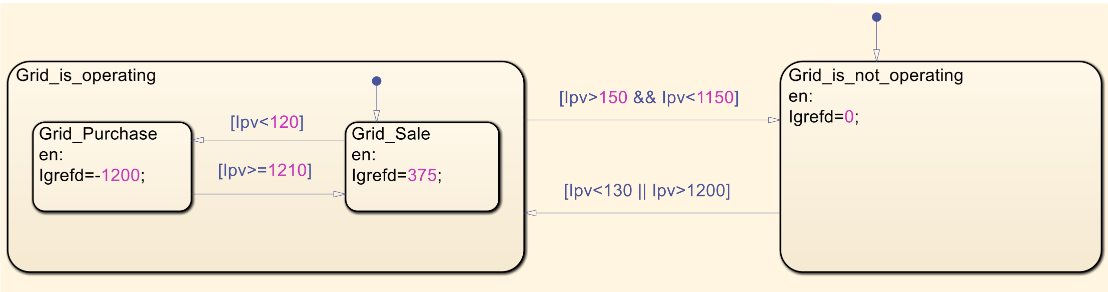

Figure 3.28. State Flow Chart for Hybrid Inverter

According to the state flow diagram, when the PV current is greater than 150A but less than 1150A, the system remains in islanded mode, with the grid remaining disconnected. This condition suggests that both the generation and storage capacities are sufficient to meet load demands without external support. Conversely, a connection to the grid is enabled while the PV current is below 130 A or above 1200 A. This means either a lack of storage or excess energy that must be dumped.

After connecting to the grid, the question is whether to buy power from the grid or sell power to the grid when you have surplus. This second selection is also based on the current through the PV. On the other hand, when the PV is less than 120A, as shown in Figure 3.28, the system runs in grid purchase mode. In this case, power is taken from the grid to charge the battery or run the load. Conversely, when PV current is greater than 1210A, the mode changes to grid sell mode (sell power to the grid).

These modes and transitions are fully embedded and executed within the controller automatically to achieve energy management without any supervision. Application of such decision trees or threshold-based logics greatly helps to regulate energy flow, to stabilize the system, and to extend battery life by controlling charge and discharge cycles. One major limitation of the hybrid inverter system is its inability to effectively tackle unbalanced load conditions, even though the sophisticated management system allows smooth transitions between grid and island operation. Although the system performs well when integrating renewable energy sources using PLL synchronization, dq0 control, and PWM-based modulation, it suffers from poor performance when loads are asymmetrical. By using SOC-based and real-time PV decision-making, a state flow chart improves autonomy. By fixing its incompatibility with imbalanced loads, it would become far more resilient, adaptable, and compliant with changing grid integration standards.

3.3 Design Specifications. Standards and Constraints

Cost, effectiveness, and dependability were all taken into consideration when creating the design parameters. Every system component in HOMER Pro was parameterized using lifetime assumptions, efficiency ratings, and realistic cost data. For example, the LONGI LR5-72HPH PV modules, which have an annual cost of $163.71/kW and O&M of $1/kW, were chosen because of their 25-year lifespan and 21.1% efficiency. Likewise, the Deye SUN-50K-SG01HP3-EU-BM4 inverter was selected because to its 15-year lifespan and 97.6% efficiency.

Supported by a Battery Management System (BMS), the battery subsystem was modeled as prismatic-cell-based units (4.8 kWh apiece) with a 98% efficiency rate. O&M costs were projected to be $28.69 per year, while capital and replacement expenditures were predicted to be $344.25/kW. Since HOMER Pro does not have a direct option for the fuel cell, a generic genset was set up on the DC bus to simulate fuel cell operation. Its replacement cost was $28/kW, and its capital cost was $30/kW. In order to adhere to operating requirements, constraints were also incorporated into the design. In particular, as Section V has shown, the grid export was capped at 100 kW. This limitation follows reasonable grid-integration rules and avoids the detrimental over-injection to the grid. In the same way, PLL synchronization, dq0 transformation, and SOC-based decision rules were implemented to enforce control constraints in Simulink, ensuring the system complies with present grid standards for voltage and frequency stability.

The definition process was influenced by the following ERRs: system reliability, renewable penetration, and financial viability (NPC and LCOE). These fiscal and engineering constraints guaranteed that the design was practical and met the criteria for renewable integration.

3.4 System Analysis or Design Analysis

The analysis phase was carried out in two stages: MATLAB/Simulink dynamic performance validation and HOMER Pro economic optimization. The system obtained a Net Present Cost (NPC) of $1.21 million and a Cost of Energy (COE) of $0.0521/kWh based on the HOMER optimization results, which are shown in Figure 3.5 and Figure 3.6. A total of 2,615,947 kWh of electricity was produced annually, of which 1,668,040 kWh were used by the load and 251,800 kWh were exported to the grid. The anticipated 57.9% renewable penetration shows how important solar PV is while maintaining dependability with backup sources and storage. Operational performance was further confirmed by the MATLAB/Simulink subsystem-level design study (Section 3).

- To ensure maximum power extraction under fluctuating irradiance, the PV subsystem (Figure 3.8-Figure 3.10) included a boost converter using a Perturb & Observe (P&O) MPPT algorithm. A peak production of 1300 kW was confirmed by the IV and PV curves (Figure 3.9), which matched HOMER estimations.
- The bidirectional buck-boost converter in the battery subsystem (Figure 3.11-Figure 3.18) was managed by PV current and SOC criteria. Charging, discharging, and neutral mode transitions were illustrated by control flowcharts (Figure 3.18).
- Stateflow-based PWM logic controlled the fuel cell subsystem (Figure 3.19-Figure 3.20), only turning on when grid power was absent and PV generation and SOC were low.
- Hybrid inverter subsystem, (Figure 3.21-Figure 3.28), which incorporates dq0 transformation, PLL synchronization, PI control of the currents, and PWM generation to guarantee stable performance in both grid-tied and islanded operation modes. Its inability to handle unbalanced loads was, however, an important limitation that confined the range of possible applications.

Besides satisfying the techno-economic optimization objectives, the multi-stage analysis also demonstrated that the desired system operated steadily under load transients, changing irradiance, and grid interruptions.

3.5 Simulation/Experimental Setup

There are two main steps in the simulation process. The techno-economic optimization was performed in the first stage through the HOMER Pro. Component details, prices, load profiles (Figure 3.1-Figure 3.2), and sun radiation (Figure 3.3). Inputs were filled. HOMER generated several configurations, evaluated their performance and cost, and recommended the best one (Figure 3.5- Figure 3.6).
The HOMER-selected component sizes were used in the second stage for full dynamic simulations with MATLAB/Simulink. The whole system model is shown in Figure 3.7 with each major element as a distinct subsystem for separate testing.

Several operating situations were examined:

- During grid disruptions, the inverter smoothly transitioned to islanded mode.
- Variable load circumstances, such as the peaks in demand seen in Figure 3.1.
- Simulink's Stair blocks are used to simulate fluctuating solar irradiation to mimic real-world fluctuation.

Outputs included fuel cell activation states, inverter synchronization waveforms, PV power curves, and battery SOC trends. The simulation also validated the energy management strategy, including the grid import/grid export logic (Figure 3.28), ensuring the transitions of modes of operations were transparent to the operator. This two-step simulation approach ensured that HOMER Pro economic optimization was supported by MATLAB/Simulink technical feasibility.

3.6 Summary

To design a grid-connected hybrid power system, an integrated method of dynamic technical validation (MATLAB/Simulink) with economic optimization (HOMER Pro) is proposed in this paper. The optimal design was found by HOMER Pro to have a Net Present Cost of $1.21M and a COE of $0.0521/kWh. This included a 450 kW inverter, 119 batteries (each 4.8 kWh), a 300 kW fuel cell, and a 1300 kWp PV array.

The dynamic nature of Simulink modeling enabled the system to be tested under different operating conditions. The PV sub-system using P&O MPPT (Figure 3.8-Figure 3.10), the battery sub-system incorporating bi-directional control (Figure 3.11-Figure 3.18), the FC logic (Figure 3.19-Figure 3.20), and the hybrid inverter implementing dq0 and PLL-based control (Figure 3.21-Figure 3.28) are evaluated in terms of stability, speed, and flexibility of response. While the results showed some degradation of performance under non-uniform load distribution, the proposed system performed well under load variation, grid disturbance, and renewable intermittency.

Overall, the study shows that a thorough framework for creating hybrid renewable energy systems may be obtained by combining HOMER Pro optimization with MATLAB/Simulink technical validation. In addition to being technically sound and reasonably priced, the system provides insightful information for potential large-scale implementation in areas with comparable resource and demand characteristics.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Results

This chapter provides simulation results based on MATLAB/ Simulink of the proposed model for optimized power generation from a PV-FC-BESS combination integrated with the grid and a local load. The system is tested under different solar insolation conditions to verify that the duty cycle can effectively regulate DC bus voltage as well as guarantee continuous power output, and is capable of energy transition between the grid and micro-grids, in addition to controlling and coordinating the multiple distributed generations. The dynamic response and performance of each component, as well as the total hybrid system, are characterized to evaluate their full potential for practical deployment.

4.1.1 Photovoltaic System Performance under Varying Irradiance

A 1300kWp PV system has been used in the model, according to the economic analysis with HOMER Pro. The solar irradiance utilization is optimized by applying the popular Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT). This algorithm, depicted Figure 3.10, operates by iteratively perturbing the panel voltage and observing the resulting change in power output. If the power output increases, the perturbation continues in the same direction; if the power decreases, the direction is reversed. The process converges to the maximum power point (MPP), and energy harvesting is maximized under different environmental conditions. Figure 4.1 shows the time-dependent irradiance profile, depicting ideal and nonideal sun scenarios. The related PV voltage, current, and power signals are depicted in Figure 4.2 and Figure 4.3. The simulation result shows that the P&O method can track the maximum power point efficiently even in the case of rapidly varying irradiance. As seen in Figure 4.4, the PV output power responds to the irradiance changes proportionally, which confirms the dynamic performance of the MPPT controller. As the irradiance rises, both PV current and power increase. For example, at high irradiance (above 800 W/m^2), the system output attains a value that is not only sufficient for fulfilling the local load demand but also for charging the battery, and the surplus energy can be for the grid. On the other hand, when irradiance becomes zero, the PV current goes to zero, thus the PV share in the system disappears, and the system has to be supported from auxiliary sources (grid, fuel cell).

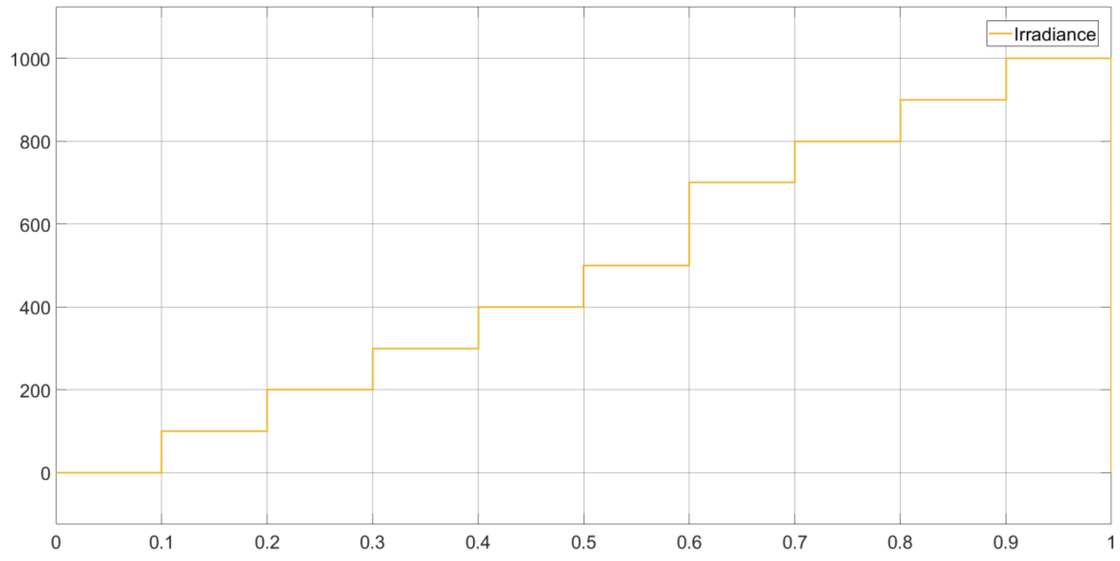

Figure 4.1. Irradiance

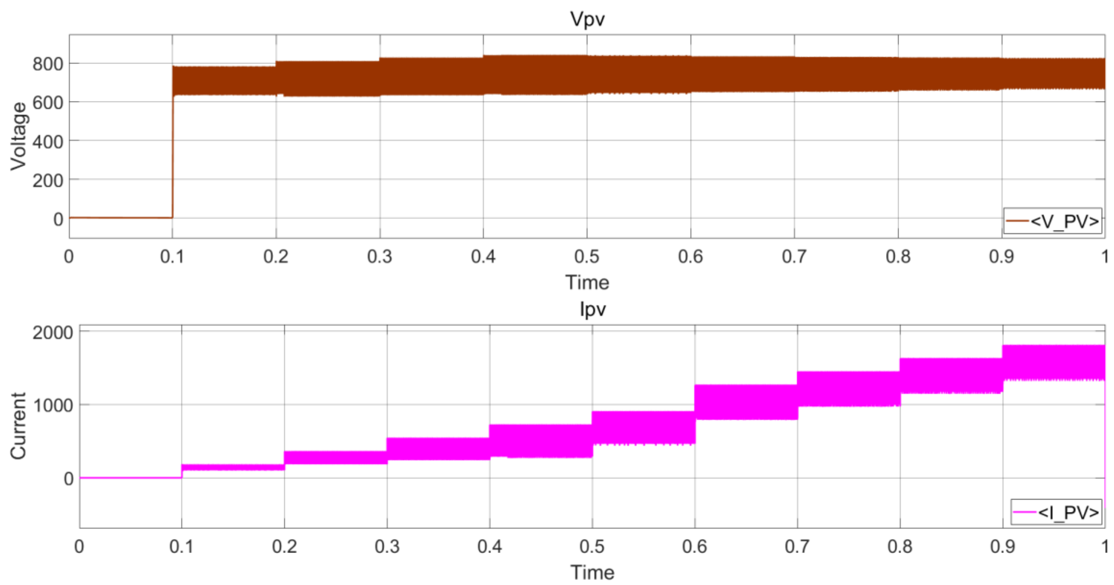

Figure 4.2. PV Voltage & Current

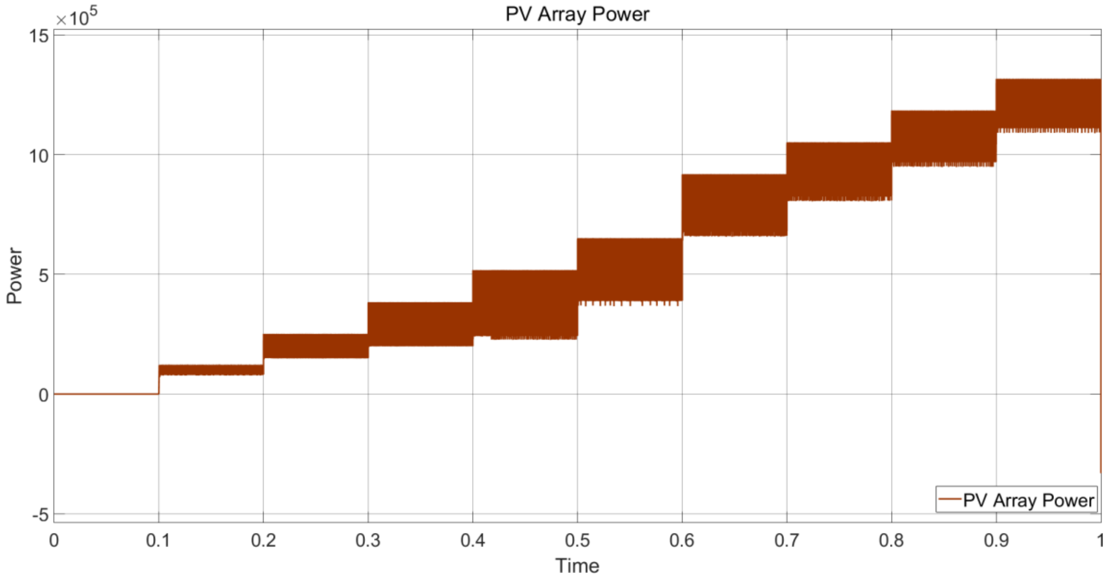

Figure 4.3. PV Power

4.1.2 Grid Interaction: Power Purchase and Injection

Among the main characteristics of the proposed system is that it utilizes the utility grid for bidirectional power flow. The system can work in grid-tied and islanded modes, and seamlessly switch between them. Figure 4.4 to Figure 4.6 analyzed the grid power characteristics.

Figure 4.4 shows the DC bus voltage, inverter current, grid voltage, and grid current. The inverter is stable and synchronized to the grid in the system. Figure 4.5 shows the grid single-phase voltage and current waveforms. The phase between the voltage and current is also a useful tool to tell the direction of the power. When the irradiance is zero and the PV current is very low, the system draws power from the grid to fulfill the local load and to charge the battery. This can also be seen in Figure 4.5, where the voltage and current are 180° out of phase, representing power bought from the grid. Figure 4.6 shows the instantaneous grid power. During periods of high irradiance (e.g., >800 W/m²), the system exports excess PV power to the grid after satisfying local demand and battery charging. The simulation confirms this behavior with positive grid power values. During moderate irradiance (e.g., between 200 and 800 W/m²), the PV array supports part of the load, while the battery may discharge to bridge the gap. Grid power during this period is observed to be zero, reflecting complete independence from the utility.

A crucial aspect of the system's resiliency is its behavior during grid outages. When the grid power goes offline, such as during load shedding or a fault, the system detects the disconnection and activates islanded operation. The transition triggers the fuel cell to compensate for the missing power, ensuring uninterrupted operation. This dynamic is clearly depicted in Figure 4.7, where the fuel cell output becomes active when the grid becomes unavailable.

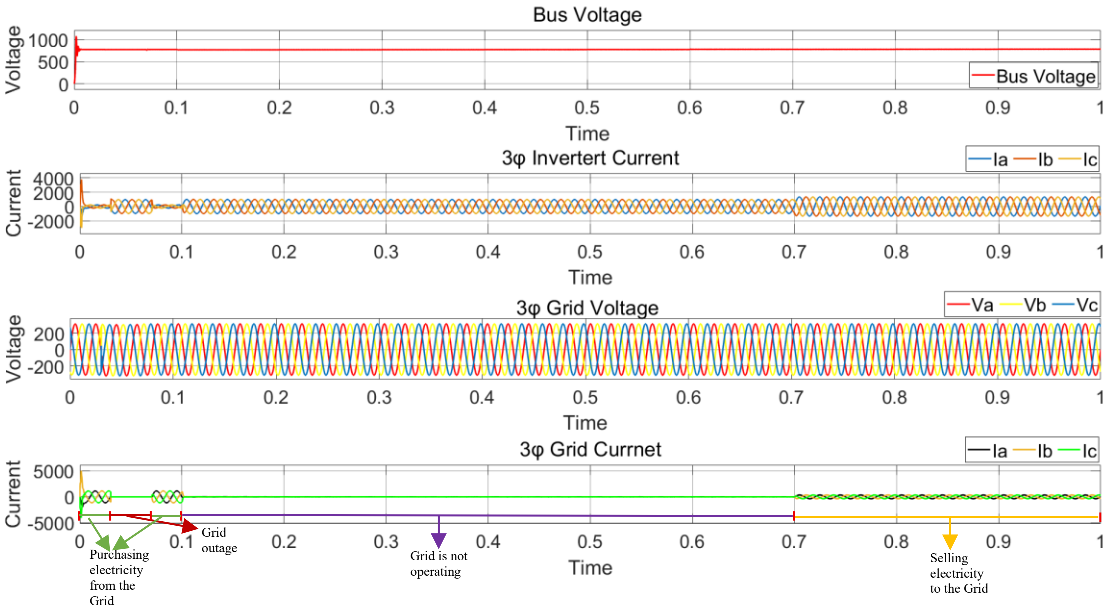

Figure 4.4. BUS voltage, Inverter Current, Grid Voltage, and current

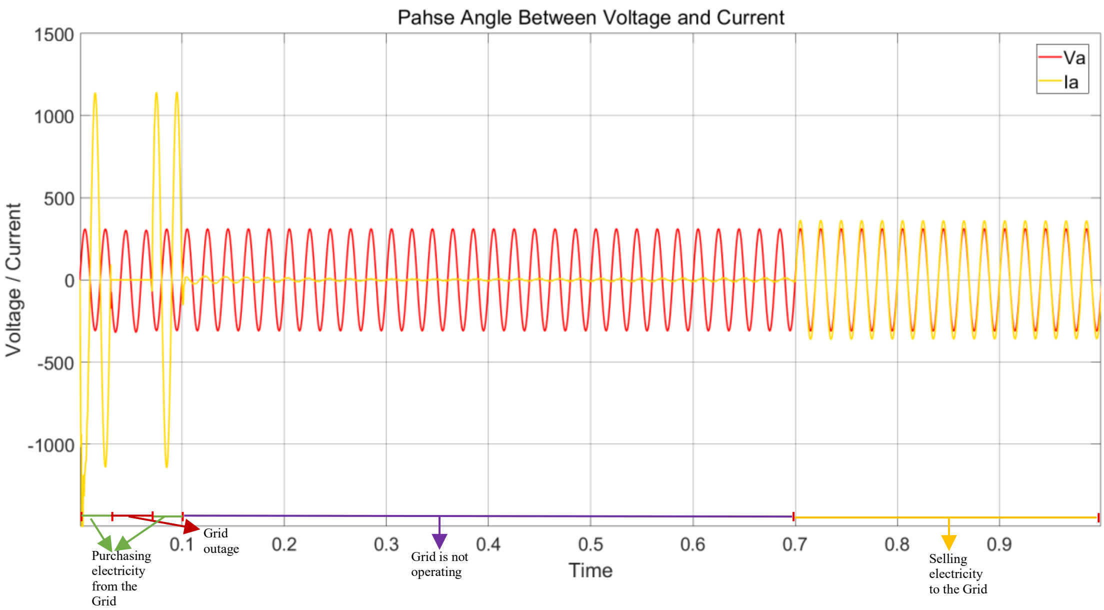

Figure 4.5. Single Phase Grid Voltage & Current

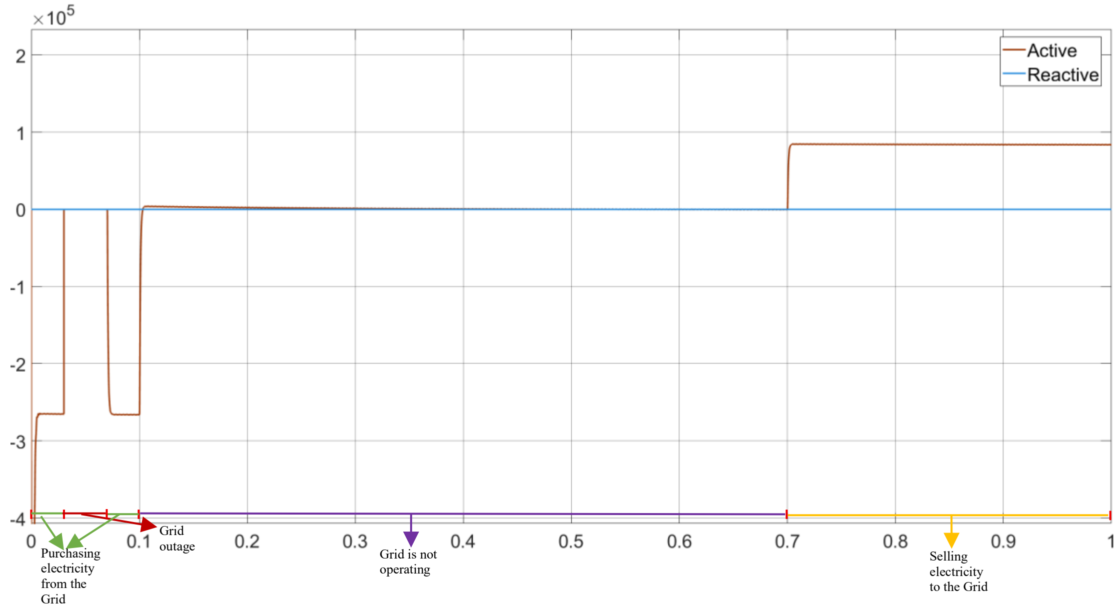

Figure 4.6. Grid Power

4.1.3 Fuel Cell Operation and Grid-Outage Resilience

The PEM fuel cell serves as a backup energy source during extended PV shortages or grid outages. Its operation is governed by a supervisory control strategy that triggers its activation only when required, either due to the unavailability of the grid or insufficient PV/battery supply. Figure 4.7 demonstrates the power characteristic of the fuel cell.

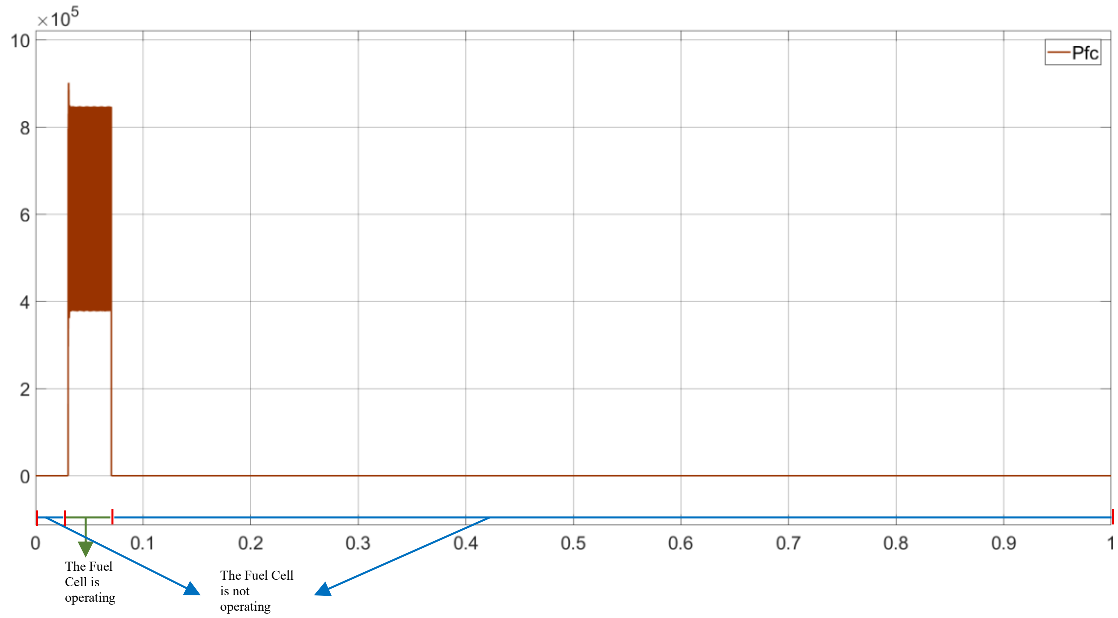

Figure 4.7. Fuel Cell Power

During irradiance dips (for example, full shading and at night), with the battery being poorly charged in the absence of the grid, the fuel cell starts producing electricity. This means the system can be self-contained and stable. As seen in the simulation, the fuel cell immediately turns on when the PV current is zero and the grid is not present. When the grid is restored and can take the load, the fuel cell is stopped, saving fuel and extending life. The results verify that the system can switch sources smoothly to provide uninterrupted power without human interference.

4.1.4 Battery Behavior: Charging, Discharging, and SOC Dynamics

The hybrid system is composed of a total of 119 batteries, each with a capacity of 4.8 kWh, resulting in an aggregated energy storage capacity of around 571.2 kWh. Battery management is important to keep a stable DC bus, to compensate for the energy supply-demand mismatch, and to prolong the system autonomy.

A special control logic, as depicted in Figure 3.18, controls the charge and discharge cycles based on system power flow and SOC of the battery. Figure 4.8 and Figure 4.9 show battery voltage, current, SOC, and power trends versus time.

At zero irradiance, the PV array does not feed the load. The battery charges and discharges according to the grid status. The battery is charged if the grid is accessible (negative battery power in Figure 4.8). Although the grid is offline and the fuel cell is up and running in the first case, the battery will still be charging, albeit more slowly. This behavior is essential for prolonging battery life and reducing reliance on the grid.

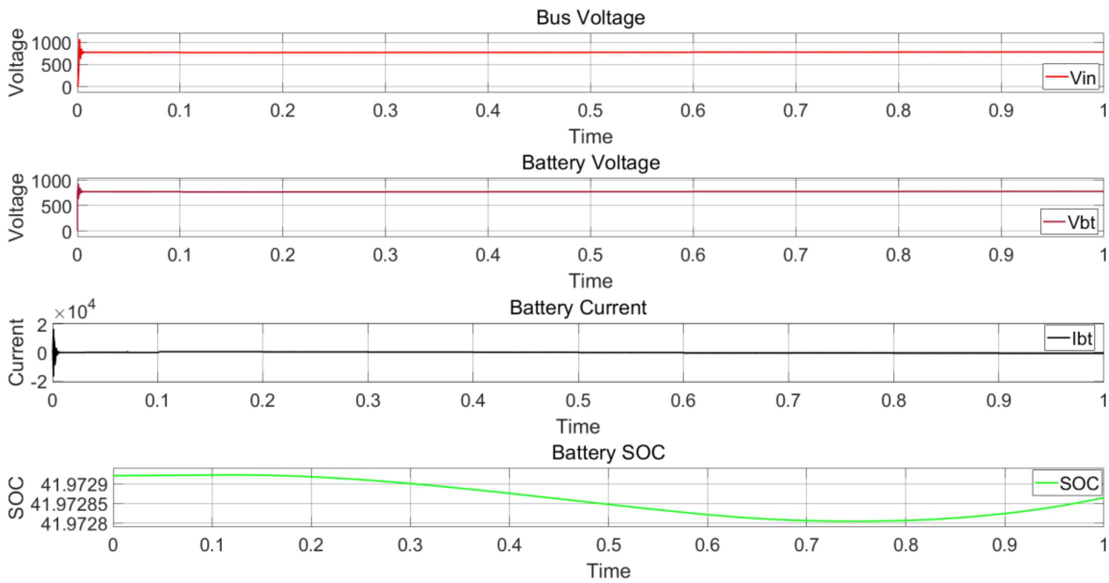

Figure 4.8. BUS Voltage, Battery Voltage, Current & SOC

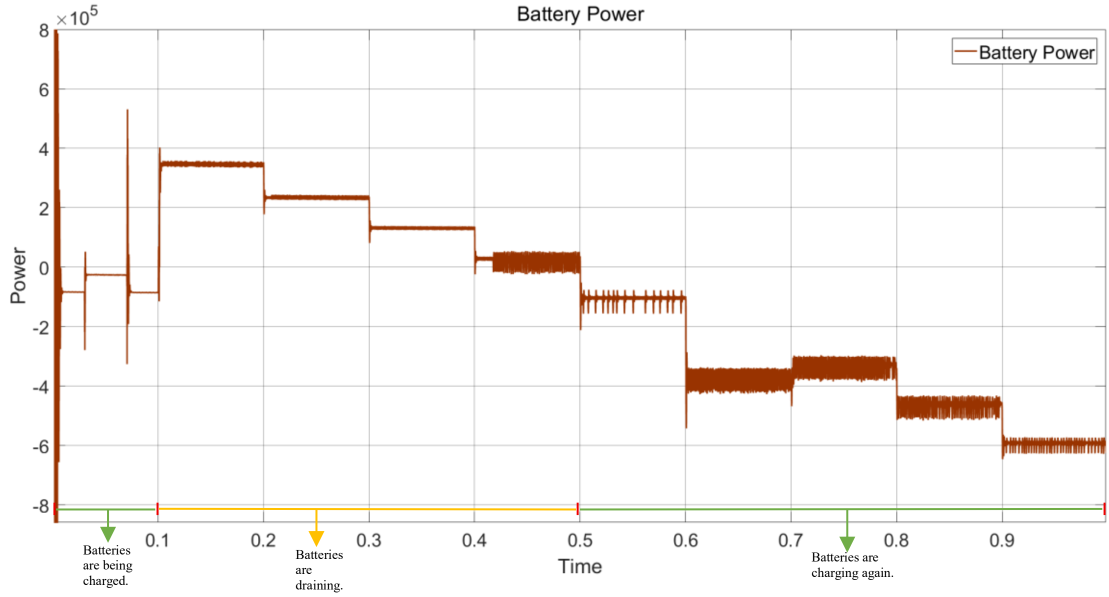

Figure 4.9. Battery Power

Under irradiance after exertion below 800 W/m², the PV current is within the limits 130A to 1200A. In that extent, PV energy is not enough to meet the demand of the load and charging. So, the battery is discharged to serve the rest load. From the irradiance higher than 800 W/m², and PV current higher than 1200 A, pv power is large. The system fulfills the load demand, the battery is charged, and excess energy is sent to the grid. This behavior is corroborated in Figure 4.9 for high irradiance, where the battery power turns negative again, indicating the battery is charging.

These power dynamics are echoed in the SOC trajectory, growing under charging and shrinking under discharging, and staying within the safe operating limits. The findings demonstrate that the battery acts as a good buffer for PV supply, which is intermittent, thus maintaining system continuity.

4.1.5 Load Stability and Power Quality

Stable power delivery to the local load is a typical and indispensable demand of the proposed system. The DC bus voltage, inverter current, load voltage, and load current are displayed in Figure 4.10. Figure 4.11 shows the load power related to this. These figures together show that the system can supply local load with constant voltage and current, even though irradiance, power source, and grid connection are experiencing fluctuations.

The power quality of the system can be evaluated as low voltage ripples, very small current harmonics, and stable power output. This results from the integrated energy sources control, highly efficient filter & regulation schemes, and embedded real-time supervision and adaptation strategies within the Simulink modeled system.

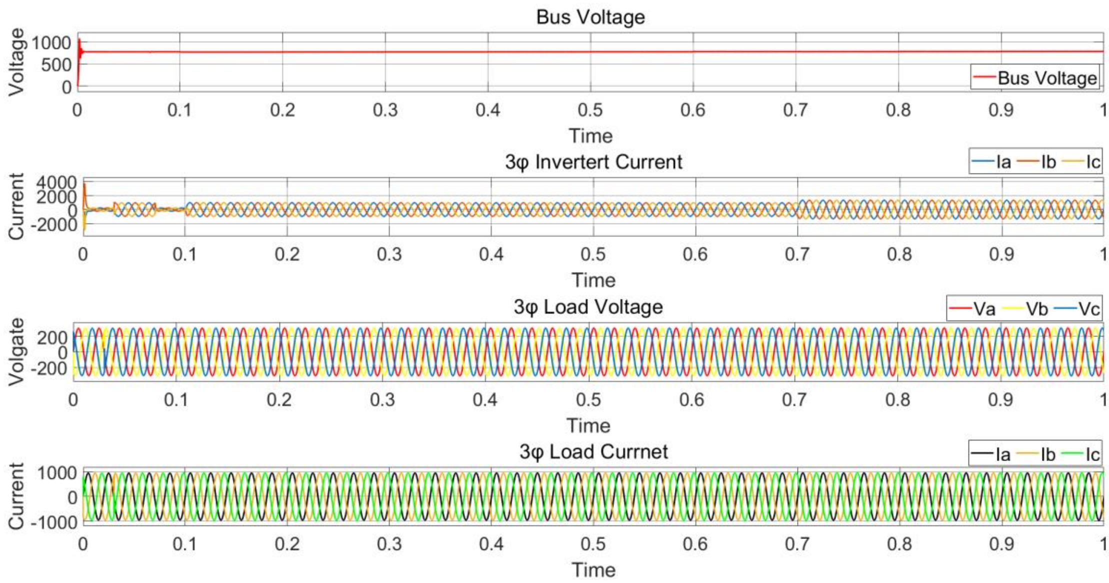

Figure 4.10. Bus Voltage, Inverter Current, Load Voltage & Current

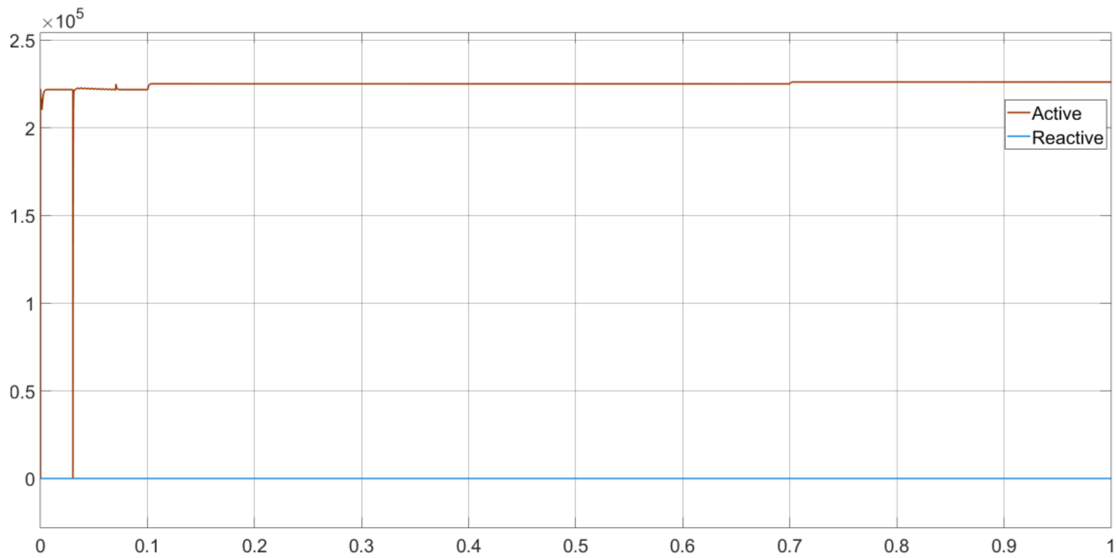

Figure 4.11. Load Power

Stable load voltage is maintained even during transient events (PV ramp-up, grid disconnection, fuel cell startup). These transitions happen without transients or power drops. Similarly, the inverter current follows these transitions smoothly and remains synchronized while it supplies the reactive and active power needs

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4.2 Discussions

The grid-connected hybrid system being proposed has good dynamic response, good source coordination, and high reliability under various operating conditions. The control architecture guarantees:

* Fast MPPT tracking and PV utilization;
* Intelligent grid synchronization and power exchange;
* Reliable backup from fuel cells during outages;
* Strategic battery uses for peak shaving, backup, and load balancing;
* Seamless transitions between operating modes (grid-tied, islanded, hybrid).

The simulation results confirm the real-time applicability of the system. The PV bundle is the source, with batteries as backup under typical working conditions. Long periods of cloudy or nighttime spread are compensated by an autonomy maintained on grid power or fuel cell running. The DC bus voltage, however, is regulated at all times, and the load power is uninterrupted.

These properties enable the integration with microgrids, rural electrification, smart buildings, and disaster-resilient infrastructure. The design is encapsulated with a series of port-based models and is scalable to different sizes of loads and levels of renewable penetration. The addition of storage and dispatchable backup also provides greater energy independence and resilience against grid instability.

CHAPTER 5
PROJECT MANAGEMENT

5.1 Task, Schedule, and Milestones

Table 5.1. Task, Schedule, and Milestones

Task	Schedule (Weeks)	Milestones
Literature Review - Study previous research on hybrid power plant systems, renewable energy integration, and monitoring technologies.	Week 1 - Week 2	Completion of a comprehensive literature review and identification of research gaps.
Software Investigation - Explore and evaluate various simulation and optimization software suitable for the project (e.g., HOMER Pro, MATLAB/Simulink).	Week 3	Selection of appropriate software tools for economic and dynamic modeling.
Economic Modeling (HOMER Pro) - Develop an economic feasibility model for the hybrid system using HOMER Pro.	Week 4 - Week 6	Completion of economic analysis and system configuration optimization.
Dynamic Modeling (MATLAB/Simulink) - Design and simulate the hybrid system's dynamic behavior, including PV, battery, fuel cell, and grid integration.	Week 5 - Week 7	Initial MATLAB/Simulink hybrid system model created and validated.
Model Finalization and Testing - Refine, test, and verify system performance under different operating conditions.	Week 8 - Week 10	Final hybrid power plant model validated with simulation results.

Report Preparation and Presentation - Prepare the final report, documentation, and defense presentation materials.	Week 14 - Week 16	Completion of final thesis report and presentation readiness.

5.2 Lesson Learned

End-of-project lessons learned retrospective is an analysis of the decisions, processes, and events that occurred during the life of a project. This view represents both positive and negative aspects of the experience, and the knowledge gained is used as a basis for continuous learning and for improving future performance. An important lesson that it teaches is that strategic and painstaking planning matters; success depends on having a well-thought-out plan that includes particular goals, a set of well-defined parameters to work within, and dates. They help to anticipate task-related risks and to develop appropriate mitigation strategies.

Keeping up with technological advancements and adapting to those developments is learning on top of learning. In a rapidly changing world, teams can stay ahead of the competition and improve their efficiency, accuracy, and competitiveness by learning new tools and methods. To maintain accountability and teamwork, it is necessary that each member's capabilities are acknowledged and that they are assigned specific roles for the same, which can help them perform the activities and communicate effectively.

Routine monitoring and evaluation of progress enables early detection of divergences so that corrections can be implemented promptly. Transparency, trust, and collaboration are maintained throughout the process via ongoing communication and the solicitation of input. Creating an environment of support and growth leads to innovation, skill building, and problem-solving as a unit.

In short, the story is that successful project management requires a fine balance between detailed planning and flexibility, technology skills, and strong leadership. When combined, these ideas enable teams to continuously improve, overcome challenges with ease, and deliver results more efficiently and effectively.

CHAPTER 6
IMPACT ASSESSMENT OF THE PROJECT

6.1 Economical, Societal and Global Impact

The developed PV/FC/battery EES grid-connected hybrid renewable energy system has great economic, societal, and global potential. It also reduces reliance on fossil fuels, stabilizes long-term energy costs, and increases grid efficiency through distributed generation, while also minimizing Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) by way of an appropriate system configuration using HOMER Pro and MATLAB/Simulink. The production of these systems also creates additional job opportunities in the manufacturing, installation, and maintenance industries, providing a boost to local economies and the national GDP. The project ensures a stable, clean, and sustainable source of energy, boosting the standard of living by powering homes, businesses, and critical infrastructure, especially in isolated areas of the country. Cleaner energy reduces pollution-related health issues and promotes community participation in sustainable solutions. This action contributes to international arrangements such as the Paris Agreement and the UN Sustainable Development Goals (UNSDGs) by providing an avenue for carbon emissions reduction, climate resilience enhancement, and technology innovation. Economic development and environmental protection are highly promoted in the hybrid energy system, the basis for a clean and fair global energy future.

6.2 Environmental and Ethical Issues

There are environmental and social impacts related to the proposed grid-connected hybrid renewable energy system that need to be addressed if it is to be sustainable and responsibly implemented. The system reduces greenhouse gases from an environmental perspective by substituting fossil fuel consumption with renewable energy sources, including solar and hydrogen fuel cells. This contributes directly to global climate goals and to ecosystem conservation by reducing pollution of the air and water. Nonetheless, concerns persist regarding the sustainability of manufacturing and disposal of components, especially for solar panels, batteries, and fuel cells, which rely on minerals such as lithium, cobalt, and rare metals. Responsible sourcing of these materials and proper end-of-life management via recycling and waste processing are equally important in preventing environmental degradation. It is environmentally friendly by undertaking its design with compact, modular, and low visual impact installations, woven into either urban or rural contexts without affecting either natural or man-made landscapes. The developers and the engineers are obliged to ensure transparency, fairness, and community participation in the project implementation. This encompasses a right to energy, respect for local communities and biodiversity, and compliance with international environmental standards and safety regulations. The system promotes environmental sustainability while calling for ethical responsibility in its entire lifecycle, from materials sourcing and system design, through operation and decommissioning, to ensure that technological development is aligned with environmental stewardship and social responsibility.

6.3 Utilization of Existing Standards or Codes

Since the proposed Power Plant is a simulation-based study, it was ensured that the modeled system follows the real engineering, safety, and grid compatibility process of operations by referring to the applicable standards and codes related to them. Although there was no hardware realization, all the components, as well as the operating conditions, were designed and analyzed according to international standards applicable to similar real systems.

The IEC 61215 and IEC 61730 standards served as a basis for the design of the photovoltaic (PV) sub-module and define safety and performance requirements for the PV modules. IEEE 1547 standards were applied for the grid-connected dynamics and the interconnection operation to model synchronization, voltage regulation, and anti-islanding protection correctly.

Development of the fuel cell model was based on the IEC 62282 series standards for the performance characterization, safety aspects, and efficiency determination of stationary fuel cell systems. In terms of process, the treatment was performed according to ISO 14687 for the hydrogen, thus mimicking the safe and efficient utilization of hydrogen in the simulation.

The BESS modeling parameters, such as charging/discharging profiles, efficiency, and degradation patterns of the battery energy storage system (BESS), were adopted based on the guidelines of IEEE 1184 and IEC 62619. Thus, it was possible to simulate battery performance and operate safely under different loads and solar irradiation conditions.

The development of converter and inverter models in MATLAB/Simulink is based on the IEC 62477-1 and IEEE 1547.1, which define the control, protection, and coordination for grid-connected power converters. The PLL dynamics of the inverter and control of the bidirectional converter were modeled according to the operation conditions, to keep a realistic grid connection.

The simulated designs were considered environmentally and ethically responsible engineering practices to ensure that they represented a responsible engineering practice and to maintain the integrity of the series by integrating the directives of the ISO 14001 (Environmental Management Systems) into the process.

In summary, the developed modeling architecture and control schemes are compliant with international standards and, therefore, safe, notwithstanding that this work is an entirely simulation-oriented study. This ensures that the simulated system rendering is true-to-life, standard-compliant, and realistically implementable hybrid power configuration for future research and development.

6.4 Other Concerns

Despite being fully simulation-based, this study acknowledges a number of factors and possible problems that might affect real-world use. One major issue is modeling accuracy, which is highly dependent on the MATLAB/Simulink and HOMER Pro assumptions, input parameters, and component properties. Variations in solar irradiation data, component efficiencies, or load behavior may have an impact on system performance and dependability in real-world applications.

Further are the scalability and integration of the proposed hybrid system. While perfect coordination of PV, fuel cell, and battery systems is observed for this strategy in the simulation, the actual hardware implementation may be limited by hardware constraints of converters and controllers, communication delays, and control tuning problems.

Based on current information, the economic assumptions during optimization, e.g., component cost, fuel price, and maintenance rates, may vary considerably with time or geographical location. Consequently, periodic reassessment under real-world market conditions would seem appropriate to evaluate their economic viability.

While environmental and safety issues such as hydrogen handling for fuel cells, battery heat management, and system protection must be addressed in real applications, they are at least conceptually factored into this simulation.

Finally, some limitations were owing to model simplifications and data accessibility. The simulation may not capture some of the dynamic behavior, grid disturbances, or nonlinear interactions adequately. For verification of the simulated results, a hardware-in-the-loop (HIL) test or pilot-scale validation should be considered in future work. All things considered, though the simulated results rightly demonstrate the feasibility of the proposed hybrid system, they also highlight the need for further experimental investigation, of which a cost sensitivity analysis and more practical testing would be recommended before large-scale implementation.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This study therefore provides the proof of technical and financial feasibility of a simulation-based grid-connected hybrid system including photovoltaic, fuel cell, and battery. This paper bridges economic planning and real-time operating performances by combining HOMER Pro optimization with MATLAB/Simulink dynamic modeling. The trade-off topology in this paper achieves a significant reduction of NPC, GHG emissions, and a stable and continuous supply in various environmental and load conditions.

The simulation results reveal that the hybrid configuration alleviates the intermittent characteristic of renewable energy, improves system reliability, and achieves smooth transfer between grid-connected and islanded operation through a unified control strategy. Therefore, this work highlights the importance of smart converter design, energy management, and standard-compliant simulation techniques to achieve realistic, scalable solutions.

In conclusion, the proposed approach enables the development of future renewable energy systems with high adaptivity, sustainability, and economic viability. Although simulation results serve as a solid basis for real implementation, further validation may be performed by means of hardware-in-the-loop (HIL) testing or pilot-scale realization.

7.2 New Skills and Experiences Learned

This prior experience provided background knowledge in the design, simulation, and analysis of hybrid renewable energy systems. System design and optimization were carried out with HOMER Pro by varying the arrangements (solar irradiance, load demand, cost, etc.) and were evaluated by NPC (Net Present Cost), LCOE (Levelized Cost of Energy).

we have expertise in time-domain modeling in MATLAB/Simulink, where we simulated the dynamics of various subsystems, including photovoltaic arrays, batteries, fuel cells, and inverters, analyzing their performances under different environmental conditions. This gave me more insight as to the dependability of the system's procedures.

we have informed ourselves on the control schema, in particular, how the bidirectional converters and smart controls enable the system to transition smoothly between operation connected to the grid and islanded operation, as well as system stability and energy flow maximization.

Subsequently, sensitivity analyses are performed to explore the impact of pertinent parameters, such as PV tilt angles and batteries' SoC, on performance and cost, which is of paramount importance for system customization to local conditions.
This research has truly given us a profound knowledge of hybrid renewable energy systems and innovative methods for enhancing their cost-effectiveness and eco-friendliness.

7.3 Future Recommendations

Future studies might also encompass the formulation of advanced control strategies based on learning methods to enhance energy management and system flexibility. The inclusion of SEBS or supercapacitors as auxiliary energy storage systems could potentially lead to enhanced efficiency and durability. The system stability and the dependence on a single energy source can be further enhanced by the use of the hybrid system in combination with other renewables, such as wind or biomass, readily. Enhancing the grid resilience via smart grid and real-time monitoring will facilitate better fault diagnosis and energy delivery. Performing long-term performance tests to investigate the influence of charge and discharge cycles on elements of the system could yield information regarding its durability. A well-defined procedure for design and best practices would facilitate the implementation and be more consistent. Access to the system may be enhanced by innovations in materials and manufacturing that enable low-cost production, making the system financially viable for use in the developing world. A comprehensive evaluation of the cost and environmental efficiency could provide insight into the feasibility for large-scale deployment and assist in making the solution more marketable. By realizing these ideas, the architecture would become more scalable, efficient, and environmentally friendly.

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APPENDIX A
TURNITIN REPORT

221-33-1728

ORIGINALITY REPORT

23%	19%	17%	13%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

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3	Md. Nurunnabi, N. K. Roy. "Grid connected hybrid power system design using HOMER", 2015 International Conference on Advances in Electrical Engineering (ICAEE), 2015 Publication	<1%
4	ijaas.iaescore.com Internet Source	<1%
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8	Achraf Nouri, Aymen Lachheb, Lilia El Amraoui. "Optimizing efficiency of Vehicle-to-Grid system with intelligent management and ANN-PSO algorithm for battery electric vehicles", Electric Power Systems Research, 2024	<1%

APPENDIX B
COMPLEX ENGINEERING PROBLEM SOLVING AND ENGINEERING ACTIVITIES

Complex Engineering Problems (P) Solving		
	Attributes	Statement from students
P1	Depth of knowledge required	The thesis requires a deep understanding of renewable energy systems, hybrid power plant design, and energy management. Knowledge of simulation software such as HOMER Pro, MATLAB/Simulink, control strategies, power electronics, optimization methods, and system integration of PV, battery, and fuel cell technologies was necessary.
P2	Range of conflicting requirements	The thesis encountered contradictory objectives to satisfy, such as high system efficiency and low system cost, matching the size of renewable generation with the size of storage, economically efficient and technically stable, and complex control strategies for the high quality of grid/islanded transitions without sacrificing the reliability, scalability, and environmental friendliness of the hybrid power system.
P3	Depth of analysis required	The thesis required an advanced level of analysis, including techno-economic optimization with HOMER Pro, dynamic performance evaluation in MATLAB/Simulink, evaluation of control strategies in grid/islanded modes, and full analysis of energy flow, efficiency, cost, and system stability under different environmental and load conditions to assure the best system performance.
P4	Familiarity of issues	This thesis assumes background knowledge on the relevant issues, including renewable energy intermittency, grid stability, power quality, component sizing, energy management, and system control. A deep comprehension of integration issues associated with PV, battery, and fuel cell systems, as well as economic viability, environmental considerations, and real-time operational restrictions, was required to design a successfully functioning system.
P5	Interdependence	The thesis consisted of a high degree of interdependence between system elements and techniques. A coordinated control and power management was needed to determine the performance of the PV, battery, and fuel cell units, and economic optimization in HOMER Pro was

		used to guide the dynamic model in MATLAB/ Simulink. Technical, economic, and environmental parameters were intentionally intertwined to balance the entire system's reliability and efficiency.

Provide your statement on which of the complex engineering activities are being solved in the designed project. Mention some or all of the following characteristics.

Complex Engineering Problems (P) Solving		
	Attributes	Statement from students
A1	Range of resources	This thesis builds on the knowledge of fundamental concepts, including the intermittency of renewable energy, grid stability and power quality, sizing of components, energy management, and system control. It necessitated a deep comprehension of the integration issues between PV, battery, and fuel cell systems, as well as knowledge about economic viability, environmental friendliness, and real-time operational restraints, to obtain an effective and dependable hybrid power system configuration.
A2	Level of interaction	The thesis involved multi-system and simulation tool interaction to a great extent. Constant communication between economic modeling in HOMER Pro and dynamic simulation in MATLAB/Simulink was mandatory, so that control strategies, energy flow, and component behavior were accurately synchronized for the hybrid system to run stably and optimally.
A3	Innovation	The thesis is novel in that it combines HOMER Pro economic optimization with MATLAB/Simulink dynamic simulation to build a hybrid power system model on one platform. Novel intelligent control strategies for smooth grid-to-island transitions, an energy management scheme optimized for the system, and system reliability enhancement were proposed to compensate for the shortcomings of conventional renewable integration methods.
A4	Consequences of society and environment	This thesis benefits society and the environment by advocating for sustainable energy production and negative impact on ecosystem services associated with fossil fuel use. The novel hybrid system not only reduces greenhouse gas emissions, but also helps in achieving clean air, energy security, reliable power supply, global net zero target, and can be considered as an eco-friendly technological development.

A5	Familiarity	The thesis demanded extensive knowledge of renewable energy systems, hybrid systems, and advanced control strategies. It was necessary to have a knowledge of software like HOMER Pro for optimization and MATLAB/Simulink for dynamic modeling, as well as a good understanding of the economic, environmental, and operational factors affecting the performance of hybrid power systems.