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Modeling and Simulation of a PV-Battery-Hydrogen Hybrid Energy Storage System for Stable Renewable Power Supply

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ABSTRACT:
The concept of hybrid energy storage systems (HESS) has gained significant topicality in terms of providing grid stability and effective use of renewable energy. The increased use of photovoltaic (PV) systems in power systems poses a problem of power intermittency, variable voltage, and excess energy control, which this study seeks to solve. In order to solve this problem, the present study will design and model a PV-Battery-Hydrogen Hybrid Energy Storage System (HESS) grid connected using MATLAB/Simulink and Simscape Electrical libraries. A rule-based energy management system (EMS) was developed to control the real time power flow between PV array, lithium-ion battery, electrolyzer and the grid, dependent on the solar irradiance and battery state of charge (SoC). The overall system goal is to ensure that when the irradiance is low the system operates continuously at 6kW of active power supply to the grid by dynamically adding PV power with battery discharge and using excess power to produce hydrogen. The DC-bus voltage was kept at approximately 600V in order to provide constant operation of converters and grid interface. The simulation findings affirm that the hybrid design is an effective stabilization of power production, better use of renewable energy and the generation of hydrogen during the oversupply production, which shows that it is a viable option in sustainable and reliable energy storage models to be used in smart grids.

KEYWORDS: Hybrid Energy Storage System (HESS); Photovoltaic (PV); Battery; Electrolyzer; Energy Management System (EMS); MATLAB/Simulink; Grid Stability; Renewable Energy; Hydrogen Production; DC-Bus Voltage Control

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Abbreviations

PV	Photovoltaic
ESS	Energy Storage System
BESS	Battery Energy Storage System
HESS	Hybrid Energy Storage System
LIBs	Lithium-ion Batteries
EMS	Energy Management System
ES1	Energy Storage 1
ES2	Energy Storage 2
PWM	Pulse Width Modulation
LCL	Inductor-Capacitor-Inductor (Filter)
DC	Direct Current

AC	Alternating Current
MPPT	Maximum Power Point Tracking
P&O	Perturb and Observe
SoC	State of Charge
PEM	Proton Exchange Membrane
DC-DC	Direct Current to Direct Current (Converter)
DC-AC	Direct Current to Alternating Current (Inverter)
MPC	Model Predictive Control
VSC	Voltage Source Converter
kW	Kilowatt
mg	Milligram
Ah	Ampere hour
RES	Renewable Energy Sources
SOE	Solid-Oxide
AEL	Alkaline
Li-ion	Lithium ion
HIL	Hardware-In-the-Loop
RTDS	Real-Time Digital Simulation
V	Voltage
Ω	Ohm
A	Ampere

1 Introduction

Due to the increase in effort to combat climate change and move the world towards clean energy, energy storage technologies have become the most researched, invested and self-implemented technologies of the past years [Chamout et al., 2024, Byrne et al., 2017]. Renewable energy sources (RES) such as solar and wind energy are episodic sort of unpredictable because they rely on the availability of sun during the day or wind throughout the year [Jaredson Lilja et al., 2023, Jung 2023, Abdin & Mérida, 2019]. The rapid change in both solar irradiance and temperature of photovoltaic (PV) causes intermittent power generation as shown in Figure 1, hence resultantly causing voltage instability, power imbalance, and major reliability issues in both microgrid configurations as well as large-scale interconnected power systems. To deal with this variability, energy storage systems (ESS) act as the link between intermittent supply of energy on one side and stable demand on the other side [Hou et al., 2023; Jiao, 2022].

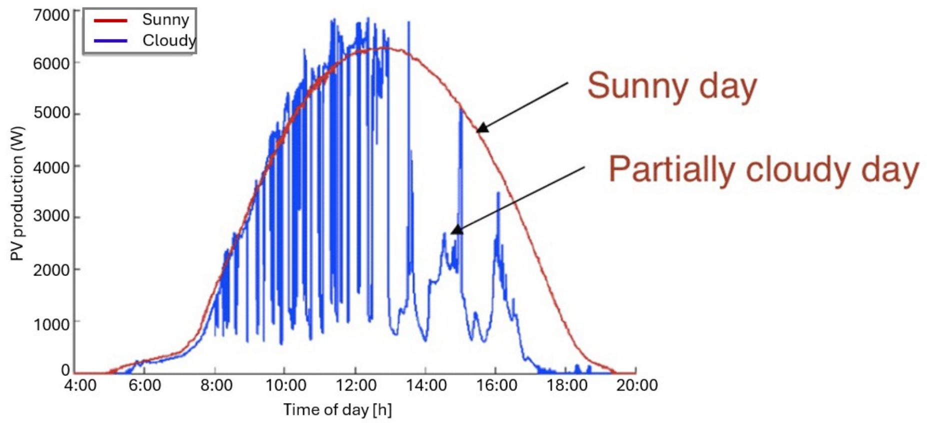

Figure 1. Typical PV power output curve, sunny and when it is cloudy [van den Akker et al., 2013].

ESS can be used for storing any excess energy in case there is low demand for the energy and discharging it when there is high demand for the energy [Al-Sharafi et al., 2017]. The current use of load balancing, peak shaving, grid stabilization, and backup power is actively conducted with the help of lithium-ion batteries (LIBs), hydrogen-based storage, and hybrid forms [Alzahrani et al., 2022]. This allows for more renewables penetration into the systems, enabling modulations of the grid flexibility, security, and energy efficiency [Krane et al., 2022]. Batteries are the best to use in a short-term energy balancing because it has a fast dynamic response and high round-trip efficiency among various ESS technologies [Mehta, (2023)]. Their low energy density, cyclic nature of life and decay during deep charge/discharge cycles are a limitation, but on their ability to offer seasonal or long-term storage services [Manfo et al., 2023, Gbadegesin et al.,2019].

On the contrary, hydrogen-based systems have one distinct benefit, which is high gravimetric energy density and long-term storage [Alzahrani et al., 2022]. By using electrolysis, excess renewable energy can be changed to hydrogen and stored to be used later in industrial, mobility, or grid purposes [Ni et al.,2008; Hassan et al.,2024]. The numerous energy conversion stages render hydrogen less efficient, however the versatility of the hydrogen sector in every sector makes it unavoidable in the emerging sector-coupled energy systems [Nyangon & Darekar, 2024].

One of the possible solutions is the hybridization of battery and hydrogen storage technologies. In this type of system, the battery serves to counteract rapid transitory disturbances and short-term load imbalances, and the electrolyzer takes up excess energy to generate hydrogen during periods of excess generation [Witt 2020, Mbouteu Megaptche et al., 2023, Alonso et al., 2024]. To coordinate all of them, it requires a smart Energy Management Strategy (EMS) capable of dynamically managing power movement, maintaining DC-bus voltages constant and ensuring the safety of state-of-charge (SoC) of the batteries, in desirable operation ranges [Gao, 2024]. The synergy also enables the renewable energy to be better utilized, there is less curtailment, and the systems are more stable and efficient. The idea has much in common with the national hydrogen roadmap of Finland, which sees the future production of renewable hydrogen in large quantities as an element of its carbon-neutrality goal by the year 2035 [Nyangon & Darekar, 2024; Yu et al., 2016].

Figure 2 shows a generalized design of a hybrid energy storage system (HESS) that is incorporated under a centralized EMS. The figure is a way of showing the energy flow between the source of energy (e.g., PV generation) and energy consumers (e.g. grid or local loads) via a shared DC energy bus. Two separate energy storage units ES1 (short-term storage, e.g. batteries) and ES2 (long-term storage, e.g. hydrogen) will be connected to their respective power converters (converter 1 and converter 2) [Bocklisch, 2015].

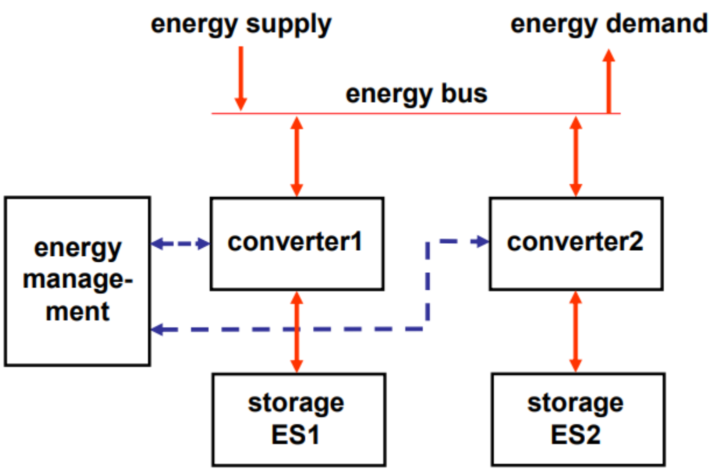

Figure 2. Simplified Structure of Hybrid Energy Storage System [Bocklisch, 2015]

The proposed study is a grid-connected PV-Battery-Electrolyzer hybrid energy storage system as the model and simulation are made to demonstrate that the power can be managed with stability, the battery can be operated with efficiency, and the hydrogen can be generated dynamically under a fluctuating irradiance environment. The model offered an integration of Energy Management System (EMS) which controls the real time flow of energy in the PV array, grid, electrolyzer, and battery. The EMS makes sure excess PV power is smartly distributed by first charging the battery if its state of charge (SoC) is in between 20%-90% and then powering the electrolyzer after both load and battery requirements are met. The hybrid energy system, therefore boosts the use of renewable energy and maintains the stability of the grid as it generates green hydrogen that is sustainable.

1.1 Problem Statement

Although there is a fast advancement in the technology of using renewables, ensuring a steady and constant power supply in PV-dominated grids is a major challenge [Obi & Bass, 2016; Shafiullah et al., 2022]. Irregularities of solar irradiance result in an imbalance of power and result in intermittent changes in DC-bus voltages and non-uniform rates of hydrogen production [Manfo & Şahin, 2024; Hannan et al., 2017]. Despite battery storage having the advantage of averaging short-term variability, it is limited in capacity and inefficient in the high-depth cycles [Manfo, & Şahin, 2023; Theodore, 2023].

However, hydrogen systems can be long-term stored, but they require fine control coordination to be effective. When the electrolyzer is switched on without paying attention to the state of PV and the battery, the system may result in voltage instability or lower hydrogen yield because of changes in the input power [Hassan et al.,2024; Holst et al., 2021]. Therefore, a smart control program is needed to decide how and when to share the power between the subsystems of PV, grid, battery, and electrolyzers in real-time. The current literature usually addresses either off-grid or standalone architecture, without considering the advantages of a grid-connected hybrid design [Atawi et al., 2022; Khatri et al., 2023; Akhtari & Baneshi, 2019]. With these kinds of systems, the grid can serve as a stabilizing reference as well as a sink/source of energy [Gulzar et al., 2023], which means that even under extreme PV variations, there is always a constant supply of energy. However, the combination of grid coupling, battery SoC limitations and the electrolyzer activation logic has not been fully investigated.

Therefore, the proposed research will help fill the urgent gap in considering the dynamic interaction between PV, battery, electrolyzer, and grid, using a MATLAB/Simulink-based model controlled by a rule-based EMS. This will improve the use of renewable energy sources without disrupting operational stability.

1.2 Methodology

The proposed research applies the simulation-based approach to model and analyze a grid-connected PV-Battery-Hydrogen hybrid system. The entire design, as described in Figure 3, is photovoltaic production, a two-way battery storage system, and an electrolysis system to which they are interconnected through a shared DC bus and an Energy Management System (EMS). The EMS manages the overall converters by controlling the switching signals and the flow of energy priorities, which is done in order to maintain a stable grid and the system is efficient. The theoretical modeling, MATLAB simulation, and performance analysis of a grid-connected PV-Battery-Electrolyzer hybrid energy storage system are incorporated in the methodology of this research. The research has a systematic flow, starting with the design of the model, its development of control, and its verification in a dynamic setting of the sun.

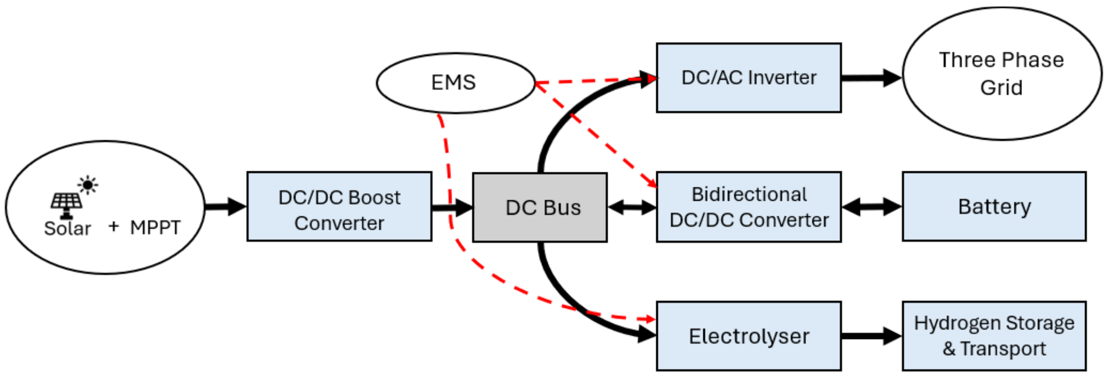

Figure 3. Overall Schematic Diagram of the Proposed Model

1.2.1 Research Objectives

The overall objective of the research is to develop, model, and study a grid-based hybrid renewable energy storage system that could provide an uninterrupted power supply, constant DC-bus voltage, and effective production of hydrogen as part of the smart grid and energy control. To accomplish this goal, the specific objectives were defined as follows:

1. Model Development - Prepare subsystem models of PV array, lithium-ion battery, DC-DC converters, DC-AC inverter, and electrolyzer in the MATLAB/Simulink (R2024b) environment.
2. Energy Management System (EMS) - Design and implement a rule-based EMS that will regulate the flow of power between the PV, battery, electrolyzer, and the grid and provide the continuity of 6kW active power to the three-phase grid.
3. SoC-Based Control - Combine the requirements of state-of-charge 20%≤SoC≤90% to optimize the health of the battery and the efficiency of the charging process.
4. Hydrogen Production Logic - Hydrogen Production Logic - This mode is activated when the PV power exceeds the load and battery power demand and only additional renewable energy is consumed to produce hydrogen.

1.2.2 Thesis Structure

The study is done in four stages, besides the introduction and conclusion. The initial stage is the introduction, and Chapter 2 is about the background and rationale, which is conducted to analyze the strategies of renewable energy integration, hybrid energy storage systems, and hydrogen generation. This review gives the theoretical basis through which the problem of PV intermittency is understood, as well as the use of energy management in hybrid systems.

Chapter 3 is subsystem modeling under MATLAB/Simulink. The photovoltaic array, bidirectional DC-DC converters, lithium-ion battery, and electrolyzer are modeled to reflect the realistic functioning characteristics. The subsystems are to interact via a common DC bus that is joined to a three-phase grid. This level is also devoted to the work on the Energy Management System (EMS). An energy control strategy based on the rule is taken to control the flow of energy between the PV and load, battery, and electrolyzer based on the real-time power balance and state of charge situations. The logic is that initially, PV power will be consumed to supply the grid, then to charge the battery, and finally to generate hydrogen in case of excess power.

In Chapter 4, the full hybrid model is modeled by simulating under variable conditions of irradiance. Explores the system behavior at various operating conditions and graphs of the system results, which include PV power, DC-bus voltage, battery SOC, and production of hydrogen.

Chapter 5 explains what the results are, how the system is doing in comparison with reference configurations, and what the system would like to demonstrate to us.

2 Background & Rationale

2.1 Overview of Existing Modeling Approaches

The interest in research in the hybrid renewable energy system (HRES), incorporating the photovoltaic (PV) generation, battery energy storage systems (BESS), and hydrogen-based energy storage, has grown over the past decade because of the growing global focus on the idea of decarbonized and flexible power system incorporation. The concept of the combination of renewable energy sources and energy storage systems has become a critical issue in contemporary power systems research. The photovoltaic (PV)-based hybrid energy systems have been subjected to a lot of focus due to their modularity, minimum impact on the environment, and a steadily decreasing cost per watt. Nevertheless, the nature of PV power is intermittent, which is determined by solar irradiance, temperature, and partial shading and leads to variations in voltages and power which complicate the matter of reliability and grid stability [Alonso et al., 2024; Kamran & Turzyński, 2024]. Many studies have been done to establish hybrid configurations in order to address the intermittency of solar energy and guarantee stable operation either under grid-connected or standalone conditions [Witt, 2020; Kamran & Turzyński, 2024; Hannan et al., 2017; Atawi et al., 2022].

In this section, critical reviews of the key developments in modeling, control, and performance analysis of PV–Battery-Hydrogen systems are made in relation to this thesis. In Aatabe et al. (2025), a stochastic control approach has been created to operate an independent PV-Battery-PEM electrolyzer system, which incorporates the uncertainty of irradiance and temperature in terms of probabilistic modeling. Their application brought about a dynamic scheme of energy management (EMS) that distributed power between the battery and the electrolyzer to reduce the curtailment of energy and enhance the production of hydrogen. The suggested stochastic EMS minimized the oscillations in DC-link voltage and increased the efficiency of hydrogen production by 8% to the traditional deterministic control. Nevertheless, they only examined isolated working conditions and not in grid-connected or multi-mode switching dynamics.

Crespi et al. (2021) talked about a hybrid power-to-power architecture, in which a PV array is energized to a lithium-ion battery bank and a hydrogen subsystem. Their MATLAB and TRNSYS simulation showed that the intermittent supply of irradiance could be sustained continuously by the coupling of electrochemical and chemical storage. The battery was characterized by rapid response, which was supplemented by the hydrogen loop, a long-term buffer. However, although the paper discussed energy balance and converter dimensions, the model control layers of converters were not comprehensive, and the transient oscillations of voltages were not characterized, which is mandatory in determining the stability in real-time.

The research paper by Nasser and Hassan (2023) has compared two off-grid storage structures, which are PV-fuel cell-hydrogen and PV-battery systems intended to be implemented in rural street lighting and desalination. In the Journal of Energy Storage model, they discovered that, hydrogen system was worse than the battery-based system due to the longer autonomy during the long, low sunlight periods, and the battery-based system was better than the hydrogen system in short-term voltage stability and response. Their relative findings indicated that a balance between both might be resilient optimally, however their analysis was not based on a control model that would integrate both energy paths into a single simulation environment.

Other developments in the same direction towards integrated hybrid systems were also introduced by Modu et al. (2024), who came up with a rule-based EMS to a hydrogen-battery microgrid with variable renewable profiles. Their findings suggested that there was an 18 % growth in the use of renewable energy and fewer DC-bus oscillations. However, the control approach used steady-state conditions and failed to determine converter level interactions and delays of PWM (Pulse Width Modulation) gating. In the same way, Qi et al. (2025) also maximized the long-term energy management of a hybrid hydrogen-battery microgrid to minimize unmet load by 30% by seasonal scheduling. Nevertheless, the model overlooked both short-term dynamics and switching behavior, which were necessary to estimate instantaneous power stability, which are the very issues this thesis is out to solve.

At the pilot-plant scale, Hidouri et al. (2025) analyzed a 1 MW PV-to-hydrogen installation integrating power-to-electrolysis (PtE) and power-to-gas (PtG) modules. Their experimental results confirmed the feasibility of control regarding hydrogen production, and it was known that it operated stably when there was varying PV input. The study however lacked the battery coupling and converter-level co-simulation which is vital in defining the stability of the DC-bus voltages. In the same manner, under experimental concentration, Koundi et al. (2023) created a DC-DC buck converter to control the current reaction of a PEM electrolyzer in variable DC-bus voltages. Although a steady flow of hydrogen was obtained with the PWM-based control, the model was not integrated with a comprehensive EMS system. Ratib et al. (2024) refined this literature by establishing simplified electrical-circuit models of PEM electrolyzers, however no longer coupled to the intermittency of renewable or to the control of power flow in any direction.

The control on the inverter side has also developed simultaneously. Vasquez et al. (2022) highlighted the relevance of a dual-loop control implemented with PLL synchronization on grid-connected renewable systems as having better power quality and voltage modulation. This method was further improved by using LCL (inductor–capacitor–inductor) filtered inverters employing active damping, with a total harmonic distortion (THD) of less than 2% during fast variation of the irradiance by Zhang et al. (2022). Although the performance of inverters was successful in these two studies, the storage elements were simply viewed as some DC sources, without considering the hybrid storage coordination or the EMS-driven working modes.

Recent studies have explored the possibility of simultaneous battery and electrolyzer subsystem operation to increase PV usage. Roy et al. (2024) have shown an example of a rule-based EMS, where the electrolyzer trigger is conditioned by the battery state of charge, and improved dispatch and lower degradation are achieved, but fixed threshold values are used and no adaptive dynamic tuning.

Altogether, the analyzed literature shows that the design of hybrid renewable energy systems continues to improve, although several gaps can still be identified. Past investigators have represented these hybrid specifications by either a detailed electrochemical representation or a simplified electrical system, based on the complexity of the simulation and the computing requirements [Atawi et al., 2022; Akhtari & Baneshi, 2019; Samende et al., 2023]. Most studies concentrated on the optimization of technology-economic or steady-state functioning, and little was done on the dynamical control at the converter level and real-time implementation of EMS. In addition, little literature has examined the interaction of battery and electrolyzer concurrent process on DC-bus voltage regulation, inverter power quality, as well as hydrogen yield within a grid-connected setting.

Table 1 provides the comparative summary of the key studies mentioned above. It brings out the types of systems, control techniques, key discoveries and constraints that characterize the existing research trends in the field of PV-Battery-Hydrogen hybrid systems. As presented in the summary table 1, recent studies are showing consistent advancement towards the development of modeling of hybrid renewable systems however does not yet incorporate the real-time coordination of PV, battery, and electrolyzer subsystems when operated within the grid. Majority of researches focus on steady-state or economic optimization as opposed to converter-level control and dynamic EMS behavior. Thus, this thesis aims at closing these gaps by coming up with a MATLAB/Simulink simulation of a grid-connected PV-Battery-Hydrogen system with an EMS logic based on rules.

Table 1. Summary of Key Literature on PV–Battery–Hydrogen Hybrid Systems

Author(s), Year	System Configuration	Control Method	Main Findings	Research Gap
Aatabe et al. (2025)	Standalone PV–Battery–PEM Electrolyzer	Stochastic control incorporating irradiance uncertainty	Improved hydrogen production efficiency by 8%; reduced DC-link voltage oscillation	Evaluated only isolated mode; no grid-connected validation
Crespi et al. (2021)	PV–Battery–Hydrogen hybrid (MATLAB + TRNSYS)	Energy balance modeling and converter dimensioning	Demonstrated continuous operation under variable irradiance	Lacked transient voltage analysis and detailed converter control
Nasser and Hassan (2023)	PV–Fuel Cell–Hydrogen vs. PV–Battery (off-grid)	Comparative system modeling for rural energy	Showed battery system better for short-term stability, hydrogen better for long autonomy	No hybrid coordination; lacked unified EMS design
Modu et al. (2024)	Hydrogen–Battery Microgrid	Rule-based EMS under variable renewable profile	Achieved 18% higher renewable utilization and lower DC-bus oscillations	Considered only steady-state; ignored converter-level delays
Qi et al. (2025)	Hybrid Hydrogen–Battery Microgrid	Long-term EMS with seasonal optimization	Reduced unmet load by 30%	Neglected short-term dynamics and switching behaviour

Hidouri et al. (2025)	1 MW PV–to–Hydrogen Pilot Plant	Experimental control with PtE and PtG modules	Validated stable hydrogen production under variable PV input	No battery coupling; lacked DC-bus co-simulation
Koundi et al. (2023)	PEM Electrolyzer Interface	DC–DC buck converter control	Achieved smooth current control and hydrogen flow	Did not integrate with full hybrid or EMS model
Ratib et al. (2024)	PEM Electrolyzer Electrical Circuit	Simplified equivalent-circuit modeling	Provided compact PEM model for control studies	No renewable coupling or dynamic response validation
Vasquez et al. (2022)	Grid-Connected Renewable System	Dual-loop inverter control with PLL synchronization	Improved voltage quality and grid stability	Ignored hybrid storage coordination (battery–H_2)
Zhang et al. (2022)	Grid-connected PV system with inverter	LCL-filter inverter with active damping	Achieved THD < 2% during irradiance variation	Treated storage as ideal DC source; no EMS coordination
Roy et al. (2024)	PV–Battery–Electrolyzer	Rule-based EMS with SoC-based electrolyzer activation	Enhanced power dispatch, reduced battery degradation	Fixed thresholds; no adaptive dynamic control

2.2 Research Gap and Justification

Despite the large amount of literature research on hybrid renewable energy systems that include PV production, a battery storage system, and hydrogen production, there are still a few important gaps in the literature. The scientific analysis of recent literatures indicate that most papers focus on the general system setups or optimization on the component scale, and little has been dedicated to the specific coordination and control of multi-storage devices under operating conditions. The research gaps to be listed include:

- The lack of coordination between the activities of PV generation, battery SoC, and electrolyzer in dynamic irradiance. In the literature of hybrid PV-Battery-Hydrogen models, most are quasi-steady state irradiance models of the sun, which do not consider the dynamics of solar irradiation that are often seen in PV output. This simpleness results in low power coordination of the PV array, the SoC of the battery, and the electrolyzer. According to studies by Hannan et al. (2017) and Abdin & Mérida (2019), renewable intermittency results in a rapid change of voltages and power, although research on real-time coordination measures that dynamically control the interplay between the energy sources and storage units is lacking. These studies also report that the variable irradiance control is still a major weakness of hybrid systems. Thus, a combined EMS that can respond to swift PV changes remains a research topic.
- The designs of hybrid EMS do not consider the SoC thresholds and real-time detection of PV surplus. Literature has numerous rule-based or optimization-based EMS that cannot include explicit SoC threshold logic and PV surplus detection, which are needed to provide realistic system protection and control. According to Sarwar et al. (2024) most EMS models use an idealized battery behavior, i.e. charge charge-discharge hysteresis and minimum SoC are not considered. Similarly, there are grid-interactive PV-battery control algorithms that activate hydrogen production contingent to the PV output without ensuring that the battery is full charged. Absence of such logical reasoning can cause over-charging, deep charging or ineffective production of hydrogen. Therefore, the hybrid-system performance necessitates EMS algorithms that combine SoC-based control with

real-time PV surplus management to achieve more accurate performance of hybrid systems.

- Only a small amount of research has been done to implement hydrogen-producing logic in grid-connected PV-Battery systems. Although some studies examine the concept of hydrogen storage in a standalone or off-grid microgrid context very few studies examine grid-connected setups where the electrolyzer is dynamically controlled with both the local load and the grid. As recent reviews (e.g., Zhu et al. (2025) point out, control of hydrogen production in grid-connected systems is under-investigated in connection to the EMS coordination with the PV variability and battery SoC. This research gap constrains the knowledge of how to use hydrogen generation to stabilize the grid and enhance the use of renewables in the interconnected grid. Thus, a hydrogen-production logic simulation framework that would be embedded in a grid-integrated PV-Battery system is necessary to move the hybrid-system research forward.
- No validated implementations that use realistic current-voltage (I-V) and power-voltage (P-V) characteristics of PV as implemented in Simulink. Quite a large fraction of the available models of hybrid systems use simplified mathematical models of PV equations, or constant-power sources, without considering the real electrical behaviour of modules. According to Fang et al. (2025) numerous published simulations have not been compared with any measured or manufacturer-specified I-V and P-V curves. This omission renders system-level investigation less believable because the power equilibrium and converter behaviour are greatly worried with PV nonlinearity. Therefore, a more comprehensive implementation of a Simulink that includes the realistic parameters of PV arrays and confirmed I-V /P-V characteristics could offer a more credible understanding of energy-flow phenomena.

A grid-linked PV-Battery-Electrolyzer hybrid energy system is developed in the current study in MATLAB/Simulink and with realistic PV module parameters and a rule-based EMS in order to fill in the previous gaps. The EMS algorithm has a dynamic distribution of energy flow between the PV array, grid, battery and electrolyzer by applying SoC constraints (20%-90%) and by dynamically operating the hydrogen production process only under surplus PV conditions. Such will provide stability in the system during dynamic irradiance and the coordination of three PWM control channels of three different converters will be used in the system to ensure the export of power to the grid within the range of 6kW under variable solar irradiance and to dynamically balance the SoC limits and excess hydrogen production.

2.3 Photovoltaic System Modeling in Hybrid Systems

The major source of renewable energy in hybrid power systems is the PV subsystem. Its electrical behavior is also necessary to be modeled to study system-level controls of converters, and also in the prediction of its performance.

2.3.1 Electrical Representation of PV Cell.

The single-diode equivalent circuit model is used in most studies on hybrid systems due to its ability to provide a good compromise between physical and mathematical simplicity [Fathabadi, 2018; Adak, 2025]. According to this model, PV cell is a current source ($\mathrm{I_{ph}}$) caused by light in parallel to a diode which is proportional to the sunlight irradiance, and loss characteristics of the cell are represented by the diode current ($\mathrm{I_d}$) controlled by the PN junction properties, series resistance ($\mathrm{R_s}$), shunt resistance ($\mathrm{R_{sh}}$) and $\mathrm{I_{sh}}$ is the leakage current across $\mathrm{R_{sh}}$ as shown in Figure 4.

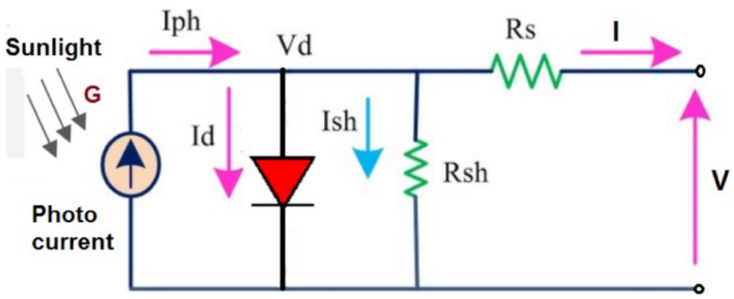

Figure 4. Equivalent Circuit of a PV Cell

The model is used to construct the analytical foundation of PV output simulation in MATLAB / Simulink. The relation between current and voltage is determined by the equation of the single diode:

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_d} - \mathrm{I_{sh}} \tag{1}$$

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_0}\left(e^{\frac{q(V+IR_s)}{nkT}}\right) - \frac{\mathrm{V} + \mathrm{IR_s}}{\mathrm{R_{sh}}} \tag{2}$$

where $\mathrm{I_0}$ is the diode reverse saturation current,
n is the diode ideality factor,
q is the electronic charge,
k is the Boltzmann constant, and
T is cell temperature.
The single-diode model has been confirmed by several researchers to be a good representation of the dynamic PV performance [Alzahrani et al., 2022], which still maintains computational efficiency to simulate large scale performance. This is the reason why it has been universally applied in hybrid PV-Battery-Hydrogen models.

2.3.2 MPPT Control and Environmental Dependence

Because the power generation of a PV array is nonlinearly dependent on the irradiance and the temperature, Maximum Power Point Tracking (MPPT) has to be employed, in order to obtain the highest possible energy. Perturb and Observe (P&O), Incremental Conductance (IncCond), and Fuzzy Logic Control are the most frequently applied in hybrid studies, as they are easy to apply and have a good level of reliability [Silveira et al., 2025]. In many hybrid studies, the P&O method is used [Mrhar et al., 2025], which periodically adjusts the operating voltage to find the operating point at which:

$$\frac{\mathrm{dP}}{\mathrm{dV}} = 0 \tag{3}$$

that indicates the voltage at the maximum power point (V_{MPP}) and the current at maximum power point (I_{MPP}) of maximum power supply.

Figure 1 depicts a regular day-to-day PV generation process on a clear and cloudy day that shows the variability that requires the integration of storage and EMS. The change in the irradiance also causes quick changes in voltage at the DC bus which can destabilize downstream components unless suppressed by a rapid-response BESS and highly synchronized EMS. Therefore, the knowledge of the PV model behavior is the analytical basis of converter and storage interface design in Chapter 3 below.

2.4 Modeling Principles of Battery Energy Storage Systems (BESS)

Battery energy storage offers temporary buffering between generation and load, ensuring smooth operation when there is an irradiance change and quality of power in the grid.

An equivalent electrical model can be used to describe the dynamic behavior of a battery, which takes both instantaneous and transient responses. The most popular model in hybrid renewable systems is the first-order RC model, which is depicted in Figure 5.

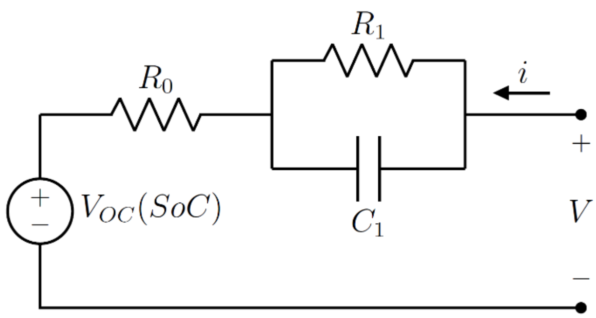

Figure 5. First-order equivalent circuit model of a battery.

It comprises an open-circuit voltage sourceV_{OC}(SoC) which depends on the SoC, an inter-circuit resistance R_0 which represents internal conduction losses and a parallel network of a resistance-capacitance (R_1&C_1) branch to model an electrochemical polarization and diffusion effects as transient during charging/discharging [Rotas et al., 2024]. The terminal voltage is given as:

$$V = V_{OC}(SoC) - iR_0 - V_{RC} \tag{4}$$

where the voltage across the parallel branch (R_1&C_1) is V_{RC}, which is calculated as:

$$\frac{dV_{RC}}{dt} = -\frac{1}{R_1C_1}V_{RC} + \frac{i}{C_1} \tag{5}$$

This model gives a realistic trade-off between complexity and precision and has been confirmed in many hybrids PV -Battery-Hydrogen applications [Zhao et al., 2024].

2.5 Modeling of Hydrogen Energy Storage and Electrolyzer

2.5.1 Concept and Importance

The Hydrogen storage is an exciting long-term energy storage technology because of its high level of energy density, long storage life, and environmental sustainability [Alzahrani et al., 2022]. The surplus electricity in the renewable-based systems is converted in electrolyzers to produce hydrogen through an electrolysis process of water. Generated hydrogen can be stored later or fed into the fuel cells to re-produce electricity [Soyturk eti al., 2024]. Power-to-Hydrogen (P2H) is a concept that has been extensively discussed to supplement battery systems to convert energy that goes beyond the diurnal cycle. Hydrogen storage can be scaled to provide seasonal energy balancing unlike batteries, as well as used in transport and industry [Alzahrani et al., 2022].

2.5.2 Modeling of Electrolyzers

The splitting of water by an electrolyzer is based on

$$H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g) \tag{6}$$

Research is dominated by three types of technologies: alkaline (AEL), proton-exchange-membrane (PEM), and solid-oxide (SOE) electrolyzers [Wikström, 2025]. They can be described as follows:

Proton Exchange Membrane (PEM) Electrolyzers: PEM electrolyzers are ideal for fluctuating uses, for instance, those that are related to climate energy from the sun and wind. They are usually used at a low thermal class of between 50°C to 80°C and have a good rating in areas of increasing or decreasing input electricity [Bonanno et al., 2024]. The PEM systems prototype has high energy density, a small system size of the system and low response time. They cost more than the alkaline systems because noble metals such as platinum and iridium are used as the catalysts [Tofighi-Milani et al., 2025]. However, the issue of their long-life cycle and membrane decay is still considered a technical issue, the solution of which is necessary for mass implementation.

A typical system for a PEM electrolyzer used for hydrogen production is described in Figure 6. The system runs on both electric and thermal energy to carry out water splitting in the PEM electrolyzer to produce hydrogen (H_2) and oxygen (O_2) [Hassan et al.,2024]. As a main product, the hydrogen is removed, whereas oxygen and extra water are directed through an O_2 separation unit. Another role mentioned in the schematic is that of a heat exchanger that controls the temperature of the system recycles thermal energy and delivers water at controlled temperature (298.15 K). To maintain the efficiency and prevent overheating, the H_2 and the O_2 outputs are cooled, and heat is dissipated. This design demonstrates necessary thermal integration and flow management of PEM systems using the variable renewable energy input.

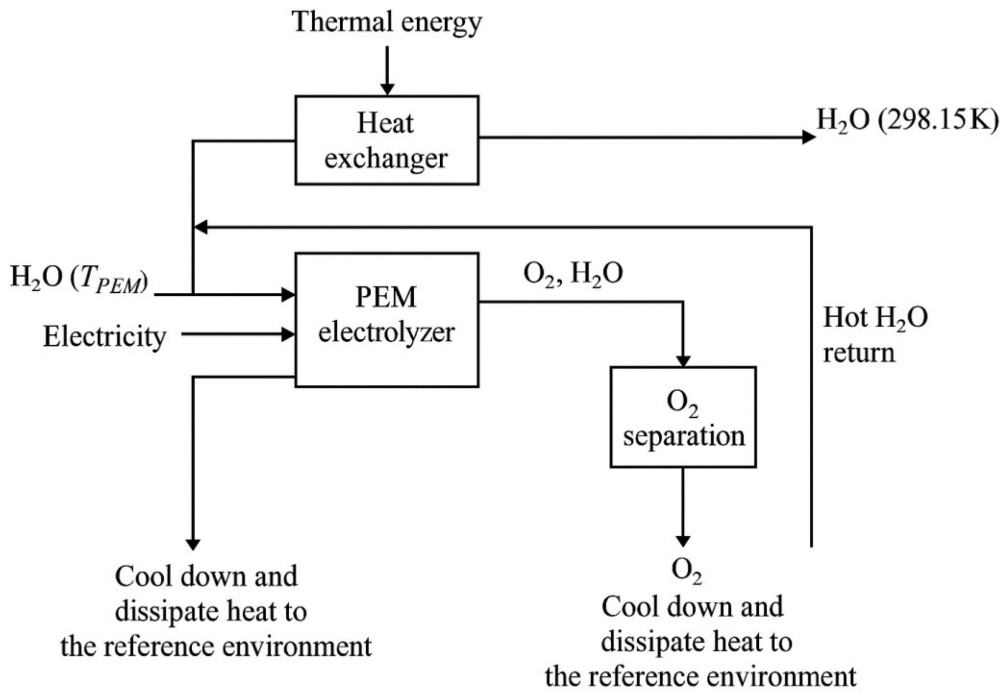

Figure 6. Operational Layout of a PEM-Based Hydrogen Production Unit [Ni et al., 2008]

Alkaline Electrolyzers: Alkaline water electrolysis is a widely adopted technology for hydrogen production that is at a more developed stage as compared to others available in the market [Emam et al.,2024]. These systems use potassium hydroxide (KOH) or sodium hydroxide (NaOH) electrolyte, and have the advantages of high reliability, low cost, simple construction, and relative ease of scaling up. However, they have a relatively slow response to variable inputs in power level and have low compatibility with fluctuating renewable generation. However, these systems are far more stable, require less capital investment, and are competitive in industrial applications and areas with relatively stable and/or low-voltage fluctuations [Emam et al.,2024; Holst et al., 2021].

Solid Oxide Electrolyzer Cells (SOECs): SOECs refer to a state-of-the-art and high-efficiency technology of electrolysis that works at high temperatures with an average of 600-1000 degrees Celsius [Singh et al., 2025]. Due to the utilization of heat from industrial waste or cogeneration, the efficiency of SOECs is much higher than PEM and alkaline systems. In addition to water, SOECs can run co-electrolysis of carbon dioxide to produce gas (syngas), which can be further converted to fuels and chemicals. Major drawbacks and current issues that are still researched and in the pilot stages include materials degradation, cyclic life, and high operating costs [Chamout et al., 2024; Singh et al., 2025].

All types are similar in that they all utilize the same principle of electrical-to-hydrogen conversion, and therefore, system-level modeling can be transferred between technologies. Electrolyzers are mostly represented as controlled DC loads that use electrical power to generate hydrogen [Tofighi-Milani et al., 2025]. At the cell level, the sum of voltage is calculated by the thermodynamic reversible voltage and various loss components. Figure 7 is an equivalent circuit that will be simplified, common in the literature.

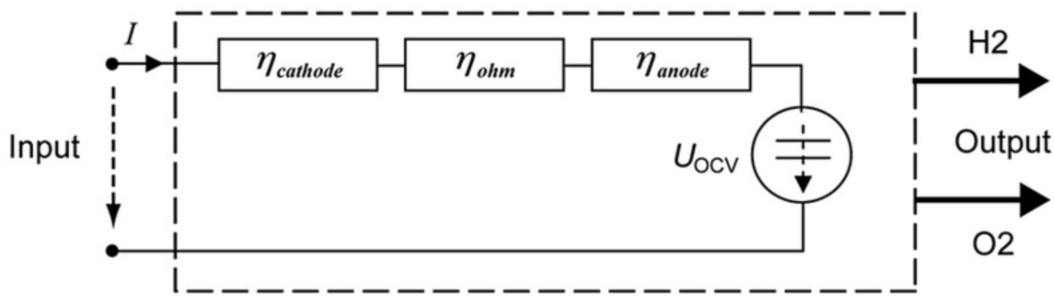

Figure 7. Equivalent Circuit of an Electrolyzer

The regulation of the relationship between the input power and the hydrogen output rate can be explained as:
Mathematically, cell voltage is given as

$$\mathrm{V_{cell}} = \mathrm{U_{ocv}} + \eta_{\mathrm{anode}} + \eta_{\mathrm{cathode}} + \eta_{\mathrm{ohm}} \tag{7}$$

where $\mathrm{U_{ocv}}$ represents the value of the reversible potential calculated using the Nernst equation and the three eta-terms represent the activation and ohmic losses in the electrodes and the membrane, respectively [Haverkort, 2024]. The total voltage in stack form is as follows:

$$\mathrm{V_{stack}} = \mathrm{N_{cell}}\mathrm{V_{cell}} \tag{8}$$

Where N_{cell} is the number of stacked cells.

The nature of current-voltage characteristics of electrolyzers is generally nonlinear, however to do a hybrid simulation on the system level, it is often adequate to make a linearized or efficiency-based approximation [Lei et al., 2024].

Now the production of hydrogen can be based on the law of Faraday, which associates the electricity flow s the flow of moles of hydrogen:

$$\dot{n}_{H_2} = \frac{\eta_F I_{el}}{2F} \tag{9}$$

$$\& \ \dot{m}_{H_2} = M_{H_2} \dot{n}_{H_2} \tag{10}$$

where $I_{el}$is the current in the electrolyzer

F=96485 Cmol^{-1} is the constant of Faraday,

The molar mass of hydrogen is M_{H_2}=2.016 gmol^{-1}

And Faraday efficiency η_F , is generally 0.95-1.

Alternatively, hydrogen rate-mass-flow may be represented as:

$$\dot{m}_{H_2} = \eta_{el} \frac{V_{el} I_{el}}{H_{H_2}} \tag{11}$$

Where $H_{H_2} \approx$ 120 $120 \mathrm{MJkg}^{-1}$ is the lower heating value of hydrogen, and

η_{el} $(60 - 80\%)$ is the overall efficiency.

The general form of equation 11 is commonly used in MATLAB/Simulink in the form of a model electrolyzer, where the output of hydrogen is directly calculated by the provided electrical power and temperature of the water.

On one side of the spectrum, there are complex electrochemical models of electrolyzer operation, and on the other side, there are simplified behavioral models of electrolyzer operation. In electrochemical models, kinetic equations of the anode and cathode that are solved using Butler-Volmer equations and include temperature and pressure dependencies [Neuman, 2025]. They are efficient in the optimization of designs however are costly to compute.

Behavioral models, on the other hand, model the electrolyzer as a nonlinear effectiveness block or a controllable DC load [Lei et al., 2024; Tofighi-Milani et al., 2025]. These formulations have been desirable model ones to use in system-level analysis because they are simple to combine with power-electronic converters and EMS algorithms.

The analysis in this thesis stops at the hydrogen generation, without converting it back to a fuel cell. This focus allows more effectively exploring real-time power-sharing and EMS performance, without the complexity of two-way H_2 conversion losses.

2.6 Energy Management System (EMS) for Hybrid Scenario

The Energy Management System (EMS) regulates the power flow between the PV, battery, electrolyzer, and the grid to ensure the balance of energy, maximum efficiency, and increase the life of the components. In general, EMS strategies can be categorized into Rule-Based, Optimization-Based EMS and Fuzzy Logic EMS [Huang et al., 2025].

2.6.1 Rule-Based EMS

The Rule-Based EMS uses logic that is defined by thresholds to regulate the functioning of the system [Safder et al., 2024]. It switches ON or OFF the components based on such factors as SOC levels, PV output, and demand variations. According to Jamal et al. (2024), it is a popular method of real-time application due to its simplicity, reliability, and low computational requirements. It can react to variations in the system fast without complex algorithms, and thus it is suitable with embedded or low-power controllers [Wai et al., 2025].

2.6.2 Optimization-Based EMS

Optimization-Based EMS uses mathematical and calculational methods like linear programming, Genetic Algorithms (GA), and Model Predictive Control (MPC) to obtain the global optimization of the system performance [Cavus, & Allahham, 2024]. These techniques are intended to reduce the operational charges, losses or emissions without compromising the performance constraints. They have, however their disadvantage of being computationally intensive, making them less practical to be applied in real time in small-scale systems [Khan et al., 2025].

2.6.3 Fuzzy Logic EMS

The fuzzy logic EMS models utilize the rule sets founded on linguistic variables (e.g., high irradiance, low SoC) to address the uncertainty and nonlinearities. Although flexible and adaptable, fuzzy systems need to be fine-tuned and tested out per new system [Maghfiroh et al., 2024].

In real-time applications, rule-based EMS is the most feasible as it has low computational complexity and is deterministic in decision-making. A study by Safder et al. 2024, and Roy et al. 2024 has shown that rule-based control provides quality power sharing of PV, battery, and electrolyzer and at the same time gives grid stability.

3 System Modeling and Control Design

The modeling and simulation of the proposed PV-Battery-Electrolyzer hybrid energy system in detail is introduced in this chapter. The models have been created in MATLAB-R2024b with the help of Simulink and Simscape Electrical libraries to model the physical and control dynamics of the hybrid configuration correctly. The parameters and equations of the modeling in this current chapter are modeled on the theoretical basis on Chapter 2.

All the subsystems, that is, the photovoltaic (PV) array, DC-DC converter, inverter with LCL (Inductor–Capacitor–Inductor) filter, battery energy storage system (BESS), and electrolyzer, were modeled with physics-based blocks and associated control algorithms. The subsystems are connected together by a 600V DC bus and the inverter is employed to supply constant rated active power ($\mathrm{P_{rated}} = 6\mathrm{kW}$) to a unity (balanced three phases) grid. Such an arrangement maintains constant power and constant DC-link voltage even in the event of varying solar irradiance.

The objective of the simulation is to explore the behavior of power-sharing and stability of DC-bus under the circumstances of PV generation variation, which are coordinated by the Energy Management System (EMS). The EMS ensures that:

1. Direct grid supply is prioritized on PV energy.
2. The battery gives backup during power shortages when $\mathrm{P_{PV}} < \mathrm{P_{rated}}$.
3. The electrolyzer takes up excess power when $\mathrm{P_{PV}} > \mathrm{P_{rated}} + \text{Battery Charging Limit}$

3.1 System Overview

The hybrid system has a PV generation unit, a battery storage system, an electrolysis based hydrogen production unit, linked by an operated power converter, and a shared common 600V DC bus. The system variably regulates energy flow according to the solar irradiance and battery SoC according to the EMS logic shown by the following summaries:

$$\begin{cases} \mathrm{P_{PV}} \leq \mathrm{P_{rated}}: & \text{Battery Discharges if SoC} > 20\% \\ & \text{and Electrolyzer OFF} \\ \mathrm{P_{PV}} > \mathrm{P_{rated}}: & \text{Battery Charges if SoC} < 90\% \\ & \text{and Electrolyzer ON if } \mathrm{P_{PV}} \text{ still surplus} \end{cases}$$

The energy management plan ensures that there is stability and efficiency in the systems as it focuses on the flow of power. At rated power less than or equal to PV power and a battery SoC greater than 20%, the battery gives up boosting the grid and the electrolyzer remains in OFF condition. When the SoC declines to 20% or less, the battery is held back against discharge. In the case that PV generation exceeds the $\mathrm{P_{rated}}$. The battery becomes charged until the SoC is 90%, and any additional energy is used to energize the electrolyzer to produce hydrogen. During these times of shortage of PV power, the electrolyzer is turned off. The general priority is to meet the constant rated power supplied to the grid, control the battery, and transform excess power to hydrogen. The complete Simulink model is depicted in Figure 8, and it depicts the PV subsystem, converter units, EMS controller, DC-bus interface, the inverter interface, and the connection of the three-phase grid.

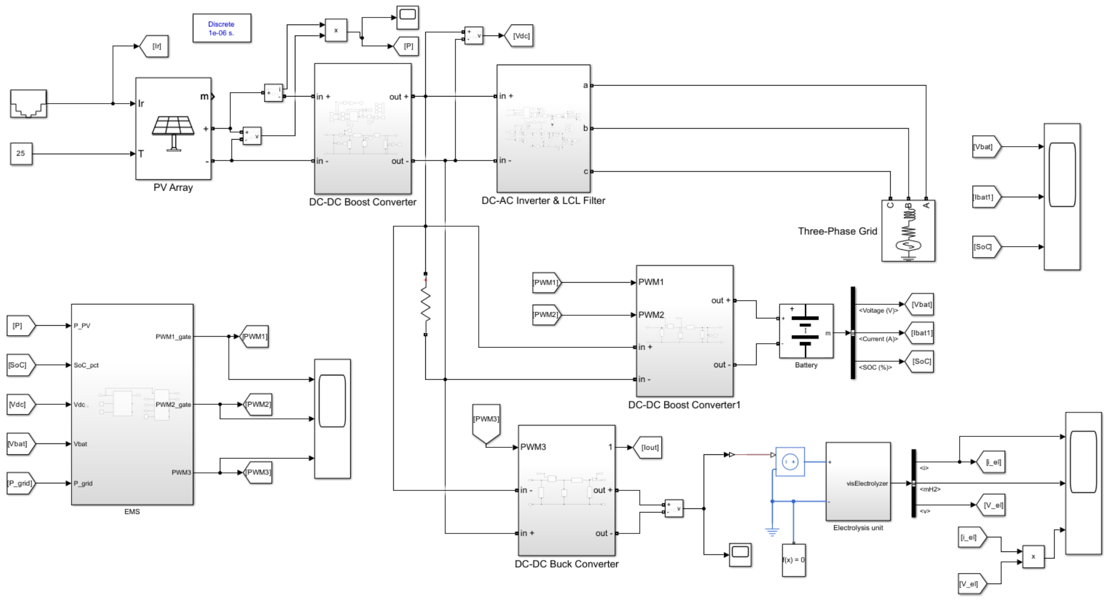

Figure 8. MATLAB Simulink Model of Proposed PV-Battery-Electrolyzer HESS.

3.2 Simulation Platform and parameters

The system model has been developed in MATLAB Simulink (R2024b) and Simcape Electrical Specialized Power Systems library. A discrete solver with time step $\mathrm{T_s} = 1 \times 10^{-6}$ was used to achieve numerical stability and switching accuracy in the solver. Some system level parameters are represented in Table 2 with their specific function.

Table 2. System Level Parameters

Parameter	Value	Description
Simulation tool	MATLAB R2024b	Simulink+Simscape Electrical
DC bus Voltage (V_{DC})	600V	Common DC-link
Grid Frequency (f)	50Hz	System frequency
Simulation duration (t_{sim})	1.8s	Dynamic analysis period
Grid type	3-phase (balanced)	Unity power factor
Rated inverter power (P_{rated})	6kW	Nominal grid injection
Control approach	MPPT(P&O) & dq control	Hybrid coordination strategy

3.3 Photovoltaic (PV) Array Modeling

The main source of renewable energy is the PV array, in which the solar irradiance is transformed into DC electric energy. It is simulated with the help of the PV-Array block (user-defined mode) of the Simscape library. The array consists of 10 modules on series within one string and 47 parallel strings, which make a total of 470 modules. The layout provides the right voltage and current levels of the 600V DC link in the normal test conditions. The parameters of the PV array are shown in Table 3.

Simulation of the array was done at irradiance of 0 to 1000W/m^2 as depicted in Figure 9 and temperature maintained at 25°C to investigate current-voltage (I-V) and power-voltage (P-V) behavior. The profile is a series of clear and cloudy-sky conditions alternating, as a simulation of the usual movement of sunlight in a short time frame (1.8s). This variable input enables experimentation of maximum power point tracking (MPPT) of the system, the battery control response, and the EMS decision-making in the time of the rapid variation of PV generation.

Table 3. System Level Parameters

Parameter	Symbol	Value
Series modules per string	N_s	10
Parallel strings	N_p	47
Cells per module	N_{cell}	60
Open-circuit voltage	V_{oc}	36.3V
Short-circuit current	I_{sc}	7.84A
Voltage at MPP	V_{MPP}	29V
Current at MPP	I_{MPP}	7.35A
Temperature coefficient of V_{oc}	-	−0.3609 %/°C
Temperature coefficient of I_{sc}	-	+0.102 %/°C
Shunt resistance	R_{sh}	313.055Ω
Series resistance	R_s	0.393Ω

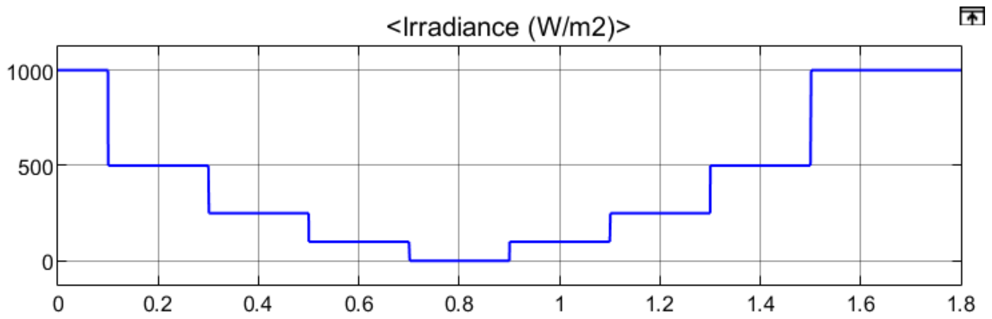

Figure 9. Irradiance Profile for Simulation

The irradiance profile was imposed with the help of a Stair Generator block, which is the dynamic solar variations that are used in testing the EMS. Figure 10 displays the respective I-V and P-V curves. These current and power output grow in direct proportion to the irradiance between 0 and 1kW/m^2 with a small increase in the open-circuit voltage. The maximum power point (MPP) in Figure 10 is seen around 300V and 100 kW at 1kW/m^2 which justifies the MPPT algorithm and PV configuration applied in this research.

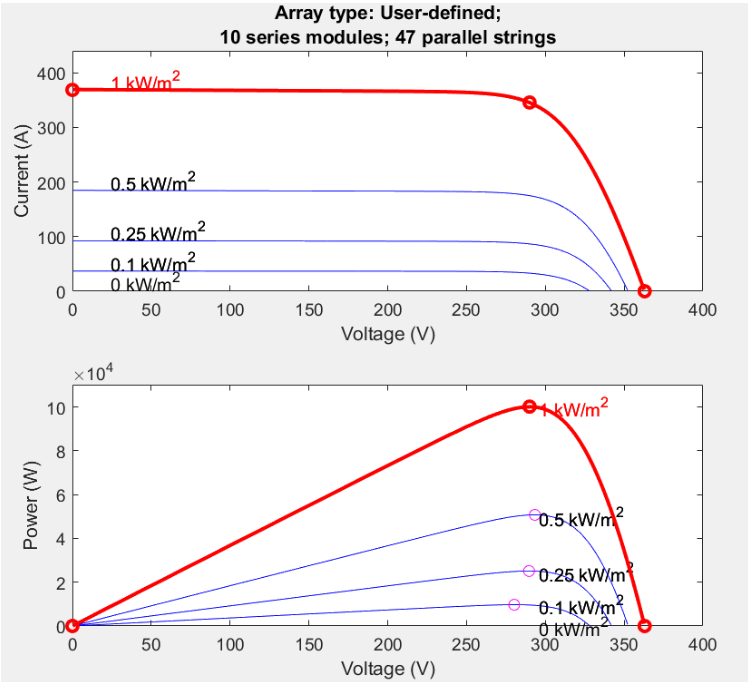

Figure 10. I–V & P–V characteristics curves of PV under different solar irradiance.

The single-diode equivalent circuit equation of a PV array controls the output current of the array:

$$I_{PV} = I_{ph} - I_0 \left[\exp\left(\frac{q(V_{PV} + I_{PV}R_s)}{nkT} \right) - 1 \right] - \frac{V_{PV} + I_{PV}R_s}{R_{sh}} \qquad (12)$$

in which the photocurrent (I_{ph}) is the irradiance-temperature function:

$$I_{PV} = \frac{G}{G_{ref}} [I_{sc,ref} + \alpha T(T - T_{ref})] \qquad (13)$$

The actual response to environmental change is realistic.

3.4 Maximum Power Point Tracking (MPPT)

The PV array would be used in varying environmental conditions, and MPPT control would be required to make the most out of the power obtained. The simplicity and reliability of a Perturb and Observe (P&O) algorithm has been adopted. The instantaneous PV power is calculated as:

$$P_{PV}(k) = V_{PV}(k) \times I_{PV}(k) \tag{14}$$

and the incremental changes with variations are,

$$\Delta P = P_{PV}(k) - P_{PV}(k-1) \tag{15}$$

$$\& \ \Delta V = V_{PV}(k) - V_{PV}(k-1) \tag{16}$$

The reference voltage is modified in accordance with the algorithm:

$$V_{ref}(k+1) = \begin{cases} V_{ref}(k) + \Delta V_s, & \text{if } \dfrac{\Delta P}{\Delta V} > 0 \\ V_{ref}(k) - \Delta V_s, & \text{if } \dfrac{\Delta P}{\Delta V} < 0 \end{cases} \tag{17}$$

Where ΔV_s is the perturbation step. The adjustment of the duty cycle in the converter is done by matching the modified reference voltage V_{ref} to the measured V_{PV}.

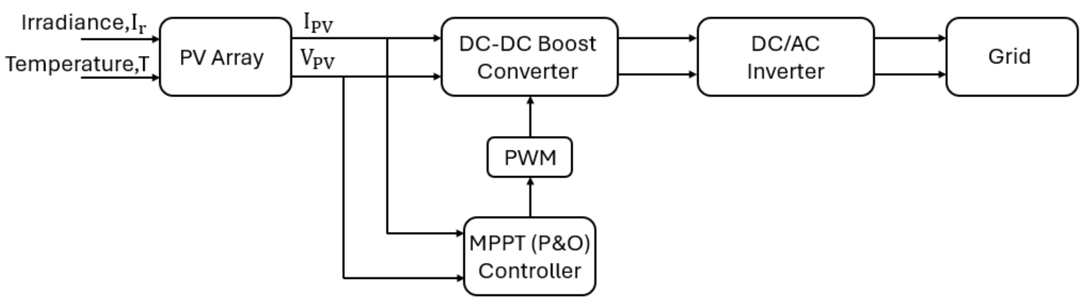

Figure 11. Schematic Diagram of MPPT Control.

The MPPT controller ensures the PV array operates on its maximum-power point even in the case of fast changes in irradiance. Figure 11 illustrates the model of a photovoltaic (PV) subsystem that consists of a DC-DC boost converter and a maximum power point tracker controller which is modeled by perturb and observe (P&O) algorithm. The MPPT constantly compares the voltage (V_{PV}) and current (I_{PV}) over the PV array to generate a reference to the pulse width modulation (PWM) device which changes the converter duty cycle. This has been made to guarantee that at various irradiance (I_r) conditions that the PV array is always at its peak power point before regulated DC power is supplied to the DC-AC inverter and the grid. Figure 12 represents the simple block diagram of the MPPT control structure and implementation in MATLAB Simulink.

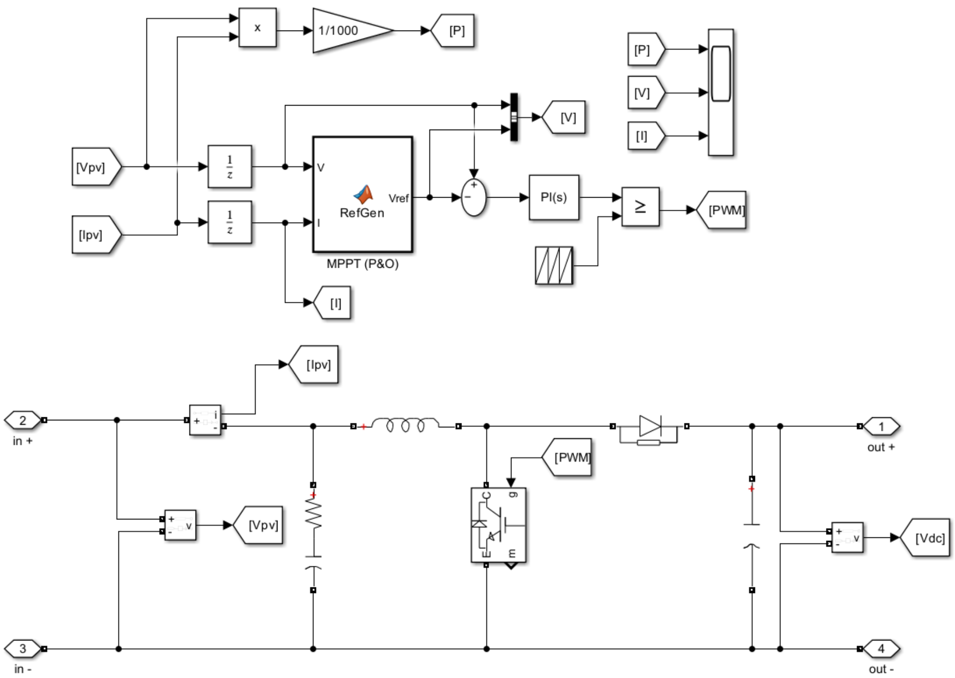

Figure 12. MPPT controller linked to PV array and DC-DC boost converter

3.5 DC–DC Boost Converter

The boost converter links the PV array to the DC bus in Figure 12 that controls the flow of voltage and power to the inverter. It includes an IGBT (Insulated Gate Bipolar Transistor) switch, a diode, an inductor and a capacitor. It operates under the duty cycle (D) through MPPT controller. The steady state voltage characteristic will be:

$$V_{DC} = \frac{V_{PV}}{1-D} \tag{18}$$

The choice of the inductor (L) and capacitor (C) is based on general design equations:

$$L = \frac{V_{PV}(1-D)}{\Delta I_L f_s} \tag{19}$$

$$\& \ C = \frac{I_{DC} D}{\Delta V_{DC} f_s} \tag{20}$$

where f_s is switching frequency, ΔI_L is switching inductor current ripple and ΔV_{dc} is allowable DC-link voltage ripple.

The converter operates in a continuous conduction mode(smooth and without any discontinuity in the flow of current). A PI controller is used to adjust the DC-link voltage in order to maintain V_{dc} = 600V at any irradiance as illustrated in Figure 12. The overall Simulink DC-DC boost converter subsystem has:

- A PWM generator of IGBT switching,
- A PI controller for voltage regulation
- The MPPT logic of dynamic power tracking.

3.6 DC Bus and Inverter Configuration

Short-term energy buffering is also provided by DC bus capacitor between the PV array, battery and inverter. The inverter is a 2-level voltage source converter (VSC) that uses IGBTs which is synchronized on a dq-synchronous reference frame in such a way that the connection to the grid is in unity power factor. The synchronization of the reference angle of the inverter with the grid voltage is done by a Phase-Locked Loop (PLL). The connection between the inverter and the grid and the LCL filter is illustrated in Figure 13. The inverter control is made up of two cascaded loops.

Outer DC-link voltage loop: This outer loop supplies V_{dc} at 60V and the reference I_d^* at the inner current loop is generated.

Inner current loop: This is a loop that regulates dq-axis currents in the following equations:

$$V_d^* = K_{p,d}(I_d^* - I_d) + K_{i,d}\int(I_d^* - I_d)dt + \omega L I_q \quad (21)$$

$$V_q^* = K_{p,q}\left(I_q^* - I_q\right) + K_{i,q}\int\left(I_q^* - I_q\right)dt + \omega L I_d \quad (22)$$

To provide a unity power factor, the current reference of the q-axis is connected to zero ($I_q^* = 0$). The dq voltages are again transformed to the abc-frame and sinusoidally modulated by PWM to produce balanced three phase AC voltages. The controlled DC power is then converted by the inverter to AC and the rated active power (P_{rated}) is fed into the grid continuously.

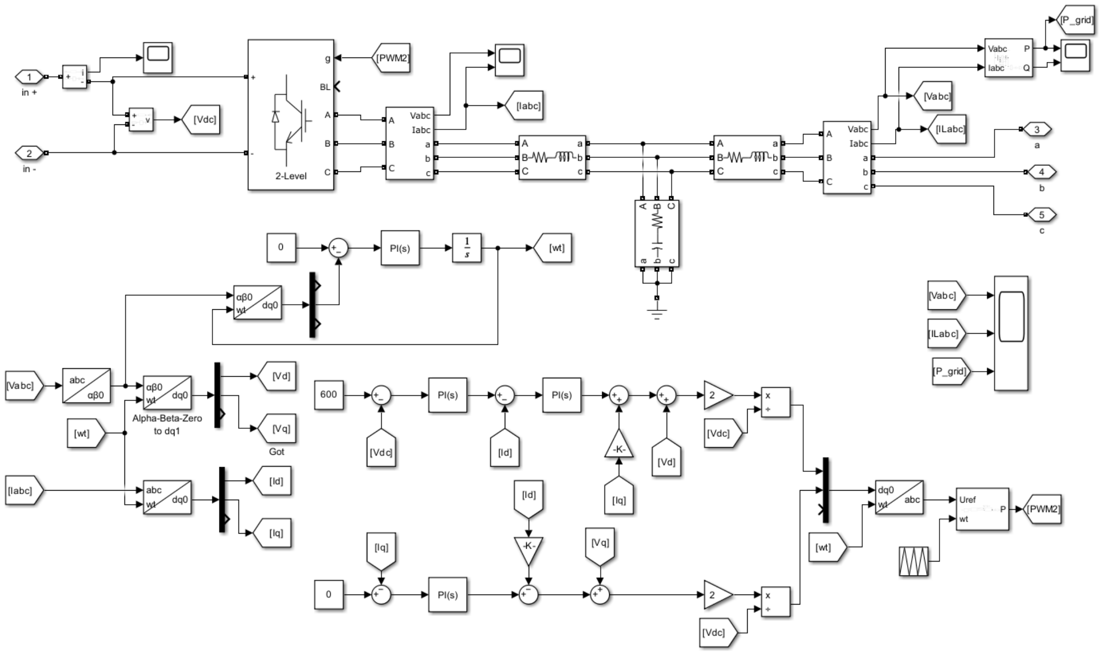

Figure 13. DC/AC Inverter subsystem with LCL filter in MATLAB Simulink

The LCL filter is interconnected between the grid and the inverter and it cuts high-frequency harmonics. The resonant frequency is designed as follows:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1 L_2 C_f}} \quad (23)$$

To dampen resonance a small damping resistor R_f is employed.

3.7 Battery Energy Storage System (BESS)

BESS offers energy buffering and dynamic stability to the hybrid configuration based on PV. It holds the DC-link voltage at approximately 600V and ensures the uninterrupted 6kW supply of power to the three-phase grid despite the intermittence in irradiance at the photovoltaic (PV) array. In a specific time when the solar input is not sufficient, the battery is used up by the boost converter to fill in the power gap, and excess power is taken by the battery in buck mode in time of high irradiance. Such a bidirectional feature will make sure that the inverter output is maintained at the rated value P_{rated}=6kW, which will improve the reliability and the flexibility of the system.

3.7.1 Battery Model Configuration

Lithium-ion (Li-ion) BESS was executed with the help of Battery block in MATLAB Simscape Electrical (R2024b). The parameters have been chosen to represent an actual medium-scale storage module that is part of a 600V DC-bus network. Table 4 summarizes the battery specifications.

Table 4. System Level Parameters

Parameter	Symbol	Value	Description
Battery type	-	Lithium-ion	Generic Li-ion model
Nominal Voltage	V_{nom}	400V	Nominal output voltage
Rated Capacity	C_{bat}	70Ah	Energy storage capacity
Full charged voltage	V_{max}	465.6V	Maximum cell voltage
Cut off voltage	V_{min}	300V	Minimum discharge voltage
Nominal discharge current	I_{dis}	30.4A	Current at nominal power
Internal resistance	R_{int}	0.057Ω	Equivalent series resistance
Minimum SoC	SoC_{min}	20%	Deep discharging protection limit
Maximum SoC_{max}	SoC_{max}	90%	Full charge threshold
Response time	T_{resp}	1s	Dynamic response delay

3.7.2 Mathematical Representation

The instantaneous terminal voltage of the battery is given by

$$\mathrm{V_{bat}} = \mathrm{V_{oc}(SoC)} - \mathrm{I_{bat}R_{int}} \tag{24}$$

The battery will be in charging condition if the battery current, $I_{bat,}$ is negative, and if I_{bat} is positive, then the battery will be discharging. V_{OC}(SoC) nearly proportional to SoC over the working circuit, and the internal resistance R_{int} causes the voltage drop of electro-chemical and other contact losses. The dynamics of change of state-of-charge with time are represented as:

$$\frac{\mathrm{d(SoC)}}{\mathrm{dt}} = -\frac{\mathrm{I_{bat}}}{\mathrm{C_{bat}}} \tag{25}$$

in which C_{bat} is the rated capacity of the battery in Ah. By integrating equation (25) with time, the SoC curve during operation can be calculated and thus can be observed by the EMS to prevent over-cycling and to observe charge limits. Now, the instantaneous power delivered or received by the battery is

$$\mathrm{P_{bat}} = \mathrm{V_{bat}I_{bat}} \tag{26}$$

This power is directly coupled to the DC bus in such a way that

$$\mathrm{P_{PV}} + \mathrm{P_{bat}} = \mathrm{P_{rated}} + \mathrm{P_{loss}} \tag{27}$$

where P_{loss} takes into consideration the converter and resistive losses. The BESS behavior in the simulation environment in the charge and discharge stages is fully defined by the equations from 24 to 27.

3.7.3 Design of a Bidirectional DC -DC Converter

A Li-ion battery is linked to the DC-link of 600V with a bidirectional DC-DC converter to control the power flow between the energy storage unit and the DC bus. Figure 14 is a converter topology that is a circuit composed of two complementary IGBT switches (PWM1 and PWM2), an inductor (L) and a capacitor (C).

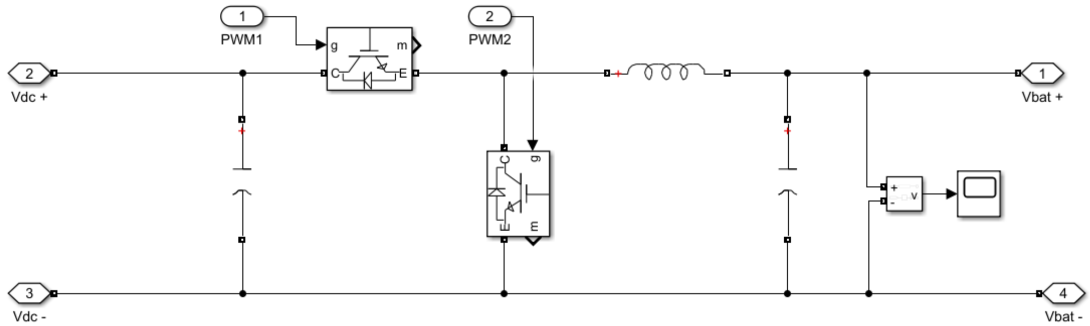

Figure 14. Bidirectional DC-DC Converter model in MATLAB Simulink

The converter allows the charging and discharging modes under the control of the proposed EMS and ensures the stability of the bus voltage and maximization of energy use. The converter duty ratio (D) is the ratio that determines the relationship between the DC bus voltage V_{DC} and battery voltage V_{bat}. Power transfer direction is selected based on the EMS and would depend on the instantaneous power of the PV (P_{PV}) and battery state of charge (SoC). There are two separate modes of operation, i.e., buck (charging) and boost (discharging), as discussed below with the help of Figure 15, where 15(a) is the schematic of the bidirectional DC-DC converter, 15(b) is in the buck mode, and 15(c) is in the boost mode.

Buck Mode (Charging): At the condition when the PV array produces more power than the rated inverter output (P_{PV}>P_{rated}), the surplus energy of the DC bus is used to charge the Li-ion battery. This is the buck mode of converter and is in Figure 15(b) where DC bus voltage is set to the battery voltage. The upper IGBT switch (PWM1) is fed with a high-frequency signal and the lower one (PWM2) is off. During the ON phase of PWM1, this energy is stored in the inductor L and when PWM1 is switched off, this energy is released into the battery through the diode circuit and resulting in a continuing current flow. The inductor thus balances out the charging current as well as prevents transients. A capacitor is a voltage stabilizer which eliminates the high-frequency switching ripples. The voltage relationship in mathematical notation is given as

$$V_{bat} = D_1 V_{DC} \tag{28}$$

in which D_1 is the duty cycle of the PWM1. This is an efficient way of pumping excess solar energy to the battery without developing bus voltage overshoot. The buck-mode circuit condition can be represented as Figure 15(b).

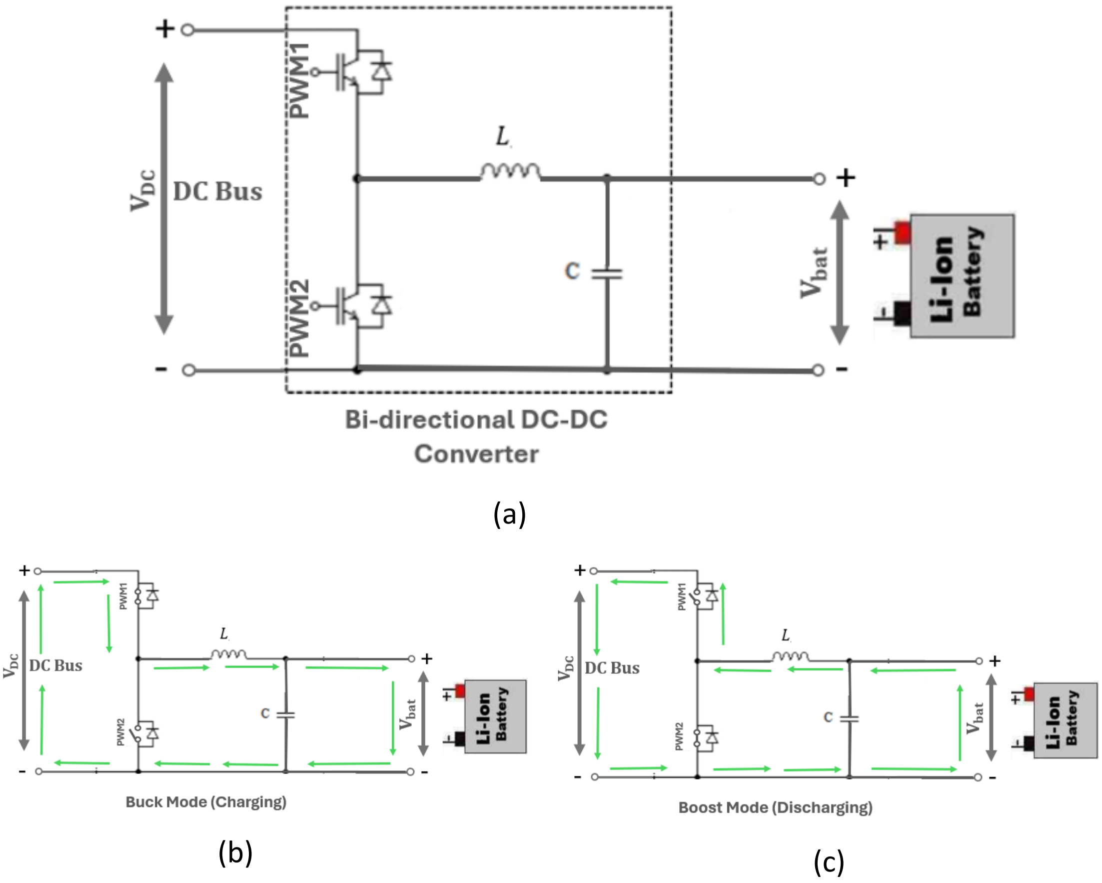

Figure 15. (a) Overall Bidirectional DC-DC Converter, (b) Buck Mode, and (c) Boost Mode

Boost Mode (Discharging): In low irradiance periods of the solar sun when the PV array generates less than the rated power ($P_{PV}<P_{rated}$), the converter goes into boost mode to

drain the battery. Here, lower IGBT switch (PWM2) is turned on whereas PWM1 is turned off. With PWM2, the inductor the current flows through the battery allowing the magnetic field of the inductor to store the energy. When PWM2 is turned off, the stored energy in the inductor leaks into the DC bus and increases the voltage in the bus to the required amount. This step-up operation enables the inverter to keep supplying the respective power to the grid even when there is an inadequate output of PV power. The boost operation is controlled by the following relation:

$$V_{DC} = \frac{V_{bat}}{1-D_2} \tag{29}$$

in which D_2 is the PWM2 duty cycle. Once more, the inductor together with the capacitor is very important in the process of ensuring the smoothness of current and voltage ripples when the mode changes. The two-way feature of the converter makes sure that only one of the two switches (PWM1 or PWM2) is ON at a time, and no cross-conduction takes place, thus ensuring efficiency. The associated circuit of the boost mode is shown in Figure 15(c).
The two operating modes collaborate to facilitate flawless exchange of energy between the battery and the DC bus and hence the hybrid PV-battery system is capable of continually delivering inverter the rated output of the grid power under varying irradiance conditions.

3.7.4 Control Characteristics

PWM (Pulse width modulation) pulses are produced at the central EMS control the converter. This chapter only conducts a summary of the functional operation; a specific sequence of control will be discussed in Chapter 3.9. The converter uses a mutually exclusive switching approach such that only one transistor is conducting at a time. The direction of power flow is determined by instantaneous PV power and SoC limits, and the duty ratio of the PWM is changed proportionately between the voltage ratio $\frac{V_{bat}}{V_{DC}}$. This will avoid over-charging and deep-discharging and will ensure that the battery is kept within its safe operating range (20%-90% SoC). The DC-link is a voltage source during charging and the charge becomes fed into the battery via the buck leg, and during discharging the stored energy is raised to the bus voltage level. The control takes care of a constant transition of current between the two modes, thus minimizing current spikes and maintainability of converters.

3.8 Electrolyzer Modeling

The electrolyzer subsystem is a dynamic energy converting unit, which converts excess electrical energy into hydrogen fuel. In the hybrid PV-battery-electrolyzer system, it guarantees that there is efficient use of renewable resources, because the surplus photovoltaic power is used to generate hydrogen during the time of high solar irradiance. The DC-DC buck converter provides a connection between the electrolyzer and the DC bus and adjusts the input voltage and input current in the same direction. The converter switch works on the PWM3 signal, produced by the proposed Energy Management System (EMS), so that the operating power of the electrolyzer would be adjusted to the PV surplus. Electrolyzer is only active when the PV generation power is more than the combined inverter rated power and battery charging demand.

3.8.1 System Configuration

The electrolyzer is simulated by taking advantage of the Electrolyzer block in MATLAB Simscape, which is able to model both physical and thermal behavior of the water splitting reaction under different electrical and thermal conditions. The electrolysis unit shown in Figure 16 consists of a water tank, temperature source, water pump, and hydrogen storage tank, constituting a complete electrochemical loop that is a symbol that represents energy and mass transfer processes. The water tank is set at atmospheric pressure, and the temperature of the reservoir is 293.15K, the cross-sectional area of the water tank is 0.01m^2. Water in the tank is pumped into the electrolyzer chamber, where electrolysis takes place. The electrical energy applied breaks the water into hydrogen and oxygen according to the stoichiometric reaction, same as equation 6, which can be rewritten as follows:

$$2H_2O(l) = 2H_2(g) + O_2(g) \tag{30}$$

The temperature source is used to hold the operating temperature, and the pump is used to keep the mass flow rate constant. The produced hydrogen is pumped into a constant volume storage tank, which has a port cross-sectional area of $0.01m^{2,}$ which is a closed chamber in which gas pressure increases in direct proportion to the mass of produced hydrogen. The output signal visElectrolyzer.mH2 is the mass of produced hydrogen (m_{H_2}) in mg (milligram), which is obtained by integrating the mass-flow rate ($\dot{m}_{H_2}$) as follows:

$$m_{H_2}(t) = \int_0^t \dot{m}_{H_2}(\tau)d\tau \tag{31}$$

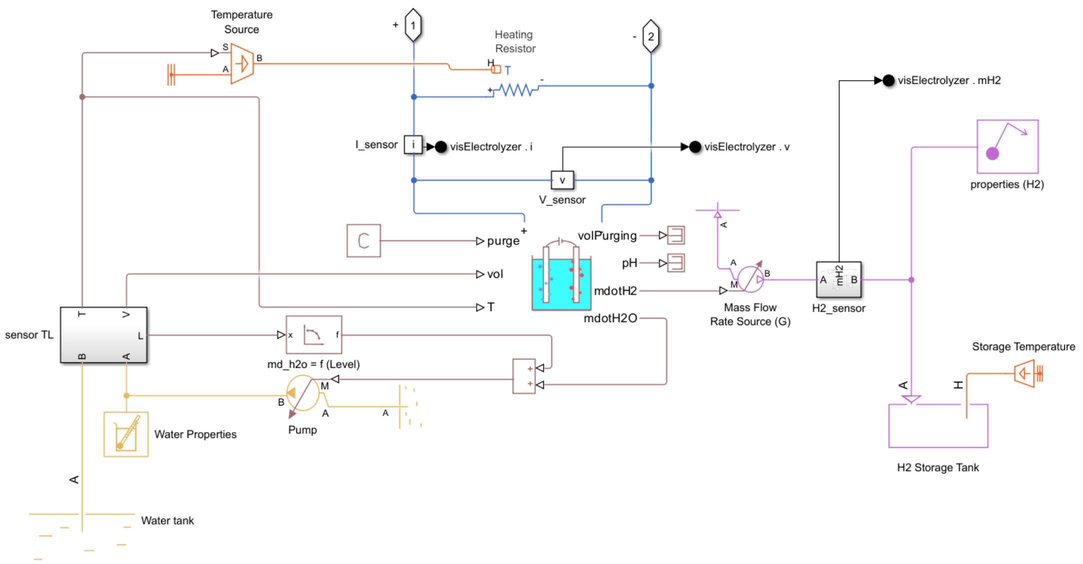

Figure 16. Modeling of the Electrolysis Unit in MATLAB

A buck converter, shown in Figure 17, is used that link the electrolyzer and the DC bus. The converter is made of an IGBT switch, a freewheeling diode, an inductor, and a capacitor. The EMS controls the PWM3 signal and varies the duty ratio (D_3) of the converter to vary the average voltage between the electrolyzer stack due to changes in the DC bus voltage:

$$V_{el} = D_3 V_{DC} \tag{32}$$

In which V_{el} is the input voltage to the electrolyzer.

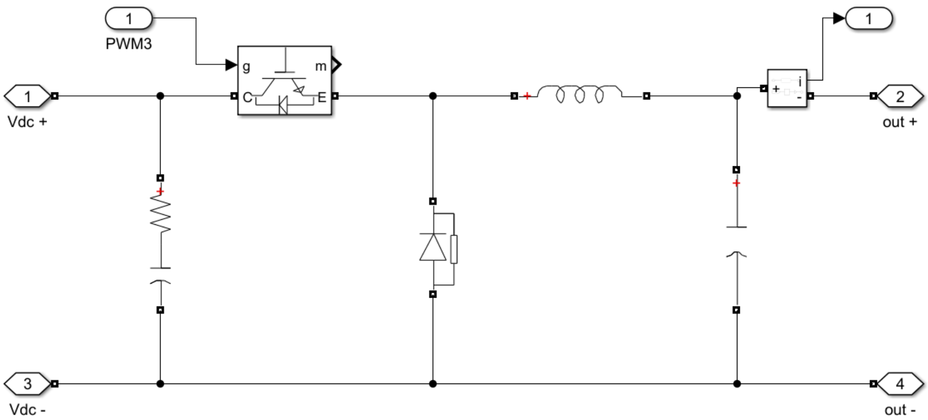

Figure 17. DC-DC Buck Converter to Connect the Electrolyzer and the DC bus

At the ON state, the switch stores its energy in the inductor and in the OFF state, it discharges its energy to the electrolyzer, therefore, it is a continuous current with minimum ripple. The EMS provides the converter enabling operational conditions as:

$$\text{Electrolyzer ON if, } P_{PV} > P_{rated} + P_{bat} \tag{33}$$

In case the above requirement is not satisfied, PWM3 is switched off, leaving the converter in the off state to isolate the electrolyzer from the DC bus. This will ensure the safe operation, unnecessary switching losses will be avoided and the current will not flow back to the bus.

3.8.2 Hydrogen Production

When the converter is switched on, the electrical energy in the DC bus is passed to the electrolyzer stack, and the electrolysis process is started. The water molecules are split up into hydrogen and oxygen gases, where the oxygen is pumped out via a purge outlet and the hydrogen is pumped to the constant volume storage tank. Within the tank, there is an accumulation of hydrogen and its thermodynamic characteristics.

The subsystem of the electrolyzer is effective in linking the electrical and chemical elements of the hybrid system. Through proper coordination of EMS, it harnesses excess solar energy and converts it to hydrogen fuel and balances the system. The buck converter offers stability to electricity and safe operation under fluctuated circumstances, and the flow and accumulation of hydrogen are constantly gauged to gauge the generated hydrogen. This overall modeling method puts in proper perspective the dynamic interactions between the PV array, the battery, and the electrolyzer to show the potential of the system to not only produce energy sufficient for the system, but also a stable grid during varying conditions of renewable power availability.

3.9 Energy Management Strategy (EMS)

The Energy Management Strategy (EMS) is a key factor in the coordination of the hybrid PV-battery- electrolyzer system. According to the comparative analysis in Section 2.6, the current study uses a rule-based EMS system of the hybrid PV-Battery-Electrolyzer system. Even though optimization-based and fuzzy-logic EMS models can reach a globally optimal or adaptive operation, they demand a lot of computational power and detailed forecasting, which is not as appropriate to the real-time MATLAB/Simulink implementation of converter-level dynamics. The rule-based approach, in its turn, offers a deterministic, fast acting, and computationally lean control and allows the delivery of constant 6 kW grid power with continuously varying irradiance. This theoretical decision makes sure that the system is feasible regarding real-time control and embedded implementation of hardware and does not compromise stability to operation and effective use of hydrogen.

The main goal of it is to ensure the uninterrupted 6kW active power supply to the grid with the inverter, however at the same time control the DC-bus voltage at 600V and keep the battery state of charge within the safe operating range of 20%-90%. Depending on the actual level of solar irradiance and SoC, the EMS decides which way the power should flow between the PV array and battery, and electrolyzer. This model of control, which is rule-based, is one of the most common control methods of hybrid renewable systems because it is simple, stable, and allows real-time decision-making [Zhao et al., 2024, Shafiullah et al., 2022]. The proposed EMS control flow diagram shown in Figure 18 is used to guarantee the maximum use of solar power, battery defense, and effective hydrogen generation under excess circumstances. The EMS constantly checks the photovoltaic (PV) power output, solar irradiance, and battery state of charge (SoC) to ensure that the grid receives a constant power supply of 6 kW. This control logic provides sustained power supply, optimum use of battery and efficient hydrogen generation at different solar conditions.

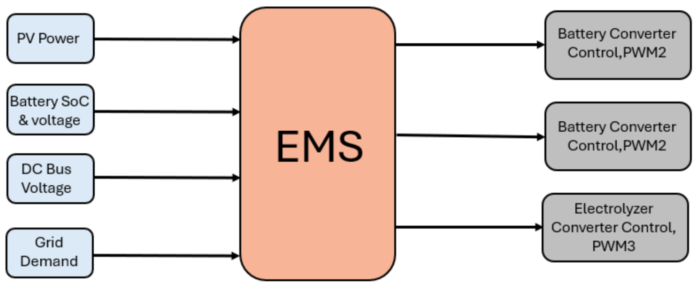

Figure 18. Energy Management System (EMS) Control Flow Diagram

The EMS will focus on accomplishing three main operational goals:

- Grid Power Regulation: Keep the three-phase grid at a fixed inverter output of 6kW (P_{rated}) irrespective of the variations in the PV.
- DC Bus Voltage Control: Maintain the stability of bus voltages (around 600V).
- State-of-Charge Management: To reduce the negative impact of excessive discharge and charging of the battery, it is advisable to maintain SoC between 20%-90% that will extend the life of the battery and its stability.

These are attained through dynamic control of operating modes of the DC converters and switching between these systems among four major operating modes, which include; PV-only, PV-battery, PV-battery-electrolyzer, and idle (no charging/discharging of battery).

3.9.1 Mode of operation and Decision logic

The EMS has a hierarchy of decision-making on a rule-based method, which keep on comparing real-time PV generation power (P_{PV}) with the rated power of the inverter (P_{rated}) and the current battery SoC. All possible transitions between the charging, discharging, and hydrogen generation modes are represented in Figure 19.

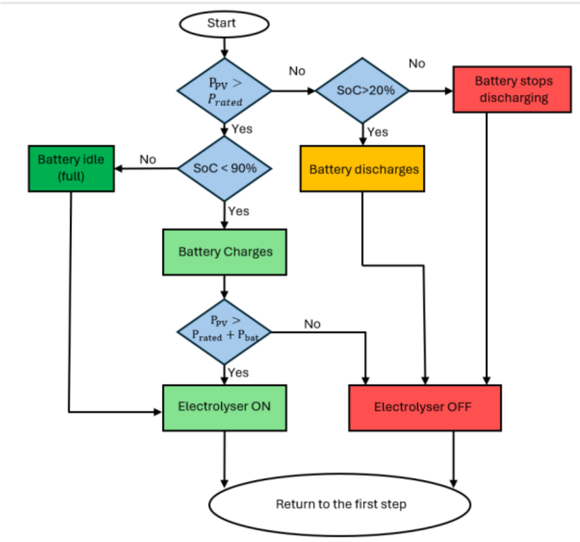

Figure 19. Proposed Rule-Based EMS for HESS

The logic of control may be summed up in the following way:

Case 1: PV Deficit Condition: At times when the photovoltaic (PV) generation is lower than the rating system demand (P_{rated}), the energy management plan calls on the battery to supply the power to the grid. Under this state, the battery should have a state of charge of more than 20% and it will discharge via the bidirectional converter in boost mode to stabilize the power to 6kW with the grid. However, once the SoC has fallen to 20% or less, then the EMS will not allow the additional release to ensure that the battery does not reach deep depletion. This stage does not imply the electrolyzer is turned ON because all the available power is given priority in ensuring the grid supply stability.

Case 2: PV Surplus Condition (Battery Charging Mode): When the solar irradiance is so high and the solar power is more than the rated grid power, the EMS changes the mode of operation to the charging mode. The surplus energy remaining after supplying the 6kW to the grids is supplied to charging the lithium-ion battery through the bidirectional DC-DC converter in the buck mode of operation. This will go on until the SoC is 90%. This mode increases the efficiency of the system since it stores the excess renewable energy that can be further utilized later when there is low irradiance. And if the surplus is still more than the admissible battery-charging power, i.e. $\mathrm{P_{PV}} > \mathrm{P_{rated}} + \mathrm{P_{bat}}$. The excess power is directed to the electrolyzer which is activated through switch PWM3 and transforms the additional energy into hydrogen. Otherwise, the battery only charges, and the electrolyzer remains in the OFF state.

Case 3: PV Surplus and Battery fully charged (Hydrogen Production Mode): Under the condition of PV generation, exceeding the rated grid power and the charging limit of the battery, and the SoC is at 90%, the EMS triggers the electrolyzer. The converter attached to the electrolyzer will work in the buck mode, and it will use the surplus DC power to generate hydrogen by electrolyzing water. This situation guarantees that no renewable energy will go to waste, and excess solar energy will be transformed into chemical energy that can be stored. In this time, the battery would not be charged to prevent overcharging and the electrolyzer would be efficient to transform the surplus PV energy into hydrogen to maintain the sustainability of the system and the use of energy in the long term.

Thus, the applied EMS to this work is balanced in its simplicity and robustness and is suitable for control prototyping and real-time embedded implementation in an integrated energy system.

4 Simulation and Results

This chapter contains the results of the simulation of the proposed PV-Battery-Electrolyzer hybrid system using the MATLAB Simulink (R2024b). The primary goal of the simulation remains to maintain a fixed 6kW power presence to the three-phase power grid when the solar irradiance conditions vary, while at the same time the lithium-ion battery and the electrolyzer remain linked to the photovoltaic (PV) source via the proposed Energy Management Strategy (EMS). The irradiance profile used throughout the whole simulation was the same as depicted in Figure 9, to maintain constant operating conditions in all test scenarios. This regulated change enables the dynamic response of the system to be properly assessed, especially of the PV array, battery, and electrolyzer under the same input conditions, and thus a comparison is made of how the system performed before and after incorporation of the HESS and EMS.

4.1 PV and Grid Performance before Adding HESS

The behavior of the PV array shown in Figure 20 is that of the array without any energy storage or hydrogen subsystem. The PV power follows closely the irradiance profile, and the transparent decreases are associated with irregular decreases in the irradiance. Normal conditions PV voltage is approximately 300V, but when clouds obscure the sun the voltage is greatly reduced, and the current waveform is proportional to the sun's intensity.

The inverter and grid features in Figure 21 reveal that in the absence of energy storage, grid active power is significantly varied with variations in PV output. Even though the grid voltage at the three phases is still balanced at around 400V (line-to-line RMS), the current waveform is distorted during the changes in the irradiance, and also the active-power output is a reflection of PV intermittency indicating the system is susceptible to the change of irradiance and the PV system is incapable of supplying the required power on its own. This phenomenon shows necessity of hybrid storage system in the form of an integrated system to stabilize grid power.

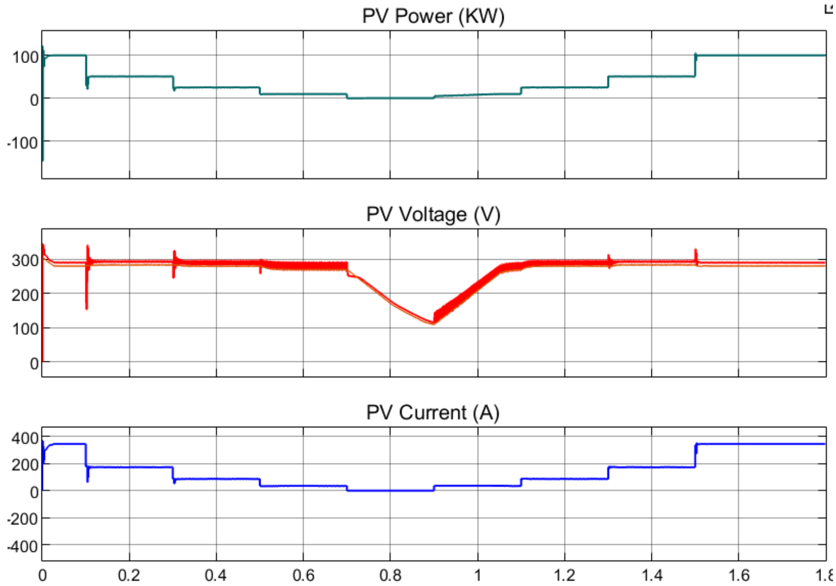

Figure 20. Graph of PV array Power, Voltage, and Current

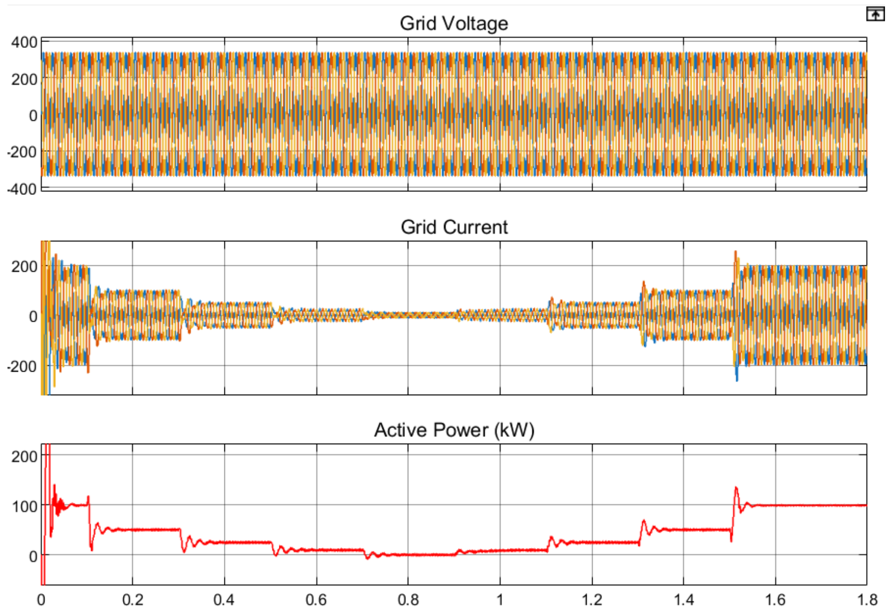

Figure 21. Graph of Grid Voltage, Current, and Active Power without EMS

4.2 DC Bus Voltage Regulation

The DC-link voltage is maintained at about 600V under all conditions of operation, as indicated in Figure 22. This stability can be achieved by the voltage control loop in the inverter, which keeps the DC-link reference ($V_{dc,ref}$=600V) by a closed-loop d-q axis PI control system shown in Figure 13. The P_{PV} is zero, but the inverter continues to receive the minimum amount of reactive power on the grid in order to keep the DC-link voltage steady to prevent fluctuations and be available to work. Physically it would be identical to a grid-based DC-link stabilization system, which holds the bus voltage constant during power outages.

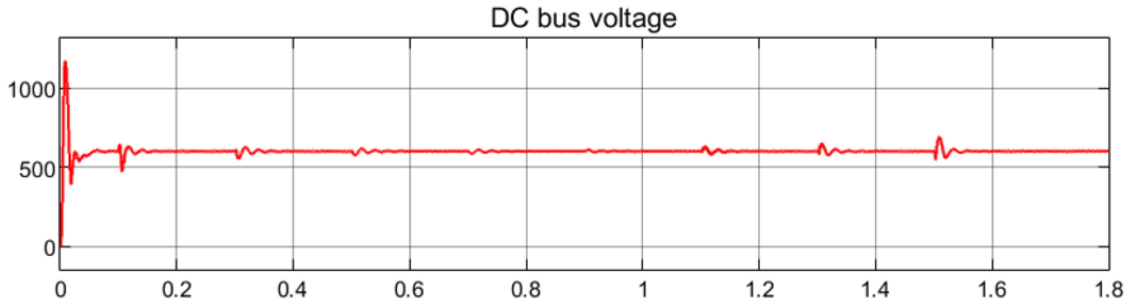

Figure 22. Graph of DC Bus Voltage in Volt (V)

4.3 Stabilization of Grid after the Addition of HESS

The implementation of the Hybrid Energy Storage System (HESS) and the Energy Management Strategy (EMS) make the work of the entire grid much smoother and more stable, as illustrated in Figure 23. In this process of stabilization, the battery is important because it dynamically makes up the fill-in contribution of the periodically varying PV output. The battery power and the current react dynamically to changes in solar irradiance, as in Figure 24, the battery discharges when the PV system is generating low amounts of power and charges when excess power is produced by the PV system. This bidirectional energy flow makes sure that the grid gets a virtually constant amount of power during periods of PV generation variations. The SoC varies slowly, which proves that the EMS is operating in the safe range (20% < SoC < 90%). When the PV output falls to 0 from 0.7-0.9s, the SoC reduces marginally (PWM2 is in ON state as illustrated in Figure 25, and the bidirectional converter is in boost mode) because stored energy is emitted to maintain the grid power. On the other hand, the rest of the time, the SoC increases (PWM1 is in the ON state as in Figure 25, and the bidirectional converter is in buck mode) under strong irradiance as the surplus PV energy is stored. This synchronized action of this battery flattens temporary noise, greatly the uniformity of grid current. The outcome is a stable and continuous power supply to the grid with fewer fluctuations and higher reliability than in the PV-only setup.

During this operating condition, the operation of the electrolyzer is fully dependent on the PV power and the battery charging demand. Figure 26 demonstrates that the electrolyzer current (i_{el}) and power (P_{el}) are closely proportional to the changes in irradiance. The electrolyzer is not active during the low or zero irradiance period (around 0.5s-1.1s) at which time, P_{PV} is not enough to supply the load and battery requirements. When the PV power surpasses the rated power plus the battery charging need, the EMS will switch the PWM3 as in Figure 25, and the electrolyzer is switched ON and uses the surplus power to produce hydrogen. As a result, the curve of hydrogen production demonstrates gradual increase in the periods of high irradiance up to approximately 0.8mg at the end of the simulation, which confirms the adequate use of surplus energy.

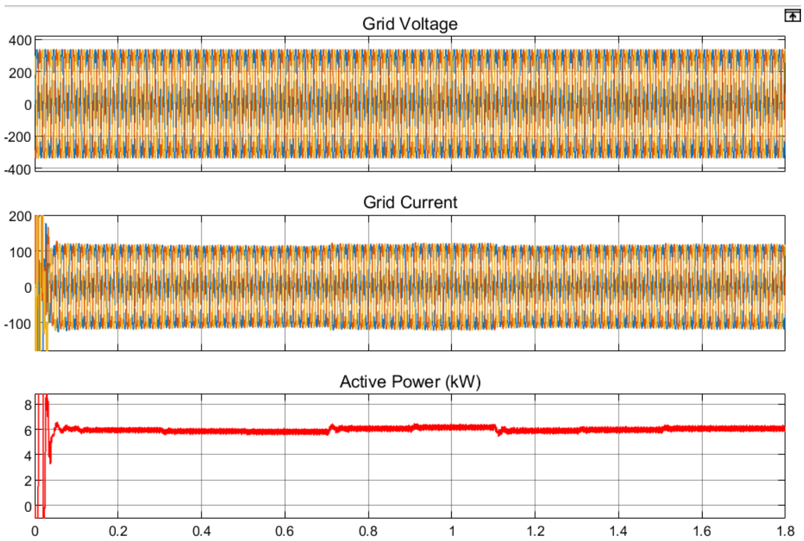

Figure 23. Graph of Grid Voltage, Current, and Active Power after applying EMS

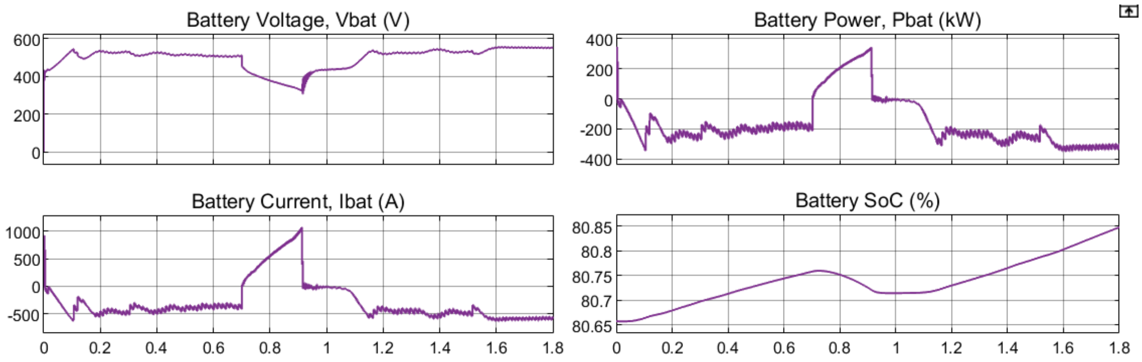

Figure 24. Dynamic response of the battery during operation within a state of charge (SoC) range of 20–90%.

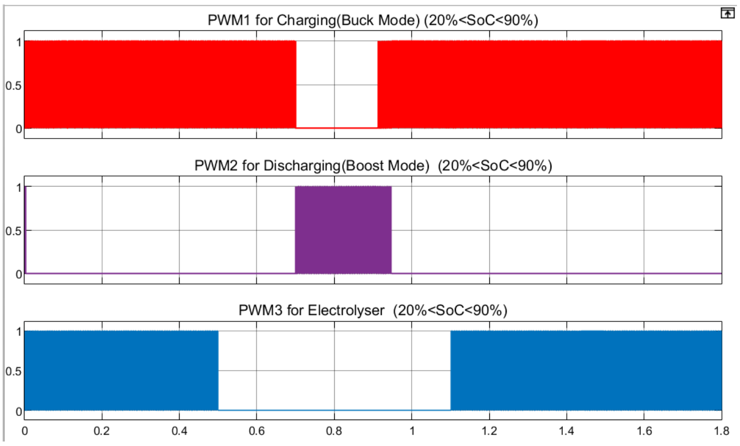

Figure 25. PWM Control Signals when SoC is between 20-90%

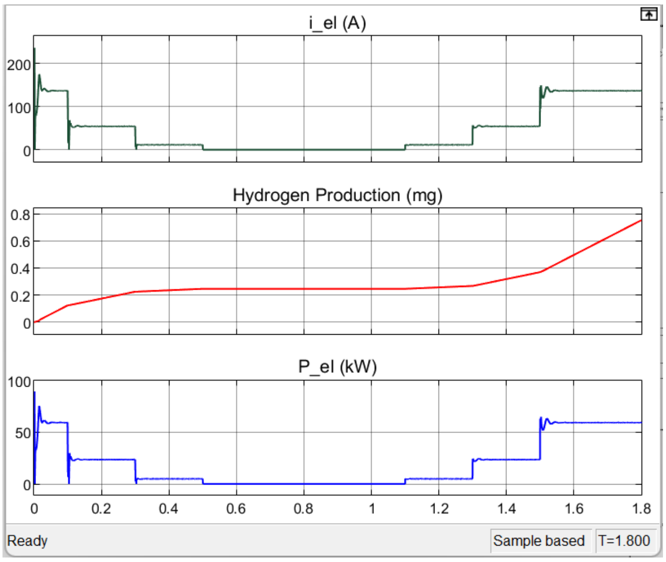

Figure 26. Graph of Electrolyzer Current, Power, and Hydrogen Production.

4.4 Operating Condition when Battery SoC>90% (Battery Full and Electrolyzer Active)

When the battery SoC reaches 90% or above in this operating state, the energy management system prevents further charging to prevent battery overcharging. As can be seen in Figure 27, the battery power and current are zero (both PWM1 and PWM2 remains OFF except from 0.7-0.9s shown in Figure 28) throughout the larger parts of the simulation, except during a small period, between 0.7-0.9s (PWM2 switches ON the boost mode), when the irradiance is lower and P_{PV} is unable to supply the rated power. The SoC goes down a bit in this period, signifying some form of controlled discharge to ensure that the equilibrium is kept between the generation and storage. PV energy will be redirected to the hydrogen production unit, since the battery is close to full, which will enhance the overall system use, ensuring that its health and stability on the grid do not suffer.

Consequently, the battery does not pick up any power from the PV system, and the extra energy flows to the electrolyzer via PWM3 control, shown in Figure 28. Figure 29 indicates the presence of current (i_{el}) and power (P_{el}) in the electrolyzer depending on the irradiance, as seen in the active situation at 0.5 to 0.7s when solar input is at a rather low level. This occurs because the EMS will focus on hydrogen generation as soon as the battery is fully charged to the upper SoC limit. As a result, the production of hydrogen grows continuously, and it reaches almost 0.9mg towards the end of the simulation, which proves that the system is efficient in terms of using excess PV energy rather than letting it go to waste or idling.

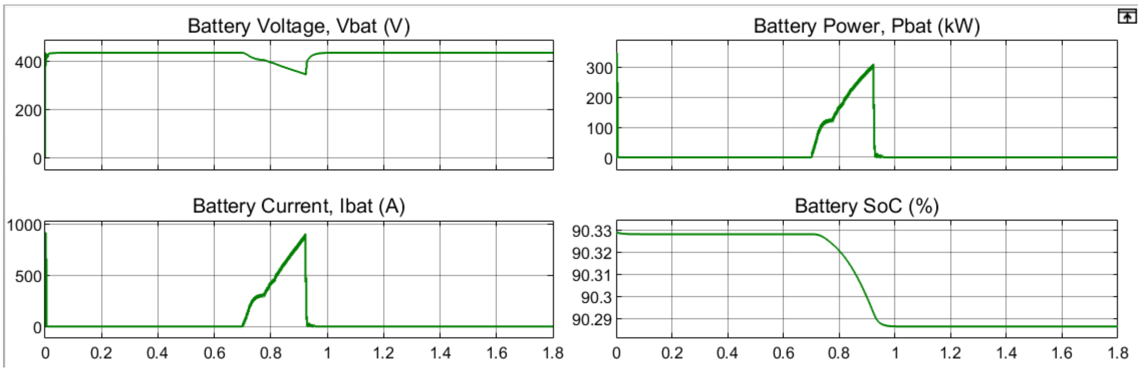

Figure 27. Battery Responses when the SoC is above 90%.

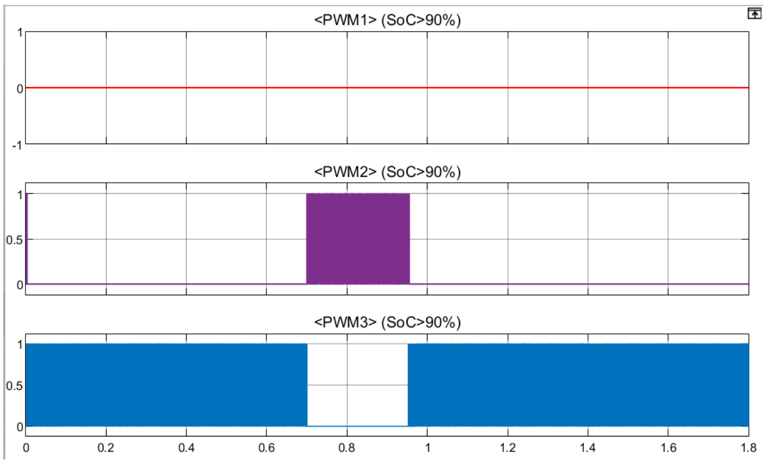

Figure 28. PWM Control Signals when the SoC is above 90%.

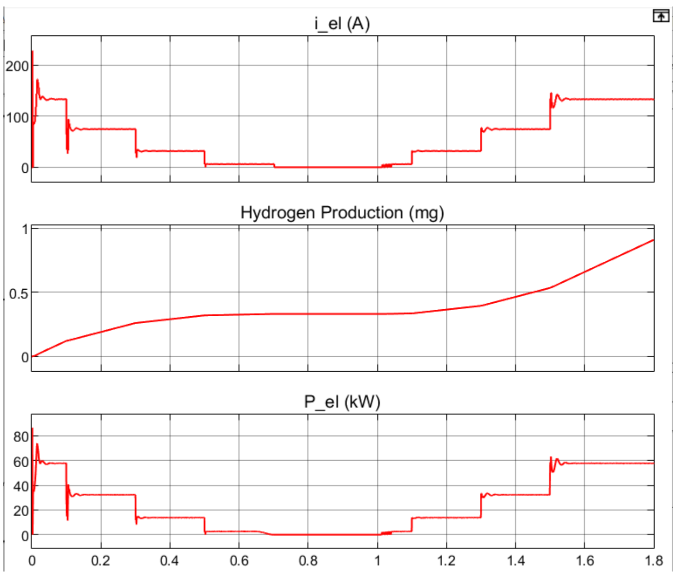

Figure 29. Graph of Electrolyzer Current, Power, and Hydrogen Production when the SoC is above 90%.

4.5 Operating Condition when Battery SoC < 20% (Battery Protection Mode)

Within this operating state, the EMS logic limits the discharge to avoid deep discharging of the battery and extends the service life of the battery in case the battery's SoC drops below 20%. The protection logic is verified in the corresponding battery waveforms Figure 30, where from 0.7 to 0.9s, even when the P_{PV} is 0, the battery stops discharging and remains idle. However, when the PV output power (P_{PV}) is still greater than the sum of the rated grid demand and the battery charging power (P_{rated}+P_{bat}) then the excess PV power is fed via PWM3 to the electrolyzer as in Figure 31. As a result, the electrolyzer response is like as Figure 26 depicts when 20% < SoC < 90% and thus, hydrogen production is proportional to the surplus of PV available. This guarantees that the system is highly efficient in the utilization of excess solar energy even in low SoC conditions if the P_{PV} still surplus after supplying to the rated power and the battery charging demand.

The simulation proves that the hybrid energy storage system is a way of helping to increase the stability of the PV-Grid interface largely. The PV-only arrangement resulted in significant active-power oscillations because of variation in the irradiance, but the suggested PV-Battery-Electrolyzer arrangement did not produce any active-power oscillations because of the irradiance variation as the proposal method offered uniform 6kW grid output, and optimal SoC management. Moreover, the electrolyzer has managed to use excess energy to produce hydrogen, which indicates that the system can be applied to integrated renewable-to-hydrogen solutions.

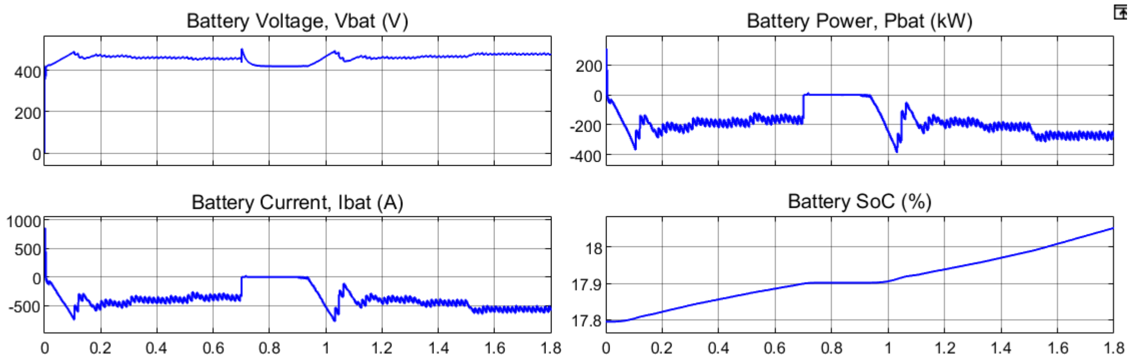

Figure 30. Battery Responses when the SoC is below 20%.

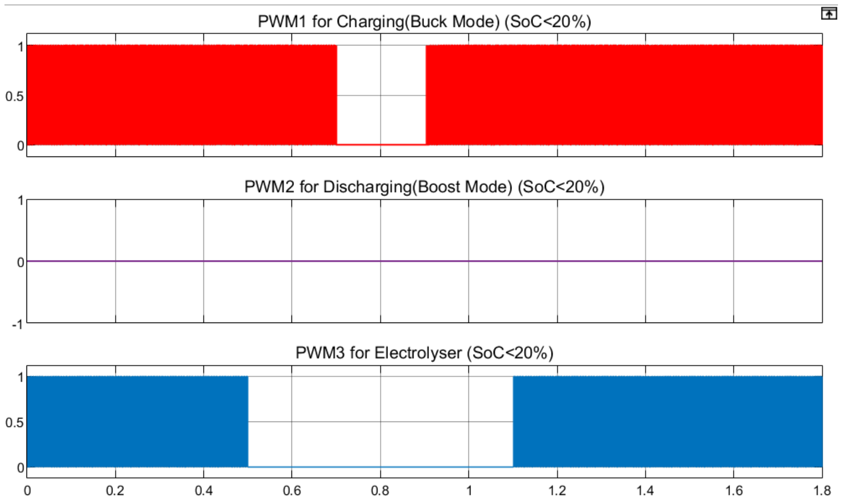

Figure 31. PWM Control Signals when SoC is below 20%.

5 Discussion

The proposed hybrid PV-Battery-Electrolyzer energy management system was achieved to provide the continuity and constant grid interaction in the changing sun irradiance. The dynamic behaviour of the proposed system is confirmed by the simulation results that were presented in the previous section. This chapter perceives such results, correlating the obtained results with the design objectives and energy management strategy of the system. It discusses the performance of the suggested control approach in the stabilization of the DC-bus voltage, conservation of the rated power supply to the grid, and the efficient production of hydrogen under the over-power conditions.

5.1 Overview of the System Performance

The general experiment with the system shows that the inclusion of battery storage with an electrolyzer into a grid-connected PV system can effectively increase the flexibility and stability of a system. PV- inverter subsystem was unable to maintain the grid power at a consistent behaviour during fluctuations of irradiance before the hybrid energy storage system (HESS) was introduced. With the addition of the battery and the electrolyzer with the proposed EMS, the DC-bus voltage was kept at 600V, and the inverter was able to produce the rated power to the grid continuously even with the sun power generation reduced to zero.

Such stability is mostly due to the synchronized working of the battery bidirectional converter and the EMS algorithm which guarantees gentle changes between the charging, discharging and idle process. On the other hand, the electrolyzer subsystem is efficient in utilizing excess PV power whenever it exists hence avoiding overcharging the battery and enhancing efficiency of the system.

5.2 Use of Battery in Grid Stabilization

The battery system was important in stabilizing the power output in the grids. When the solar irradiance was decreasing the battery discharged to fill the difference so that the inverter remained supplying the grid at the rated output. On the other hand, when solar power was too much the battery would charge effectively until the upper SoC limit (90%) was reached. This two-fold functionality was necessary in balancing the power and preventing the quick variation of the grid power as witnessed with standalone PV systems.

The discharge response of the battery in the periods of low irradiance when $P_{PV}<P_{rated}$ was such that the DC bus voltage was sustained constant, and the inverter output was not impaired. The SoC protection limits (20% < SoC < 90%) were used to avoid overcharge and overdischarge hence long-term battery health and operational safety. The smooth transitions that have been witnessed between battery charge and discharge modes affirm that the proposed EMS managed to control real-time power flow across the hybrid system. T

5.3 Contribution of Electrolyzer and Hydrogen Generation

The subsystem of the electrolyzer augmented the battery by transforming any excess PV energy into hydrogen that is stored. Its working was in close connection with the logic of EMS: it was OFF when $P_{PV}\leq$Prated, and ON when $P_{PV}> P_{rated} + P_{bat}$, which was a really surplus state.

The hydrogen generation graph clearly indicates that the production ranged at a high rate when the irradiance was high, whereas when it was low or zero (0.5-1.1 s) the electrolyzer was shut down which is an indication of a well-coordinated control. Once the battery was fully charged (SoC > 90%), excess PV energy was used to generate hydrogen so that the EMS could then use it to produce energy without curtailment. This action represents the process of system supporting sector coupling, which transforms electrical energy into chemical form, and it can be further utilized in either fuel or storage of energy.

5.4 EMS Effectiveness

The EMS algorithm was effective in managing the work of all the system components. The operational logic was well matched to the switching signals (PWM1, PWM2, and PWM3):

- PWM1 was turned ON in charging mode (battery charging in buck mode).
- PWM2 was working with discharging mode (battery support in boost mode).
- PWM3 activated the electrolyzer when excessive PV power was recorded.

Time-domain PWM reactions were used to confirm that there was no overlap or instability between converter channels, and only one channel of the bidirectional converter could be active at once. The EMS made sure that the dynamic balance of generation, storage, and hydrogen conversion was maintained. This proves the fact that the suggested rule-based EMS can be applied to real-time systems of distributed energy systems.

5.5 Comparative Analysis with Reference Configuration

The hybrid PV-BESS-Electrolyzer model had better voltage and power stability than reference PV-only configuration. The PV-only system had severe power swings and temporary oscillation with different irradiance, as compared to the hybrid system which had steady grid power generation.

The short-term intermittency was alleviated by finding an energy storage method, and the electrolyzer served as an energy sink to take up the surplus power, hence reducing curtailment. This two-storage system can be applied to increase grid reliability and lifespan of the PV system because it limits the stress on the inverter and DC-link capacitor. Furthermore, renewable energy generation through hydrogen production provides a new value to the renewable energy, leading to energy security and sustainability at the system level.

5.6 Summary of Key Findings

1. The suggested hybrid system was effective in sustaining constant power of 6kW to the grid during the varying weather conditions of the sun.
2. Transient fluctuations in the battery energy storage system were counterbalanced by charging or discharging as the need arose.
3. The electrolyzer made good use of excess PV energy to produce hydrogen.
4. The inverter ensured the DC-bus voltage and grid-synchronized working under all conditions.
5. The EMS showed strong decision-making and control coordination without any switching, overlapping and instability.

In general, the simulation confirms that the incorporation of a battery and an electrolyzer within an intelligent EMS can considerably enhance the reliability, stability, and efficiency in the use of energy in PV-based grid systems.

6 Conclusion and Future Work

The study was able to design, model, and simulate a grid-connected hybrid PV-Battery-Electrolyzer system that could be used to stabilize the power delivery and effectively generate hydrogen generation under different conditions of solar irradiance. The physical subsystem models used in the development of the system were created in both Simulink and Simscape Electrical environments, and the PV array, bidirectional DC-DC converter for the battery, DC-DC boost converter, DC-AC inverter, and electrolyzer were included. An organized Energy Management System (EMS) was introduced to control the energy flow within the subsystems in accordance with the power balance and battery state of charge (SoC).

The simulation results indicated that the proposed hybrid setup was successful in maintaining grid stability, where the active power of 6kW was delivered with a regulated DC-bus voltage of 600V. The d-q control loop of the inverter gave strong voltage control even when the sun was not shining or the irradiance was variable. The Perturb and Observe (P&O) MPPT algorithm was used to keep the PV array at the maximum power point, and the battery system was used to dynamically offset the power cuts in case of insufficient irradiance. In case of excess power in PV generation compared to the power demand of the grid, the excess power was stored in the battery until it reached 90% SoC. The rated grid power was initially used to charge the battery (when the SoC was under 90%). At the same time, when more PV power was available to satisfy the grid load and charging conditions, the electrolyzer was switched ON to convert the surplus into hydrogen. This co-ordination allowed them to keep energy depository as well as to generate hydrogen concurrently to ensure that they utilize the solar power efficiently and to keep the grids steady. The EMS was also able to set SoC limits to prevent deep discharge, overcharge, and retain safe and efficient converter switching with no overlap and instability.

A comparative analysis of the pre-HESS (PV-only) and post-HESS (PV–Battery-Electrolyzer) running proved that there is a notable increase in grid stability. The hybrid system was able to smooth out power variations due to irradiance change and evidenced coordinated use of energy, which is a benefit of having an integrated storage as opposed to isolated PV systems. The electrolyzer operation was highly correlated with the EMS logic, where it was inactive when low irradiance as compared to high irradiance and works effectively when PV power was above the rated point which confirms the correct operation chain of solar to hydrogen.

Overall, the given system proves the possibility and usefulness of electrical and hydrogen energy storage integration within the renewable energy networks. It ensures grid stability, optimal use of renewable energy, and the viability of the future power by connecting the production of electricity to long-term hydrogen storage.

Future Work

The presented work of this thesis can be extended in various ways. The possible improvement is to implement a fuel cell subsystem to reconvert the stored hydrogen into electricity to provide a fully reversible hybrid system. To achieve further optimization of the EMS, fuzzy logic control or model predictive control (MPC) could be used to enhance the responsiveness and reduce the energy loss in transient conditions. Also, hardware-in-the-loop (HIL) or real-time digital simulation (RTDS) testing may be performed to test the dynamics of the system in the presence of the real operational disturbances. Economic analysis, scalability of the system, and the performance of the system over the life cycle of the technology may also be researched in the future, and the techno-economic feasibility of involving hybrid energy storage coupled with practical deployment strategies. Environmental impact assessment and carbon footprint would also be included to get a comprehensive picture of the sustainability potential of such hybrid renewable systems in the smart grid implementation.

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Appendices

Appendix 1. System Parameters Used for Simulation

Parameter	Value
Simulation tool	MATLAB R2024b
Grid Frequency (f)	50Hz
Simulation duration (t_{sim})	1.8s
Grid type	3-phase (balanced)
Rated inverter power (P_{rated})	6kW
Control approach	MPPT(P&O) & dq control

PV Parameters:

Parameter	Value
Series modules per string (N_s)	10
Parallel strings (N_s)	47
Cells per module (N_{cell})	60
Open-circuit voltage (V_{oc})	36.3V
Short-circuit current (I_{sc})	7.84A
Voltage at MPP (V_{MPP})	29V
Current at MPP (I_{MPP})	7.35A
Temperature coefficient of V_{oc}	−0.3609 %/°C
Temperature coefficient of I_{sc}	+0.102 %/°C
Shunt resistance (R_{sh})	313.055Ω
Series resistance (R_s)	0.393Ω

Battery Bank Parameters:

Parameter	Value
Battery type	Lithium-ion
Nominal Voltage (V_{nom})	400V

Rated Capacity (C_{bat})	70Ah
Fully charged voltage (V_{max})	465.6V
Cut off voltage (V_{min})	300V
Nominal discharge current (I_{dis})	30.4A
Internal resistance (R_{int})	0.057Ω
Minimum SoC (SoC_{min})	20%
Maximum SoC (SoC_{max})	90%
Response time (T_{resp})	1s

Electrolyzer Parameters:

Parameter	**Value**
Resistance (R_{el})	0.25 Ω
Cross-sectional transport area (A)	30,000 cm^2
Distance anode–cathode (X_d)	2
Number of cells (N_{e_cell})	100
Initial pH	7
Constant pH	6