People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

University of M'Hamed BOUGARA - Boumerdes

Institute of Electrical Electronic Engineering IGEE

Final Year Project Report Presented in Partial Fulfilment of the Requirements of the Degree of

MASTER

In Power Engineering

Option : **Power & Telecommunication**

Title:

Energy Management of PV & Battery Standalone Hybrid System

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Academic year : 2023/2024

Abstract

The increasing demand for sustainable and reliable energy sources has led to the emergence of hybrid renewable energy systems as viable alternatives for standalone applications. This report presents a comprehensive study on the design, modeling, control, and simulation of a hybrid renewable energy system using Matlab Sumilink comprising a photovoltaic (PV) array integrated with a battery storage system. A detailed mathematical model is developed to capture the dynamic behavior of the PV array and battery storage system, considering factors such as solar irradiance and battery state of charge.

The proposed control strategy ensures optimal operation and seamless transition between PV and battery sources using MATLAB functions. The control algorithm is implemented and validated through simulation studies utilizing advanced software tools, providing a realistic representation of the hybrid system's performance under various operating conditions.

This study demonstrates the effectiveness of the hybrid renewable energy system in enhancing energy reliability and sustainability, offering a practical solution for standalone energy applications. The findings provide valuable insights into the dynamic interactions within hybrid systems and underscore the potential for significant improvements in energy efficiency and operational costs.

Dedication

I dedicate this work to my parents. To my sister. To all my family members for their encouragements. To everyone who loves me and everyone I love.

Oussama Larbi

This thesis is dedicated to all my family members, especially my parents, brothers and sister, whose unwavering support and encouragement have been my greatest strength. To all my teachers and friends, thank you for your guidance and help throughout this journey.

Riadh

Acknowledgments

First and foremost, all praise and thanks giving to Allah the most powerful and most merciful who gave us the ability and patience to accomplish the work presented.

We would like to thank my supervisor, CHALA Slimane , for their invaluable guidance, support, and encouragement throughout this research. Their insights and expertise have been instrumental in shaping the direction and outcome of this thesis.

Also we would like to thank my colleague, DAIF Mouhanad , for its invaluable guidance throughout this research.

We are also grateful to our INSTITUTE for providing us with the necessary resources and a conducive environment to carry out my research. The knowledge and skills I have acquired here have been pivotal to my academic and professional growth.

We would also like to acknowledge the contributions of my colleagues and fellow researchers, whose discussions and feedback have been invaluable in refining my work.

Lastly, We are deeply appreciative of the efforts of everyone who directly or indirectly contributed to the completion of this thesis. Your support has been instrumental in helping me achieve this milestone.

Thank you all.

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List of Abbreviations

- **HES** Hybrid Energy System
- **HRES** Hybrid Renewable Energy System
- **PV** Photovoltaic
- **AC** Alternating Current
- **DC** Direct Current
- **SOC** State of Charge
- **DOD** Depth of Discharge
- **EMS** Energy Management System
- **RBS** Rule Based Strategies
- **BEMS** Building Energy Management Systems
- **OBS** Optimization Based Strategies
- **FBS** Frequency Based Strategies
- **AGC** automatic generation control
- **AI** Artificial Intelligence
- **DS** Deterministic Strategies
- **LOS** Local Optimization Strategies
- **GOS** Global Optimization Strategies
- **SOH** State of Health
- **PWM** Pulse Width Modulation
- **MPPT** Maximum Power Point Tracking
- **P&O** Perturbation and Observatio
- **MPP** Maximum power point

General Introduction

The development and implementation of renewable energy systems has been prompted by the increasing emphasis on sustainable energy solutions across the world. The capacity of photovoltaic (PV) systems to capture solar energy, a plentiful and clean resource, makes them stand out among the others. To provide a steady and dependable power source, energy storage devices, such batteries, must be included due to the random nature of solar power output. In order to maximize the performance and dependability of a PV and battery standalone hybrid system, this thesis investigates the system behavior under various conditions. In addition to enhancing performance and reliability, standalone PV and battery hybrid systems play a crucial role in areas lacking a reliable grid infrastructure. These systems provide a dependable source of electricity where traditional grid connections are either unavailable or unreliable. This capability is particularly beneficial in remote regions, islands, and rural areas, where establishing conventional power infrastructure is economically or logistically challenging. By harnessing solar energy and storing it in batteries, these systems not only ensure continuous power availability but also contribute to reducing dependency on fossil fuels and mitigating greenhouse gas emissions. Thus, they serve as a sustainable and resilient energy solution, addressing energy access issues and promoting environmental sustainability in diverse geographical settings. Chapter 1 provides a comprehensive overview of hybrid energy systems, emphasizing the integration of PV panels and battery storage. This chapter discusses the fundamental principles of hybrid systems, their components, and the importance of effective energy management.

In Chapter 2, we delve into the modeling of the PV and battery standalone hybrid system. This chapter outlines the theoretical and mathematical models used to represent the various components of the hybrid system, including the PV panels, batteries,converters and inverters. Accurate modeling is crucial for simulating the system's behavior under different conditions and for designing effective energy management strategies.

Chapter 3 focuses on the control strategies implemented to manage the energy flow within the hybrid system. This chapter details the Maximum Power Point Tracking (MPPT) techniques used to maximize the efficiency of the PV panels, and the Proportional-Integral (PI) controllers employed to regulate the charging and discharging processes of the battery. Additionally, the chapter discusses the use of bipolar Pulse Width Modulation (PWM) to control the inverter and the functions designed to manage load distribution. These control mechanisms are critical for ensuring the optimal operation of the hybrid system, balancing energy production with consumption, and maintaining system stability.

The results of our research are presented and analyzed in Chapter 4. This chapter discusses the behaviour of the system under the energy management and control strategies, using simulation. The performance of the hybrid system is evaluated under different scenarios, and the findings are discussed briefly.

The important elements of energy management in PV and battery standalone hybrid systems are covered in this thesis' conclusion. This research attempts to progress the area of renewable energy systems and promote sustainable energy solutions through an organized strategy.

Chapter 1

Overview on Hybrid renewable energy systems and Energy Management

1.1 Introduction

This chapter highlights the significance of HRES in the production of sustainable energy, examines its possible advantages, and discusses the difficulties in putting HRES into practice. The main elements of HRES, including as energy storage and photovoltaic (PV) systems, are covered in further detail in this chapter. In order to maximize financial gains and enhance system performance, it concludes by talking about several energy management techniques.

1.2 Hybrid Energy Systems

There are several approaches to define hybrid energy systems. The most comprehensive, and arguably most helpful, is this one: "Hybrid energy systems are combinations of two or more fuels for the same device, or two or more energy conversion devices (such as electricity generators or storage devices), that when integrated, overcome limitations that may be inherent in either." This definition is helpful since it covers a broad variety of scenarios and highlights the crucial aspect of energy conversion multiplicity [1].

1.2.1 Stand-alone hybrid systems

Systems that generate electricity without relying on the utility grid as shown in Figure 1.1, are referred to as stand-alone systems. These are better suited for the most isolated areas where no other energy source is available and the grid cannot reach. Since standalone systems are frequently the most economical option for applications located distant from the utility grid, they make up the bulk of solar installations in remote parts of the world. Auxiliary power units for emergency services or military usage, lighthouses and other remote installations, and manufacturing plants with sensitive electronics are a few examples[2].

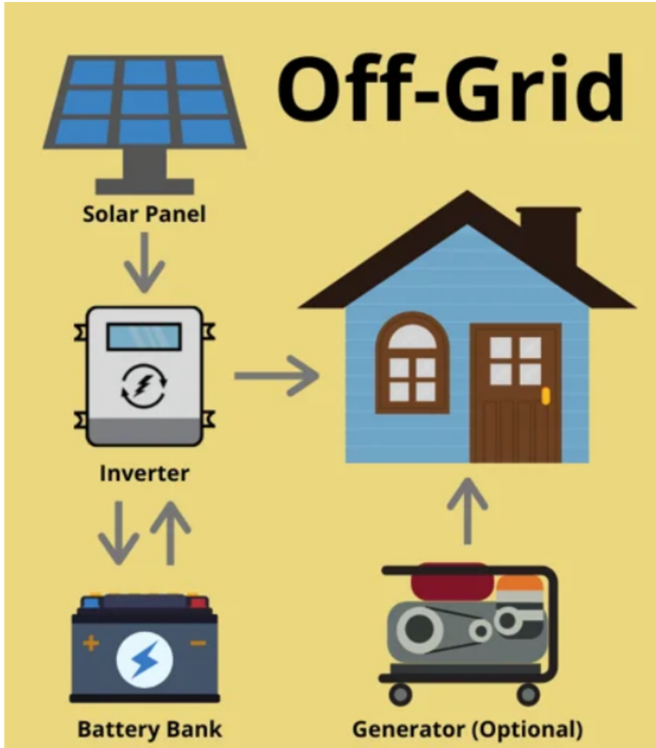

Figure 1.1: Stand-alone hybrid systems

1.2.2 hybrid solar system

Grid-tied and off-grid elements are combined in hybrid solar systems to provide a flexible energy option. These systems combine grid connectivity, battery storage, and solar panels to provide effective energy management. Reduced reliance on the grid, backup power during blackouts, and possible cost savings through energy-efficient use are among the advantages. By using just solar energy and batteries, off-grid devices function separately from the grid. Off-grid solutions offer total energy autonomy, but because of their limited battery capacity, they come with higher initial costs and need regular energy management. The decision between off-grid and hybrid systems is based on grid access, budget, and energy requirements. For household energy solutions, hybrid systems often provide a balanced approach by fusing affordability, dependability, and sustainability[3].

1.3 Solar Cell Integration

Solar or photovoltaic cells are semiconductor-based devices that convert solar light directly into electrical energy. A direct current (DC) electric field is created when sunlight strikes the semiconductor material on the surface of the solar cell, exciting the electrons to flow.

The generated electricity can then be used to replenish batteries, power electronics, or feed back into the electrical grid. Solar cells have become a major source of renewable energy in recent years because of their ability to generate clean, renewable power directly from the Sun [4].

1.3.1 Efficiency of solar cells

The model of the solar cell influences its properties. A perfect solar cell is believed to be similar to a perfect diode with a current source connected in parallel, as shown in Figure 1.2[5].

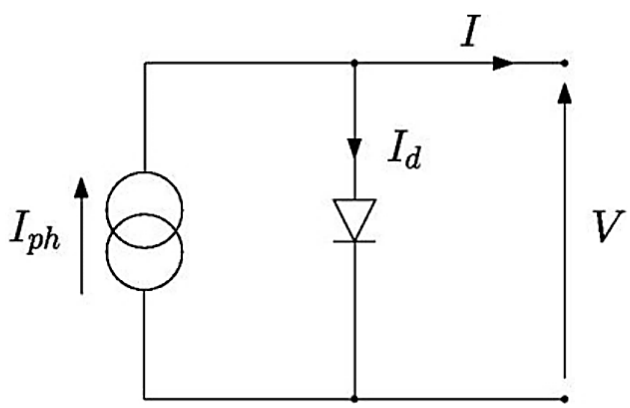

Figure 1.2: Equivalent diagram of the ideal solar cell

1.3.1.1 Open-circuit voltage (Voc)

This is the maximum voltage that a solar cell can produce when it is not connected to a load. It represents the voltage at which the current flowing through the cell is zero[6].

$$V_{oc} = \frac{nkT}{q} \ln\left(\frac{I_{\mathrm{ph}}}{I_0} + 1\right) \tag{1.1}$$

Where:

- Iph is the light generated current.
- I0 is the saturation current.
- n is the ideality factor.
- T is the temperature in Kelvin.
- k is the Boltzmann's constant.
- q is the charge of the electron[7].

1.3.1.2 Short-circuit current (Isc)

A solar cell that has its terminals shorted out can only generate this much current. It is a representation of the current that passes through the cell in the absence of any resistance[6].

$$J_{\mathrm{sc}} = qG(L_n + L_p) \tag{1.2}$$

Where: G is the generation rate, and Ln and Lp are the electron and hole diffusion lengths respectively[8].

$$I_{\mathrm{sc}} = J_{\mathrm{sc}} \times A \tag{1.3}$$

Where: Jsc is the open circuit current density, A is the area of the solar cell.

1.3.1.3 Fill factor (FF)

This represents the efficiency with which light is converted into electrical energy by a solar cell. It is the relationship between the solar cell's maximum power and the sum of its open-circuit voltage and short-circuit current[6].

$$\mathrm{FF} = \frac{V_{\mathrm{m}} \times I_{\mathrm{m}}}{V_{\mathrm{oc}} \times I_{\mathrm{sc}}} \tag{1.4}$$

1.3.1.4 Efficiency

This indicates how effectively a solar cell generates electrical energy from sunlight. This is the solar cell's electrical power output divided by the solar power that it receives[6].

$$\eta = \frac{V_{\mathrm{oc}} \times I_{\mathrm{sc}} \times \mathrm{FF}}{P_{\mathrm{in}}} \tag{1.5}$$

1.3.1.5 Maximum power point (MPP)

This is the operating point of a solar cell that produces the maximum power output. It is the voltage and current combination that gives the highest product of voltage and current.

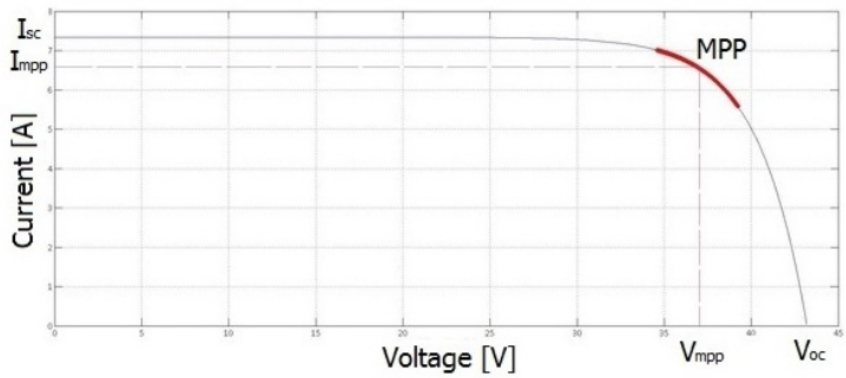

Figure 1.3: Maximum Power Point

1.3.2 The influence of temperature and irradiation

1.3.2.1 The influence of temperature

For the operation of a solar panel, the PV cell must be exposed to solar radiation. This causes heating, and temperature affects the various characteristics of the cell [9]. The solar irradiance was set to 1000 W/m^2, and the temperature was varied from 25°C to 75°C. The resulting trends are presented below:

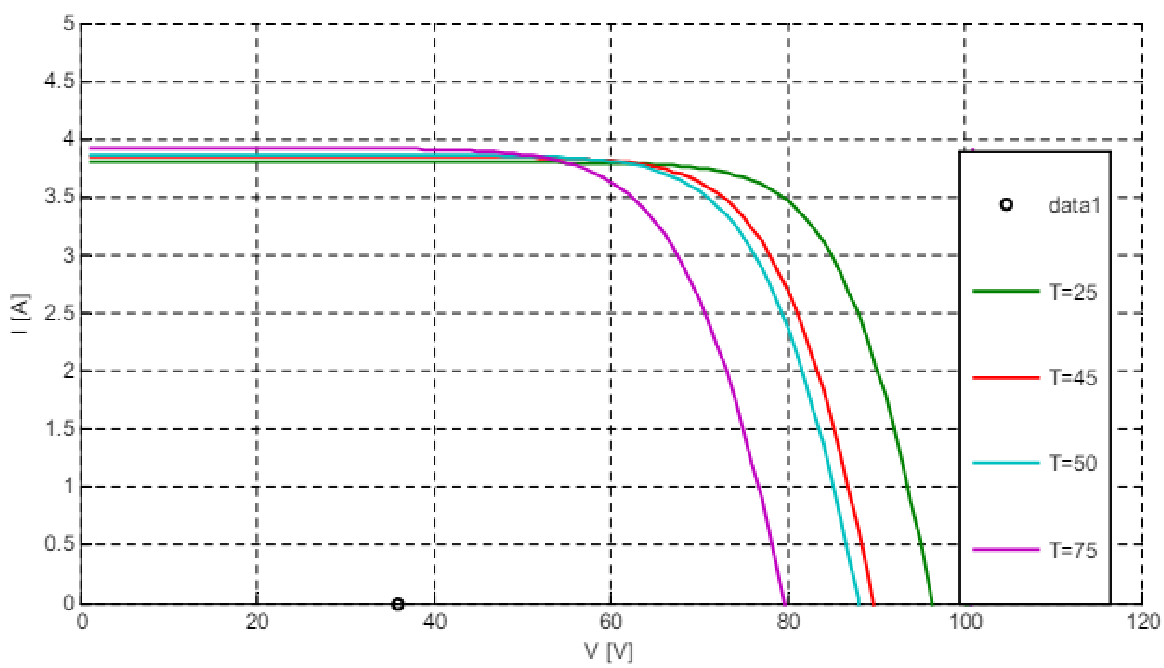

Figure 1.4: Influence of Temperature on PV Current

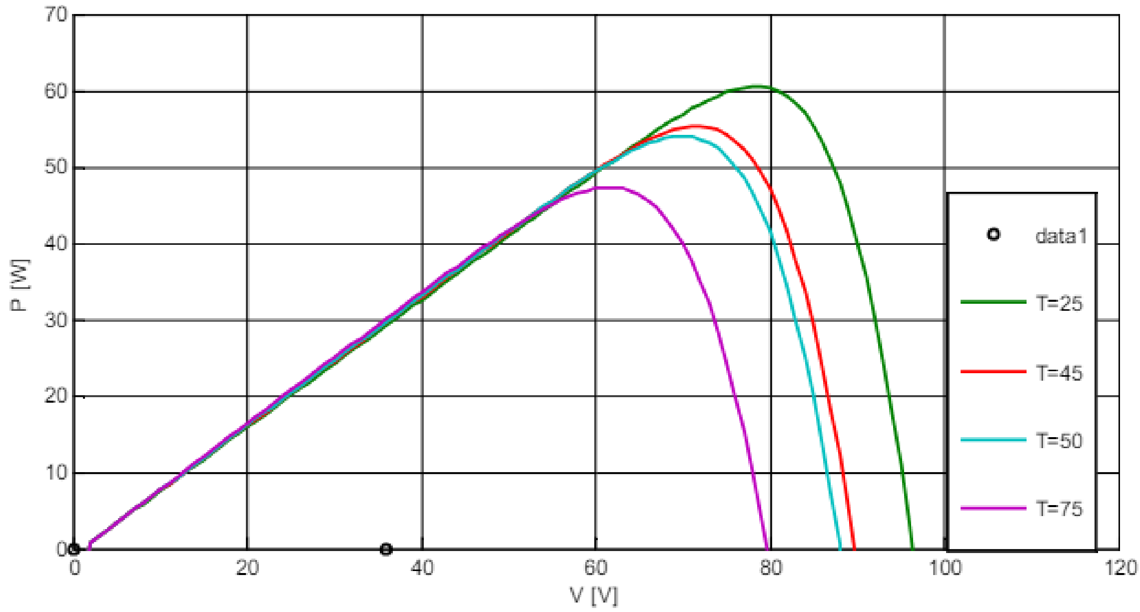

Figure 1.5: Influence of Temperature on PV Power

It is observed that an increase in temperature primarily leads to a decrease in voltage, consequently reducing the power of the PV system. Figure I.5 shows that an increase in temperature from 25°C to 75°C results in a 25% drop in power.

1.3.2.2 The Influence of Irradiation

A constant temperature of 25°C was maintained while varying the solar irradiance (G) from 200 W/m² to 1500 W/m². The obtained results are illustrated in the following figures.

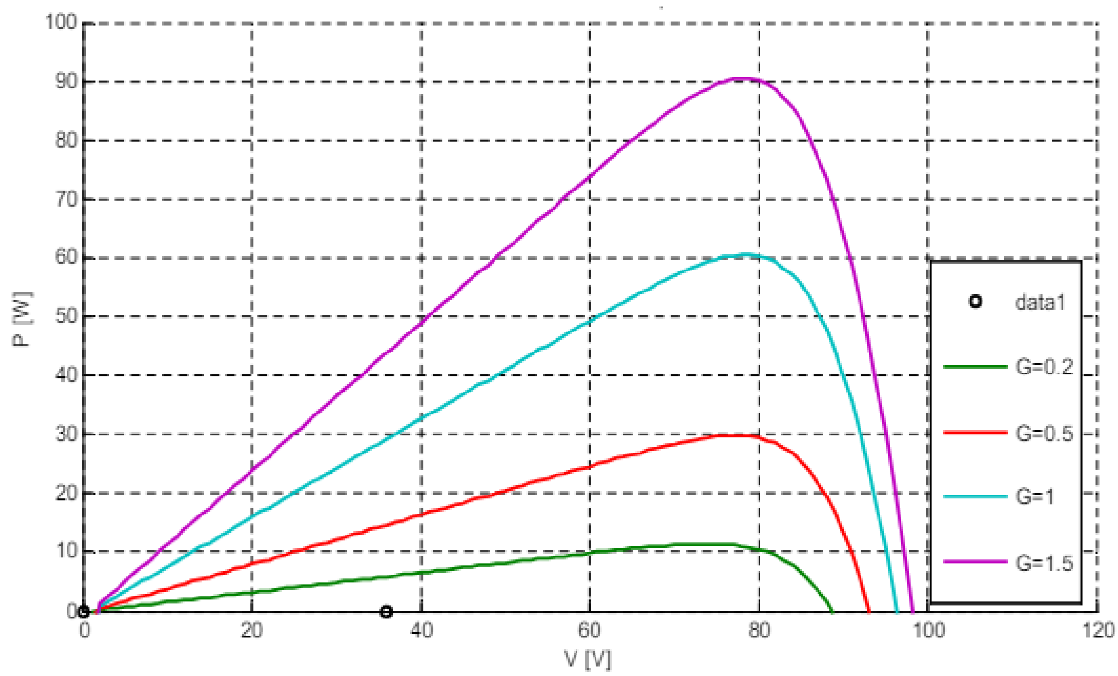

Figure 1.6: Influence of Irradiance on PV Power

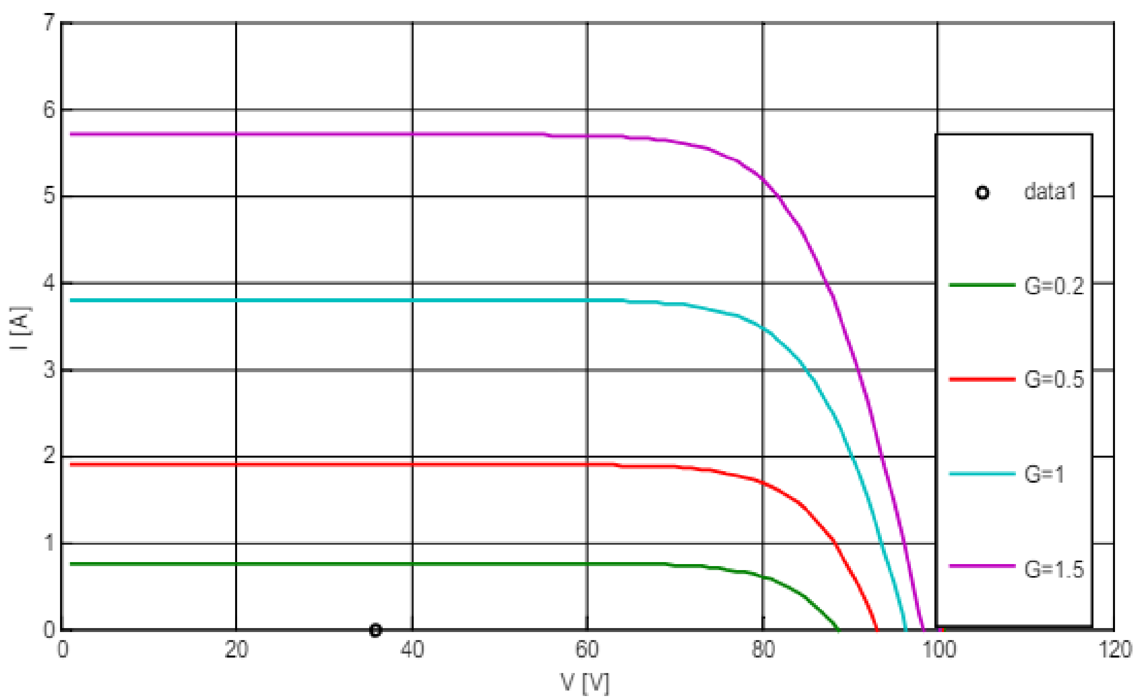

Figure 1.7: Influence of Irradiance on PV Current

1.3.3 Advantages and disadvantages of solar energy

1.3.3.1 Advantages of solar energy

• Renewable energy source: Solar energy is a renewable energy source, which means that it is replenished by the sun's radiation and will never run out.

• Low operating costs: Once installed, solar cells have very low operating costs, as they do not require any fuel or regular maintenance.

• Environmentally friendly: Solar energy produces no emissions or pollution, making it a clean and environmentally friendly source of energy.

• Reduced dependence on fossil fuels: Solar energy reduces our dependence on fossil fuels, which are a finite resource and a major contributor to climate change.

• Versatility: Solar cells can be installed in a wide range of locations and applications, from large-scale power plants to small rooftop installations.

1.3.3.2 Disadvantages of solar energy

• High upfront costs: Solar cell installations can have high upfront costs, including the cost of the solar panels, installation, and necessary components such as batteries and inverters.

• Weather-dependent: Solar energy production can be affected by weather conditions, such as clouds, rain, and snow, which can reduce the amount of sunlight available to the solar cells.

• Limited efficiency: Solar cells currently have a limited efficiency, with commercial cells typically converting only around 15-25% of the incident solar energy into electrical energy.

• Land use: Large-scale solar energy installations require significant amounts of land, which can be a challenge in densely populated areas.

• Energy storage: Solar energy is not always available when it is needed, which means that energy storage solutions such as batteries are necessary to ensure a continuous supply of power.

1.4 Energy Storage Systems

Energy storage systems play a pivotal role in ensuring the reliability and stability of power generated from intermittent sources like solar cells. This section reviews the state-of-the-art in energy storage technologies, ranging from traditional batteries to emerging solutions like supercapacitors and advanced storage materials. By synthesizing existing research, we aim to identify the most suitable energy storage systems for integration with solar cells, taking into account factors such as scalability, efficiency, and cost-effectiveness.

1.4.1 Important features of batteries

Efficiency: The efficiency of a battery is usually denoted by round-trip efficiency at nominal conditions and is often in the range of 70-80 percents , where the efficiency is dependent on discharge rate among other factors.

Life span: The life span is often quantified by the number of charge/discharge cycles. Several factors affect the life span, amongst others, discharge rate, depth of discharge and temperature conditions.

State of charge (SOC): This refers to the relative capacity at the moment. A state of charge of 1 implies that the current battery capacity is equal to the rated capacity.

Depth of discharge (DOD): Depth of discharge is the reverse of the state of charge.

Self discharge: Batteries in idle condition will discharge at some rate. Self discharge refers to the rate at which the battery discharges if not in use.

Operating temperature: Temperature range for normal operation.

Specific energy density: The amount of energy possible to store per kg, given in Watt hours per kg.

Specific power density: The power capability in Watt per kg [10]

1.4.2 Battery types

There are many different battery types, some of them are plotted in figure 1.8 by their specific energy density and specific power density.

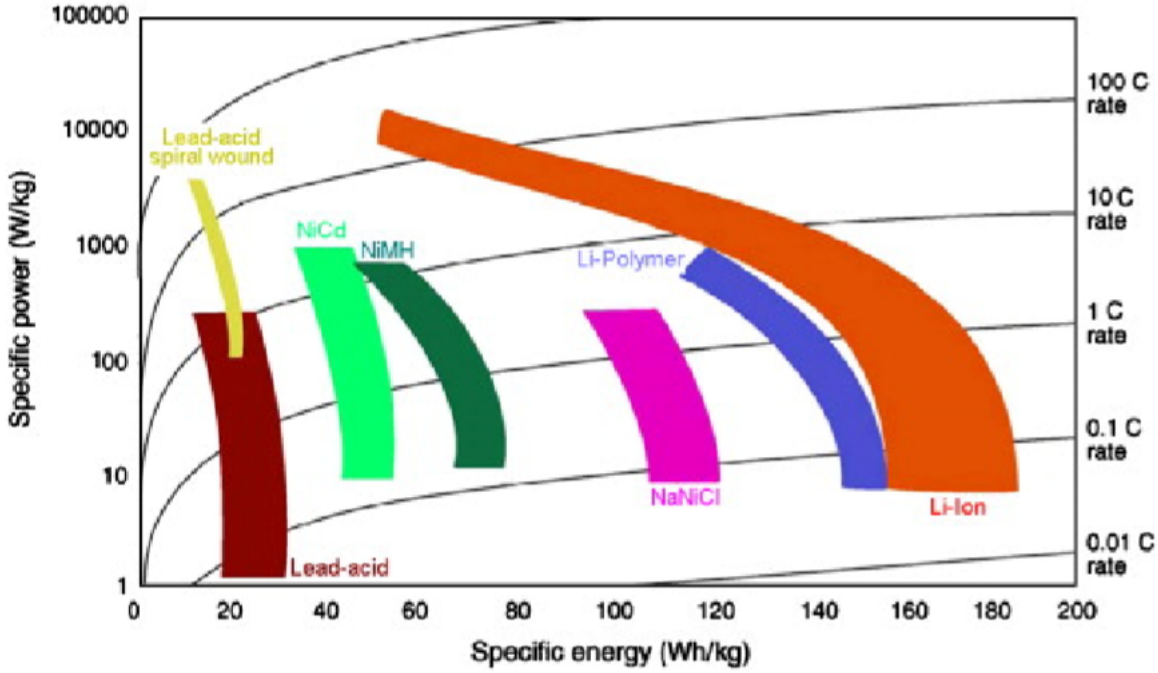

Figure 1.8: Distribution of different electrochemical batteries by their power and energy density

Lead acid: This battery type is the oldest and most mature technology and has been used for many power system applications. The main advantage of lead-acid battery is the low cost compared to other types.

Li-Ion: Lithium Ion batteries are very low-weight, energy dense, and power dense as shown in figure 1.8 These characteristics make them suitable for many portable applications. The production cost is high and the batteries lifetime degrade with deep discharges. Data for from a lithium ion discharge curve is used in the battery simulation in this paper.

1.4.3 Battery capacity

The capacity of a battery is actually dependent on the rate at which it is discharged. This dependence is expressed by the Peukert equation (1.6).

$$C_p = I^K \cdot T \tag{1.6}$$

In equation (1.6)Cp is the Peukert capacity [Ah], I is the discharge current [A], T is the maximum discharge time and k is the Peukert coefficient. Manipulating the equation and introducing the rated discharge time and rated capacity produces equation (1.7) :

$$I_t = C\left(\frac{C}{IH}\right)^{k-1} \tag{1.7}$$

Where H is the rated discharge time in hours, C is the rated capacity at the discharge time of H, I is the actual current in [A], k is the Peukert coefficient and It is effective capacity [Ah] at the discharge rate of I. It is clear from equation (1.7) that the higher the current, the lower the actual capacity will be.

1.5 Energy Management

Energy management in power systems is crucial for ensuring the balance between supply and demand, maintaining grid stability, and integrating renewable energy sources. The increasing complexity of modern power grids, driven by the proliferation of distributed generation and variable renewable energy, necessitates advanced energy management strategies. This chapter reviews the primary approaches to energy management, focusing on Rule-Based Strategies (RBS), Frequency-Based Strategies (FBS), and Optimization-Based Strategies (OBS).

1.5.1 Energy Management Strategies

1.5.1.1 Rule-Based Strategies (RBS)

Rule-Based Strategies (RBS) involve using predefined rules to control energy consumption and generation. These strategies are often simple to implement and do not require extensive computational resources. For example, load shedding rules can be applied during peak demand periods to prevent overloading the grid.

- **Advantages:**

1. **Simplicity:** Easy to design and implement.
2. **Low Cost:** Minimal computational requirements and infrastructure needs.
3. **Reliability:** Well-suited for predictable and stable conditions.

- **Limitations:**

1. **Lack of Flexibility:** Rigid rules may not adapt well to dynamic changes in the grid.
2. **Suboptimal Performance:** May not achieve the best possible outcomes compared to more sophisticated methods .

- **Applications:**

1. **Industrial Load Management:** RBS are widely used in industrial settings where energy consumption patterns are predictable. Specific rules might be set to turn off non-essential equipment during peak hours, helping to manage the load and reduce energy costs.

2. **Building Energy Management Systems (BEMS):** These systems use rule-based controls to manage heating, ventilation, and air conditioning (HVAC) systems, lighting, and other building services to optimize energy use and comfort levels.

3. **Emergency Load Shedding:** In critical situations where the grid is under severe stress, RBS can be used to quickly shed non-essential loads to prevent widespread blackouts.

1.5.1.2 Frequency-Based Strategies (FBS)

Frequency-Based Strategies (FBS) utilize the system frequency as a key indicator of the balance between supply and demand. When the frequency deviates from its nominal value, it signals an imbalance that needs to be corrected by adjusting generation or load.

- **Advantages:**

1. **Real-Time Response:** Provides immediate feedback and adjustment to maintain grid stability.

2. **Automatic Control:** Reduces the need for manual intervention.

- **Limitations:**

1. **Sensitivity:** Can be overly sensitive to minor fluctuations, leading to frequent adjustments.

2. **Complexity:** Requires precise measurement and control mechanisms.

- **Applications:**

1. **Grid Frequency Regulation:** FBS are commonly used in grid operations to maintain stability. For instance, automatic generation control (AGC) systems adjust the output of generators to keep the frequency within acceptable limits.

2. **Renewable Energy Integration:** As renewable energy sources like wind and solar can cause fluctuations in frequency, FBS can help manage these variations by adjusting loads or dispatching reserve power.

3. **Microgrids:** In microgrid systems, FBS can ensure stable operation by balancing local generation and demand, especially when isolated from the main grid.

1.5.1.3 Optimization-Based Strategies (OBS)

Optimization-Based Strategies (OBS) employ mathematical and computational techniques to find the optimal balance of energy generation, distribution, and consumption. These strategies consider various constraints and objectives, such as minimizing costs, reducing emissions, and ensuring reliability.

- **Advantages:**

1. **Efficiency:** Can achieve near-optimal solutions, improving overall system performance.

2. **Flexibility:** Capable of handling complex, multi-objective problems.

Limitations:

1. **Computational Intensity:** Requires significant computational resources and sophisticated algorithms.

2. **Data Dependency:** Relies heavily on accurate and timely data.

- **Applications:**

1. **Smart Grid Optimization:** OBS are extensively used in smart grid applications, where advanced algorithms optimize energy dispatch, demand response, and the integration of renewable energy sources. Techniques such as linear programming, dynamic programming, and genetic algorithms are commonly employed [11].

2. **Energy Market Participation:** Power system operators use OBS to optimize bids in electricity markets, considering factors like price forecasts, generation costs, and regulatory constraints.

3. **Renewable Energy Scheduling:** OBS help in scheduling the generation from renewable sources while ensuring the reliability of the grid, considering the variability and uncertainty associated with these sources .

4. **Distributed Energy Resources (DER):** OBS can optimize the operation of DERs like rooftop solar panels, battery storage, and electric vehicles, improving overall system efficiency and reducing costs[11].

1.5.2 Advantages of Energy Management in PV Systems

- **Increased Efficiency and Performance:**

Effective energy management strategies, such as Maximum Power Point Tracking (MPPT), enhance the efficiency of PV systems by ensuring that the PV panels operate at their optimal power point under varying environmental conditions. This maximizes energy capture and improves overall system performance. Additionally, incorporating advanced algorithms and real-time monitoring can further optimize energy production and reduce losses.

- **Grid Stability and Reliability:**

PV systems, when integrated with energy storage and smart grid technologies, can contribute significantly to grid stability and reliability. Energy storage systems, such as batteries, allow excess energy generated during peak sunlight hours to be stored and used during periods of low generation or high demand, thereby smoothing out fluctuations and ensuring a steady power supply. Moreover, demand response strategies enable PV systems to adjust energy consumption patterns based on real-time grid conditions, helping to balance supply and demand.

- **Economic Benefits:**

Energy management strategies can lead to substantial economic benefits for both consumers and PV system operators. By optimizing the use of generated energy and minimizing waste, these strategies can reduce energy costs. Programs such as net metering and feed-in tariffs provide financial incentives for feeding excess energy back into the grid, creating additional revenue streams for PV system owners. Furthermore, the integration of energy storage can reduce peak demand charges by supplying stored energy during high-demand periods.

- **Environmental Impact:**

Optimizing PV systems through effective energy management directly contributes to environmental sustainability by maximizing the use of clean, renewable energy and reducing reliance on fossil fuels. This leads to a decrease in greenhouse gas emissions and other pollutants associated with conventional energy generation. Enhanced PV system efficiency also means that less land and fewer resources are needed to produce the same amount of energy, reducing the environmental footprint of solar power installations.

- **Energy Independence:**

For remote or off-grid applications, PV systems equipped with robust energy management and storage capabilities can provide reliable and independent power sources. This is particularly beneficial for rural or isolated areas where extending the electrical grid is not feasible. By ensuring a stable supply of electricity, PV systems can support local development, improve living standards, and reduce dependence on external energy sources.

- **Integration with Other Renewable Sources:**

Hybrid systems that combine PV with other renewable energy sources, such as wind or hydro, can offer enhanced energy security and reliability. Effective energy management in these hybrid systems ensures that the strengths of different technologies are leveraged, providing a more consistent and reliable power supply. For instance, during periods of low solar irradiance, wind or hydro resources can compensate, thereby ensuring continuous energy availability.

- **Support for Electrification Initiatives:**

Energy management in PV systems plays a crucial role in supporting electrification initiatives, particularly in developing regions. By providing a reliable and scalable energy solution, PV systems can accelerate the electrification of underserved areas, promoting economic development and improving quality of life. Effective management ensures that these systems can meet growing energy demands and adapt to changing conditions, making them a sustainable long-term solution.

- **Enhanced Grid Integration:**

Advanced energy management techniques facilitate the seamless integration of PV systems into existing power grids. This includes synchronizing PV generation with grid demands, managing intermittency, and ensuring compliance with grid codes and standards. Improved integration helps utilities to better manage distributed generation, enhance grid resilience, and support the transition to a more decentralized energy system[12].

1.6 Conclusion

This chapter comprehensively explored hybrid energy systems, solar cell integration, energy storage systems, and energy management. It highlighted the versatility of stand-alone and hybrid solar systems, examined the efficiency and environmental factors affecting solar cells, and discussed their advantages and disadvantages. The critical features, types, and capacities of batteries were covered, emphasizing their role in energy reliability. Finally, various energy management strategies were presented, showcasing their benefits in enhancing system efficiency and sustainability. Together, these insights provide a holistic understanding of optimizing solar energy systems for maximum efficiency and reliability.

Chapter 2

System Modeling

2.1 Introduction

This chapter delves into the critical components and processes of solar energy systems, providing a comprehensive overview of photovoltaic cell modeling, photovoltaic cell arrays, battery modeling, and the adaptation stage involving various converters and inverters. Beginning with the foundational principles of photovoltaic cell modeling, we explore how solar cells convert sunlight into electrical energy. Following this, we examine the configuration of photovoltaic cell arrays, demonstrating how individual cells are interconnected to generate significant power outputs. The chapter also covers battery modeling, essential for efficient energy storage and management, addressing the intermittent nature of solar power. Finally, we investigate the adaptation stage, focusing on the roles of DC-DC converters, including boost and buck-boost converters, and DC-AC inverters, which are crucial for optimizing energy conversion and ensuring compatibility with diverse electrical systems.

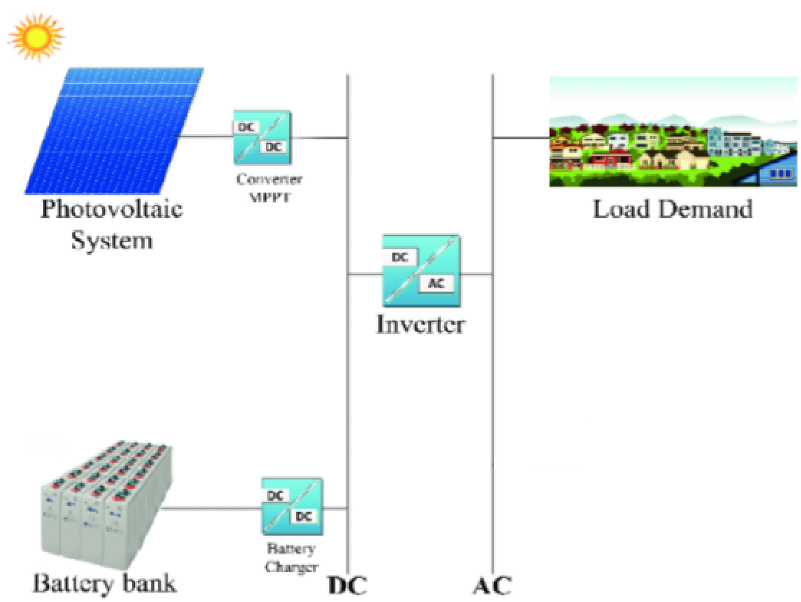

Figure 2.1: Typical Pv System

2.2 Photovoltaic cell modeling

The real photovoltaic module can be represented by the equivalent electrical circuit shown in Figure 2.2, consisting of a current generator that produces a current in parallel with a diode, which models the P-N junction, and two resistances:

- R_s: this is the series resistance that represents the contact and connection resistance.

- R_{sh}: this is the shunt resistance connected in parallel, which represents the leakage current.

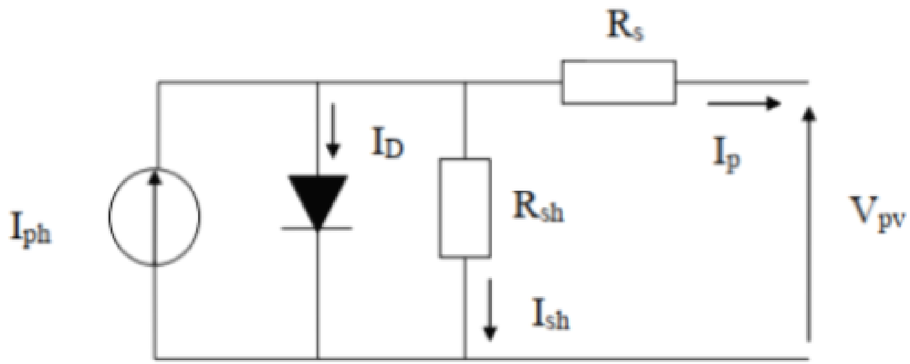

Figure 2.2: Real electrical circuit of the PV module

According to Kirchhoff's law, the relationship of the current generated by the PV module is given as follows:

$$I_{\text{pv}} = I_{\text{ph}} - I_d - I_p \tag{2.1}$$

$$I_{\text{pv}} = I_{\text{ph}} - I_s \left[\exp\left(\frac{V_d}{V_t}\right) - 1 \right] - \frac{V_{rsh}}{R_{sh}} \tag{2.2}$$

$$V_{rsh} = V_d \tag{2.3}$$

$$V_{rsh} = R_s \times I_{\text{pv}} = V_d \tag{2.4}$$

So:

$$I_{\text{pv}} = I_{\text{ph}} - I_s \left(\exp\left(\frac{V_{\text{pv}} + R_s I_{\text{pv}}}{V_t}\right) - 1 \right) - \frac{V_{\text{pv}} + R_s I_{\text{pv}}}{R_{\text{sh}}} \tag{2.5}$$

With:

I: the current supplied by the cell.

Is: the saturation current of the diode.

Iph: photo current produced.

Vt:Thermal voltage at temperature T.

Id:The current flowing through the diode.

R_s: The series resistance

R_{sh}: The shunt resistance

2.3 Photovoltaic cell array

2.3.1 Series connection

In having a number (Ns) of cells in order to increase the voltage of the PV generator, series connection is employed. The cells are then traversed by the same current, and the resulting characteristic of the series grouping is obtained by adding the elementary voltages of each cell [13]. The electrical characteristics of a series connection of cells (Ns) are summarized by the following equation:

$$V_{\text{cos}} = N_s \times V_{\text{co}} \tag{2.6}$$

$$I_{\text{ccs}} = I_{\text{cc}} \tag{2.7}$$

With:
- V_{cos}: the sum of the open-circuit voltages of Ns cells in series.
- I_{ccs}: the short-circuit current of Ns cells in series.

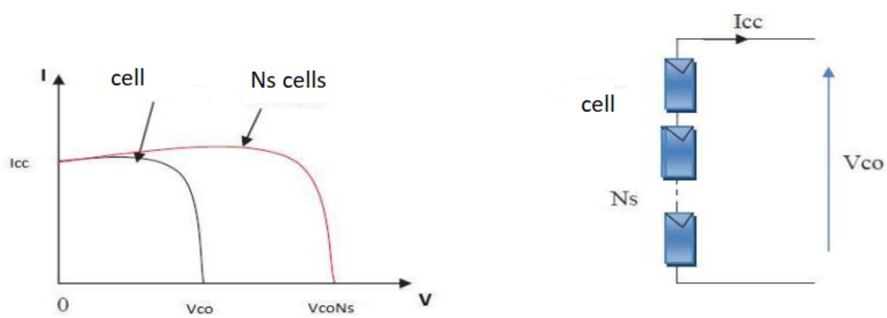

Figure 2.3: Series connections of PV cells

2.3.2 Parallel connection

Having a number (Np) of cells in parallel to increase the current of the PV generator. The cells are subjected to the same voltage, and the resulting characteristic of the grouping is obtained by adding the currents[13]. The electrical characteristics of a parallel connection of (Np) cells are summarized by the following equation:

$$I_{\text{ccp}} = N_p \times I_{\text{cc}} \tag{2.8}$$

$$V_{\text{cop}} = V_{\text{co}} \tag{2.9}$$

With:

- I_{ccp}: the sum of the short-circuit currents of (Np) cells in parallel.
- V_{cop}: the open-circuit voltage of (Np) cells in parallel.

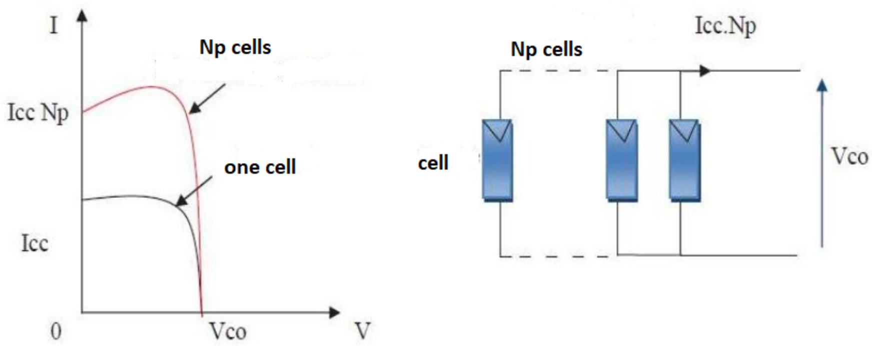

Figure 2.4: Parallel connections of PV cells

2.3.3 Series/parallel (mixed) connections

The series connection of multiple cells forms a cell string where there is an increase in voltage for the same current. Assembling multiple cell strings in parallel forms a module where there is an increase in current and a conservation of voltage [13].

2.4 Battery modeling

The most common type of storage used in a PV system is a lithium-ion battery. Lithium-ion batteries are primarily used to supply and store energy in photovoltaic systems due to their high energy density, efficiency, and longer lifespan compared to lead-acid batteries. The following reactions explain the electrochemical reactions in lithium-ion batteries:

Overall Reaction:

$$\text{LiCoO}_2 + \text{C}_6 \leftrightarrow \text{Li}_x\text{CoO}_2 + \text{C}_6\text{Li}_x \tag{2.10}$$

During each time step, the state of charge (SOC) at time t (per unit) is calculated from the previous time step SOC, adding or subtracting the charge of the battery current:

$$\text{SOC}(t) = \text{SOC}(t\Delta t) + \frac{1}{C_N}\int_{t\Delta t}^{t} I_b(\tau)d\tau \tag{2.11}$$

where:

- Δt is the length of the time step in hours.
- $I_b(\tau)$ is the current that effectively affects the battery charge.
- C_N is the nominal capacity of the battery in Ampere-hours (Ah).
- τ is the time between $t\Delta t$ and t.

The battery current $I_b(t)$ is calculated as:

$$I_b(t) = \begin{cases} I_{bat}(t) \cdot \eta_{bat}^{\text{ch}} & \text{if } I_{bat}(t) > 0 \text{ (charge)} \\ \frac{I_{bat}(t)}{\eta_{bat}^{\text{d}}} & \text{if } I_{bat}(t) < 0 \text{ (discharge)} \end{cases} \tag{2.12}$$

where:

- $I_{bat}(t)$ (positive for charging, negative for discharging) is the battery current.
- η_{bat}^{ch} is the charging efficiency.
- η_{bat}^{d} is the discharging efficiency.

Usually, both efficiencies are considered to be the same, equal to the square root of the roundtrip efficiency.

Lithium-Ion Battery Degradation:

The cycle life of lithium-ion batteries is significantly influenced by the depth of discharge (DOD). According to research, the battery cycle life decreases as the DOD increases, which is consistent with the observed performance in lead-acid batteries but more pronounced due to the different electrochemical properties and design of lithium-ion cells.

The battery voltage at each time step is calculated depending on whether the battery is charging or discharging:

$$V_b(t) = \begin{cases} V_0 - g \cdot \text{DOD}(t) + \rho_c(t) \cdot \frac{I_{bat}(t)}{C_N} + \rho_c(t) \cdot M_c \cdot \frac{I_{bat}(t)}{C_N} \cdot \frac{\text{SOC}(t)}{C_c - \text{SOC}(t)} & \text{if } I_{bat}(t) > 0 \text{ (charging)} \\ V_0 - g \cdot \text{DOD}(t) + \rho_d(t) \cdot \frac{I_{bat}(t)}{C_N} + \rho_d(t) \cdot M_d \cdot \frac{I_{bat}(t)}{C_N} \cdot \frac{\text{DOD}(t)}{C_d(t) - \text{DOD}(t)} & \text{if } I_{bat}(t) < 0 \text{ (discharging)} \end{cases} \tag{2.13}$$

In these equations:

- $V_b(t)$ represents the battery voltage at time t.
- V_0 is the open-circuit equilibrium cell voltage at the fully charged state.
- g is an electrolyte proportionality constant.

- DOD(t) is the depth of discharge at time t.
- $\rho_c(t)$ and $\rho_d(t)$ represent the aggregated internal resistance during charge or discharge.
- M_c and M_d are coefficients related to internal resistance.
- C_N is the nominal capacity of the battery.
- SOC(t) is the state of charge at time t.
- C_c and $C_d(t)$ represent the normalized capacity of the battery during charge or discharge.

The depth of discharge (DOD) can be expressed in terms of the state of charge (SOC) using the equation:

$$\text{DOD} = 100\% - \text{SOC} \tag{2.14}$$

The transformation of active chemicals is proportional to the DOD during charging and discharging once the other operating circumstances are known. Research has shown that a lithium-ion battery's cycle life decreases with increasing DOD, as illustrated by the various studies on lithium-ion battery degradation[14].

2.5 Adaptation stage in solar system

2.5.1 DC-DC converter

A controlled DC output can be supplied from a DC input thanks to the DC-DC converter. As seen in Figure 2.5, they serve as an interface in photovoltaic systems between the PVG and the load. The load will vary because of variations in temperature and radiation because it needs to be changed to meet the solar generator's current and voltage in order to provide the most power. A DC-DC converter is a device used in power electronics that converts one input voltage form to another output voltage for use in switching circuits [15].

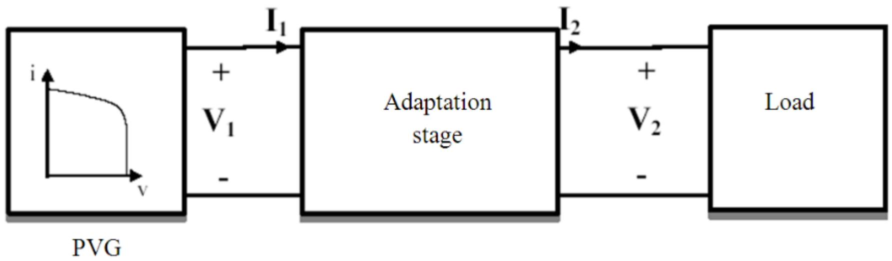

Figure 2.5: Block diagram of a typical standalone PV system

2.5.2 Topologies

Different DC-DC converter topologies exist. They fall into two categories: non-isolated topologies and isolated topologies [16]. By altering the transformer turns ratio, the isolated topologies are utilized for high frequency, small-sized electrical isolation transformers that offer DC isolation between input and output. For these kinds of applications, flyback, half-bridge, and full bridge topologies are common. These kinds are employed when, for safety concerns, electrical isolation is preferred [17].

The non isolated topologies do not have isolation transformer. They are further categorized into three types:

- Buck converters (step down)
- Boost converters (step up)
- Buck-Boost converters (step up and down)

The Table 2.1 illustrates the transformer turns ratio K and duty cycle D with different non isolated topologies.

Table 2.1: Characteristics of Different Converters

Converters	**Transformer Ratio and Duty Cycle**
Buck	D
Boost	$\frac{1}{1-D}$
Buck-Boost	$\frac{-D}{1-D}$

2.5.3 Boost converter

When PV systems are connected to utility mains via an inverter stage, the boost topology is utilized to increase the voltage. The output voltage of this kind of converter is always higher than the input voltage [18]. As a result, the step-up chopper may utilized with MPPT systems in which a higher output voltage than an input voltage is required [19]. In Figure2.6, the circuit topology is displayed.

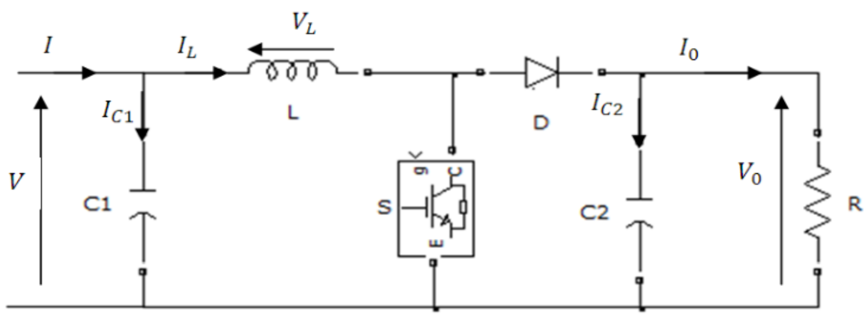

Figure 2.6: Boost converter

- **Waveforms:**

The waveform of the current and voltage of the Boost converter during continuous conduction mode is show below in Figure 2.7 [20].

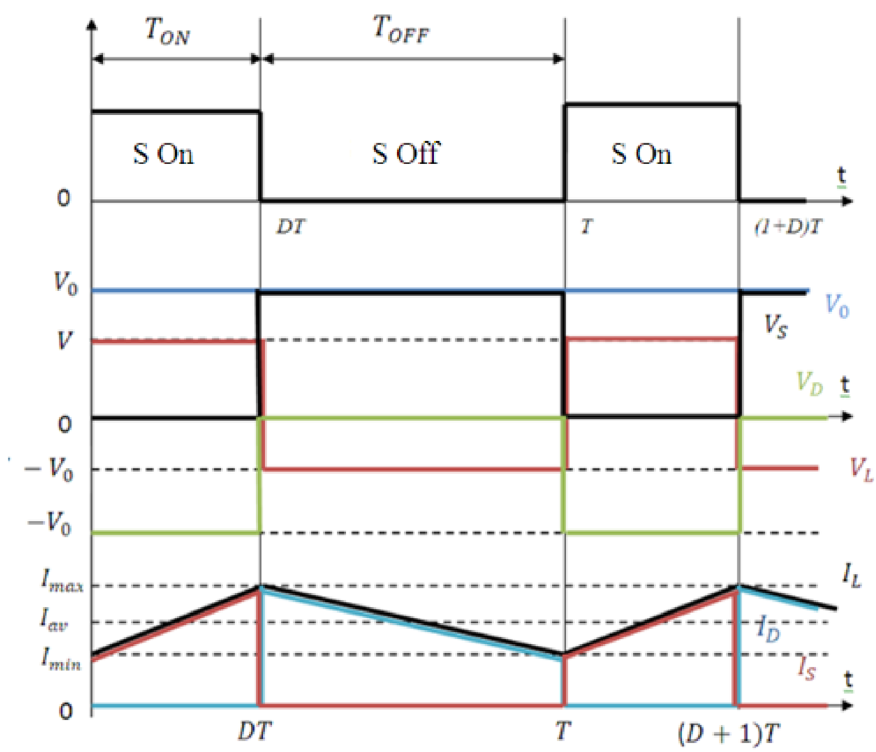

Figure 2.7: Circuit schematic of Boost converter

The diode D is reverse biased from t=0 to t=ton while the switch S is on. As a result, the output stage is isolated and the current in inductor L increases linearly as a result of the input voltage source. On the other hand, the capacitor C is partially discharging and powering the load. In Figure 2.8, the comparable circuit is displayed.

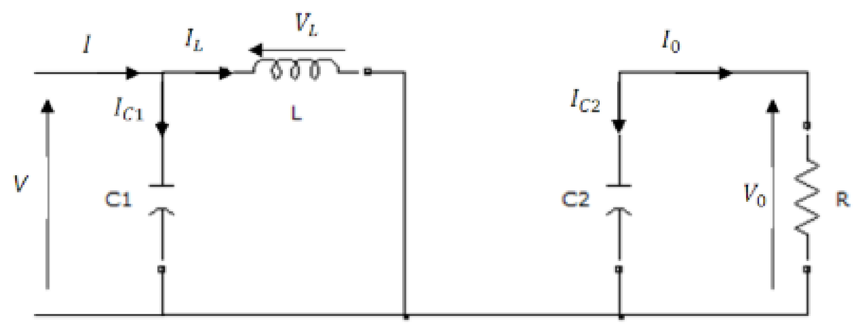

Figure 2.8: Equivalent circuits when S is on

The output stage gets energy from the input source and the inductor simultaneously when the switch S is off, which occurs from t=ton to t=T (duration = toff). In Figure 2.9, the comparable circuit is displayed.

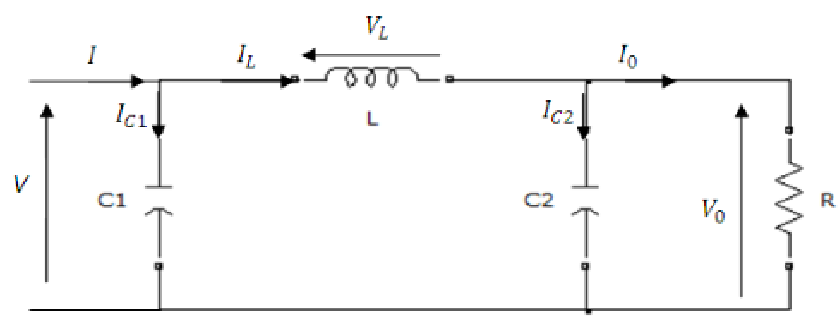

Figure 2.9: Equivalent circuits when S is off

- **Voltage output Calculated:**

Since in steady state time integral of the inductor voltage over one time period must be zero [21]:

$$V_{\mathrm{TON}} = T_{\mathrm{OFF}}(V_0 - V) \tag{2.15}$$

Dividing both sides by T and rearranging items yield

$$\frac{V}{V_0} = \frac{T}{T_{\mathrm{OFF}}} = \frac{1}{1-D} \tag{2.16}$$

Then:

$$V_0 = \frac{1}{1-D} V \tag{2.17}$$

Where:

T: The switching period.

D: The duty cycle.

It's clear from equation 2.19 the value of V0 is greater than that of V, hence the name of Boost.

- **Calculation of I0:**

The diode current is given by [21]:

$$I_D = I_0 + I_{C2} \tag{2.18}$$

Current I0 can be calculated using the following equation:

$$I_{0\,\mathrm{aver}} = I_{D\,\mathrm{aver}} - I_{C2\,\mathrm{aver}} \tag{2.19}$$

Similarly, when S is turned off, the following approximation is used:

$$I_0 = I_{L\,\mathrm{aver}}(1-D) \tag{2.20}$$

- **The ripple current and voltage:**

The inductance voltage is given by:

$$V_{\mathrm{TON}} = L\Delta I_L \tag{2.21}$$

We can determine ΔI_L with:

$$\Delta I_L = \frac{VD}{Lf} \tag{2.22}$$

And the corresponding waveform of voltage $\Delta V0$ is:

$$\Delta V_0 = \frac{DI_0}{fC2} \tag{2.23}$$

Where:
f: is the chopping frequency

2.5.4 Buck-Boost Converter

Bidirectional DC/DC converters serve as an intermediary between a storage device and the DC link, thereby enabling the storage devices to be charged and discharged. Depending on the voltage of the battery, the BDCs can operate in two modes. In the Boost mode, the converter provides power to the DC link when the DC link voltage is greater than the battery voltage. On the other hand, the converter functions in Buck mode, enabling the battery to be charged using any extra power from the DC connection, when the battery voltage is lower than the DC link voltage.

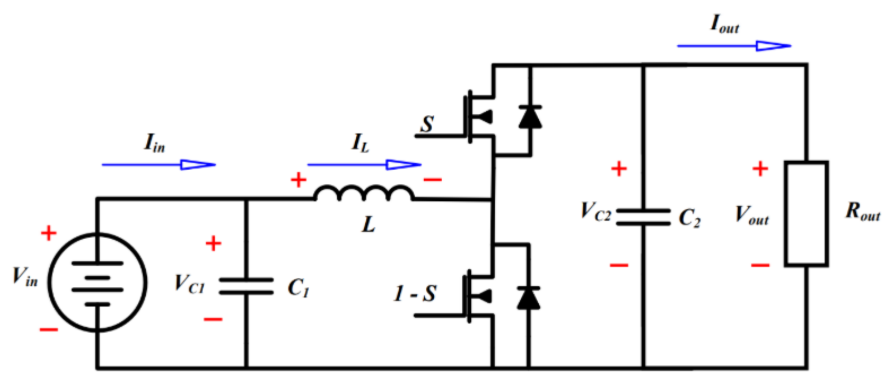

Figure 2.10: Bidirectional Buck-Boost converter

Two switching transistors, two capacitors, and an inductor make up the topology of a BDC converter. The switching transistor's diode is an essential component of the circuit design because it permits bidirectional current flow between the battery storage device and the DC connection. Figure 2.10 [22] shows the bidirectional Buck-Boost converter's circuit schematic. The dynamic state space equations of the bidirectional Buck-Boost converter can be obtained by examining its ON and OFF switching states. The converter's operating behavior is characterized by these equations. Equations can be used to express the dynamic equations of the bidirectional Buck-Boost converter.

$$\frac{dI_L}{dt} = \frac{V_{C1}}{L} - \frac{V_{C2}}{L} \cdot (1 - S) \tag{2.24}$$

$$\frac{dV_{C1}}{dt} = \frac{I_{\text{in}}}{C1} - \frac{I_L}{C1} \tag{2.25}$$

$$\frac{dV_{C2}}{dt} = \frac{I_L}{C2} \cdot (1 - S) - \frac{V_{C2}}{C2.R_{\text{out}}} \tag{2.26}$$

where:

- IL is the inductor current.
- VC1 and VC2 are the voltages across capacitors C1 and C2, respectively.
- S is the switch state.
- Iin is the input current.
- L is the inductance.
- C1 and C2 are the capacitances.
- Rout is the load resistance.

The duty cycle of BDCs can be represented as follow:

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{D}{1 - D} \tag{2.27}$$

In a DC-DC converter, the duty cycle (D) is the percentage of time that the switch is turned on. This equation can be used to calculate it:

$$D = \frac{T_{\text{on}}}{T_{\text{on}} + T_{\text{off}}} \tag{2.28}$$

where TOFF is the switch's OFF time (the moment it is open) and TON is the switch's ON time (the moment it is closed). Typically, $0 \leq \text{D} < 1$ is used to describe the duty cycle as a decimal fraction between 0 and 1. The required output voltage, the input voltage, and the converter's operating parameters will determine the duty cycle's precise value. It can be changed to regulate the DC-DC converter's output voltage or power conversion ratio.

2.5.5 DC-AC Inverter

Three-phase AC power is favored in many industrial and commercial applications because it is more efficient and can run motors, pumps, and other equipment more effectively. A three-phase DC-AC converter Figure 2.11 makes it possible to use in these applications, DC electricity is transformed into three-phase AC power.

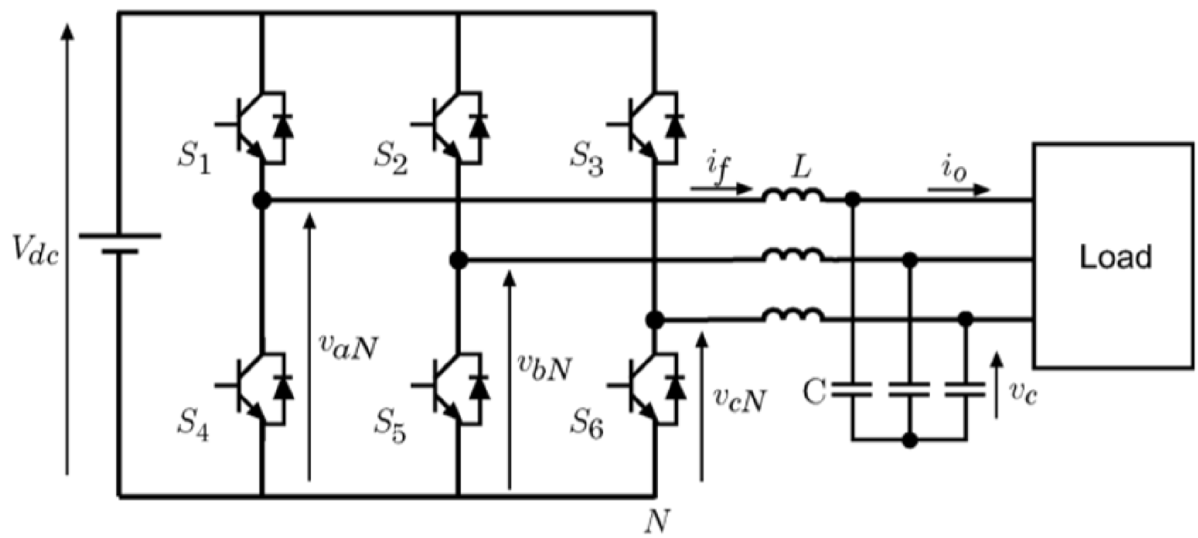

Figure 2.11: DC-AC Inverter.

Six IGBTs are used in a typical three-phase bridge inverter setup; each phase leg is made up of an upper and lower IGBT connected in a bridge configuration. This configuration makes it possible to generate a three-phase AC output and regulate the flow of current in each phase. Figure 2.11 depicts the power circuit of a three-phase voltage-source inverter. In this specific example, the converter and filter models are given, and it is assumed that the load is unknown.

In order to avoid short-circuit scenarios, the two switches in each leg of the converter also work in concert. Consequently, three binary switching signals, Sa, Sb, and Sc, may be used to indicate the switching states of the converter as follows [23]:

$$Sa = \begin{cases} 1, & \text{if } S1 \text{ is ON and } S4 \text{ is OFF} \\ 0, & \text{if } S1 \text{ is OFF and } S4 \text{ is ON} \end{cases} \tag{2.29}$$

$$Sb = \begin{cases} 1, & \text{if } S2 \text{ is ON and } S5 \text{ is OFF} \\ 0, & \text{if } S2 \text{ is OFF and } S5 \text{ is ON} \end{cases} \tag{2.30}$$

$$Sa = \begin{cases} 1, & \text{if } S3 \text{ is ON and } S6 \text{ is OFF} \\ 0, & \text{if } S3 \text{ is OFF and } S6 \text{ is ON} \end{cases} \tag{2.31}$$

2.6 Conclusion

In summary, this chapter has provided an in-depth exploration of the essential elements of solar energy systems, from photovoltaic cell modeling and array configuration to battery modeling and the adaptation stage with various converters and inverters. Understanding these components is fundamental to harnessing solar power efficiently and effectively. Photovoltaic cell modeling and arrays lay the groundwork for substantial power generation, while battery modeling ensures reliable energy storage to mitigate the variability of solar energy. The adaptation stage, with its focus on DC-DC converters and DC-AC inverters, enhances system efficiency and compatibility. Together, these advancements contribute to the development of robust solar energy systems, driving the transition towards a sustainable and renewable energy future.

Chapter 3

Control and Energy Management of the system

3.1 Introduction

In the previous chapter, we extensively modeled and discussed the various components of our Hybrid Renewable Energy System (HRES). In this chapter, we turn our attention to the critical process of managing each component to ensure peak reliability, performance, and efficiency. We will explore control methodologies for overseeing the operation of different HRES components, with a particular focus on the integration of energy storage and photovoltaic (PV) systems. Key elements of effective control strategies include optimizing the power production of PV panels and managing the charge and discharge cycles of batteries. By implementing these approaches, we can achieve efficient and reliable operation of the HRES.

3.2 MPPT Control

It is an electronic setup within the regulator that allows for extracting the maximum energy from a solar photovoltaic installation. The MPPT regulator optimizes the efficiency of solar panels by up to 30% for a given photovoltaic panel, the batteries will receive 30 % more electricity compared to a traditional solar regulator .

PV cells are used to supply energy with the goal of obtaining the maximum power from the panel. An MPPT server is used to control the chopper. This technique has been developed since 1968 and has played a crucial role in the operation of the panel .

The principle of control is to vary the duty cycle D automatically until the optimal value is obtained in order to maximize the panel's power. Regardless of the weather conditions temperature and irradiance , the converter control places the system at the maximum operating point (V_{mpp}, I_{mpp})[24].

- **Perturbation and Observation (P&O) Technique**

The P&O algorithm involves altering the operating point of the PV module by increasing or decreasing the duty cycle of a DC-DC converter and measuring the output power before and after the perturbation. If the power increases, the algorithm continues to perturb the system in the same direction. Otherwise, the system is perturbed in the opposite direction. As the name suggests, this method operates by perturbing the system and observing the impact on the power output of the PV generator [25].

Figure 3.1 shows the 4 possible options presented during MPP (Maximum Power Point) tracking, with point 1 being the previous position and point 2 the current position for each case (A, B, C, and D).

- casA: $\Delta P < 0$ and $\Delta V < 0$
- casB: $\Delta P < 0$ and $\Delta V > 0$
- casC: $\Delta P > 0$ and $\Delta V > 0$
- casD: $\Delta P > 0$ and $\Delta V < 0$

In cases A and C, the duty cycle should be decreased, leading to an increase in the PV module voltage.

In cases B and D, the duty cycle should be increased so that the PV module voltage decreases.

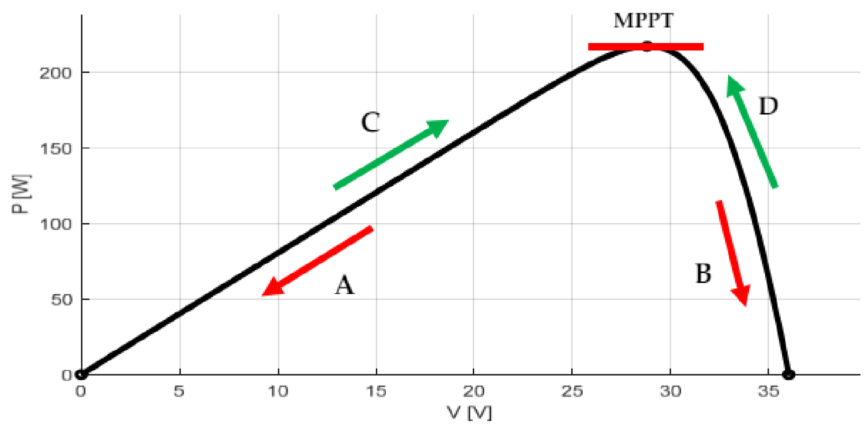

Figure 3.1: The operation of the PO algorithm

The algorithm can be mathematically represented by the expression:

$$V(K) = V(K-1) + \Delta V \,\text{sign}\left(\left. \frac{dP}{dV} \right|_{V=V_{n-1}} \right) \tag{3.1}$$

Condition	**Change in Voltage/ Perturbation ΔV_{pv}**	**Change in Power ΔP_{pv}**	**Action of Next Perturbation Duty Cycle**
1	$\Delta V_{pv} > 0$	$\Delta P_{pv} > 0$	Decrease
2	$\Delta V_{pv} < 0$	$\Delta P_{pv} > 0$	Increase
3	$\Delta V_{pv} > 0$	$\Delta P_{pv} < 0$	Increase
4	$\Delta V_{pv} < 0$	$\Delta P_{pv} < 0$	Decrease

Table 3.1: Perturbation Conditions and Actions [26]

According to the flowchart in the previous figure, the following block diagram has been created:

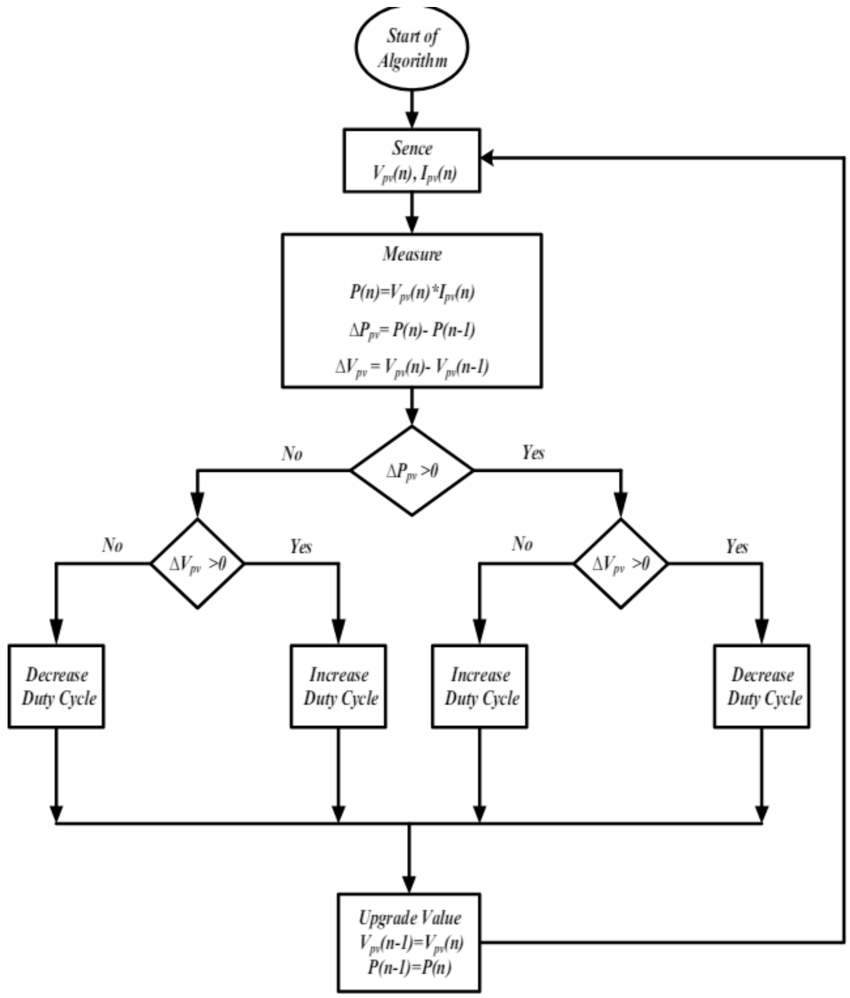

Figure 3.2: Flowchart of MPPT P&O algorithm [26]

3.3 Buck-Boost Converter Control

The control approach of the bidirectional converter is based on controlling the battery's charging and discharging at a predetermined Dc link voltage. The bidirectional DC-DC converter's control mechanism is depicted in Figure 3.3.

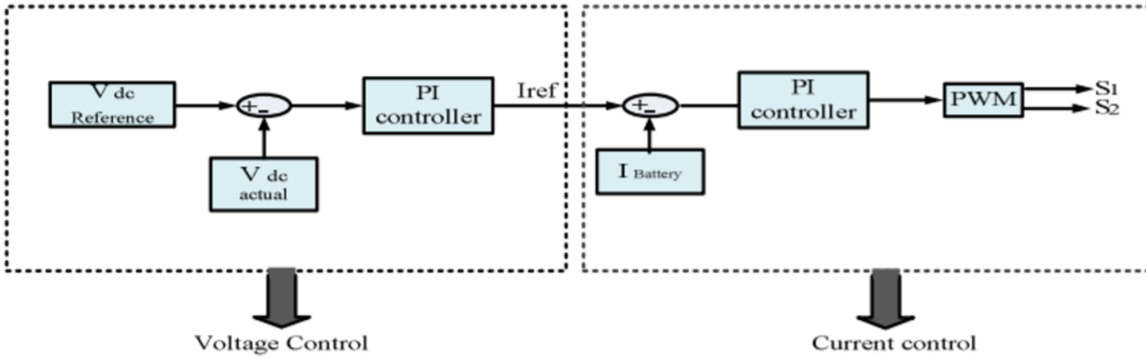

Figure 3.3: Control algorithm for dc-dc buck-boost converter

•Step-down mode (Charging): At greater irradiance, the surplus voltage will exceed the load requirement and the produced voltage will exceed the DC-link reference value. Consequently, DC-link will be used to charge the battery system.

• Step-up mode (discharging): In this scenario, the battery will charge the DC-link to keep its voltage at the reference value since the voltage generated will be lower at lower irradiance than the DC-link voltage. The DC-link PI controller maintains the reference voltage as the load and PV irradiance changes. This is the purpose of the voltage control method used for DC-Link[27].

3.4 Control Function for The Loads

The 'controlLoads' function manages the states of five different switches based on a control variable m and the State of Charge (SoC) of a battery system. The function aims to optimize the load control depending on these parameters.

3.4.1 Parameters

- m: A control variable that determines the operational mode over time. It takes integer values ranging from 1 to 5.

- SoC: The State of Charge of the battery, which is a measure of the remaining capacity of the battery expressed as a percentage.

Output:

- [v1, v2, v3, v4, v5]: An array representing the states of the five switches (loads). Each switch can either be ON (1) or OFF (0).

3.4.2 Detailed Function Behavior

1. **SoC Threshold:**

- The function uses a predefined State of Charge threshold set at 30

- This threshold is used to determine the behavior of the switches when the battery charge is low.

2. **Initial Conditions Based on SoC:**

- If the SoC is greater than or equal to the threshold (30%), the function checks the value of m to determine the states of the switches.

- If the SoC is less than the threshold, the function sets a default state for the switches irrespective of the value of m.

3. **Switch States Determination:**

- Case 1 SoC greater than or equal 30%:

- m = 5: All switches (v1, v2, v3, v4, v5) are turned ON.

- m = 4: Switches v1, v2, v3, and v5 are ON; v4 is OFF.

- m = 3: Switches v1 and v2 are ON; v3, v4, and v5 are OFF.

- m = 2: Same as $m = 3$: Switches v1 and v2 are ON; v3, v4, and v5 are OFF.

- m = 1: Switches v1, v2, and v3 are ON; v4 and v5 are OFF.

- Case 2 SoC less than 30%:

- Regardless of m, switches v1 and v2 are ON, while v3, v4, and v5 are OFF.

By using this function, the system can dynamically adjust the states of the loads based on the battery's State of Charge and the control variable, thereby optimizing power consumption and ensuring efficient battery usage.

This function ensures that critical loads (v1 and v2) are always powered, even when the battery charge is low, while selectively enabling or disabling other loads based on the control variable m when the charge is sufficient.

The MATLAB code that was used for the simulation can be found in Appendix .

3.5 PULSE WIDTH MODULATION

A voltage across the load in a particular pattern is provided by the PWM signal's duty cycle variation, which appears to the load as an AC signal. The signal is sent through a low pass filter to produce a pure sin wave. Either a digital microcontroller or basic analogue components can be used to construct the pattern at which a PWM signal fluctuates in power. Any of the two fundamental Topologies provide sinusoidal PWM, which regulates the inverter's output[28].

3.5.1 BIPOLAR PWM INVERTER

In a single inverter leg, the upper and lower switches operate in a complementary manner, meaning that when one switch is turned on, the other is turned off. Consequently, we only need to consider two independent gating signals, v_{g1} and v_{g3}, which are generated by comparing a sinusoidal modulating wave (v_m) with a triangular carrier wave (v_{cr}). The inverter terminal voltages, denoted as V_{AN} and V_{BN}, are then obtained. The output voltage of the inverter, V_{AB}, is given by the difference $V_{AB} = V_{AN} - V_{BN}$. Since the waveform of V_{AB} alternates between positive and negative DC voltages, this method is referred to as bipolar Pulse Width Modulation (PWM).[28]

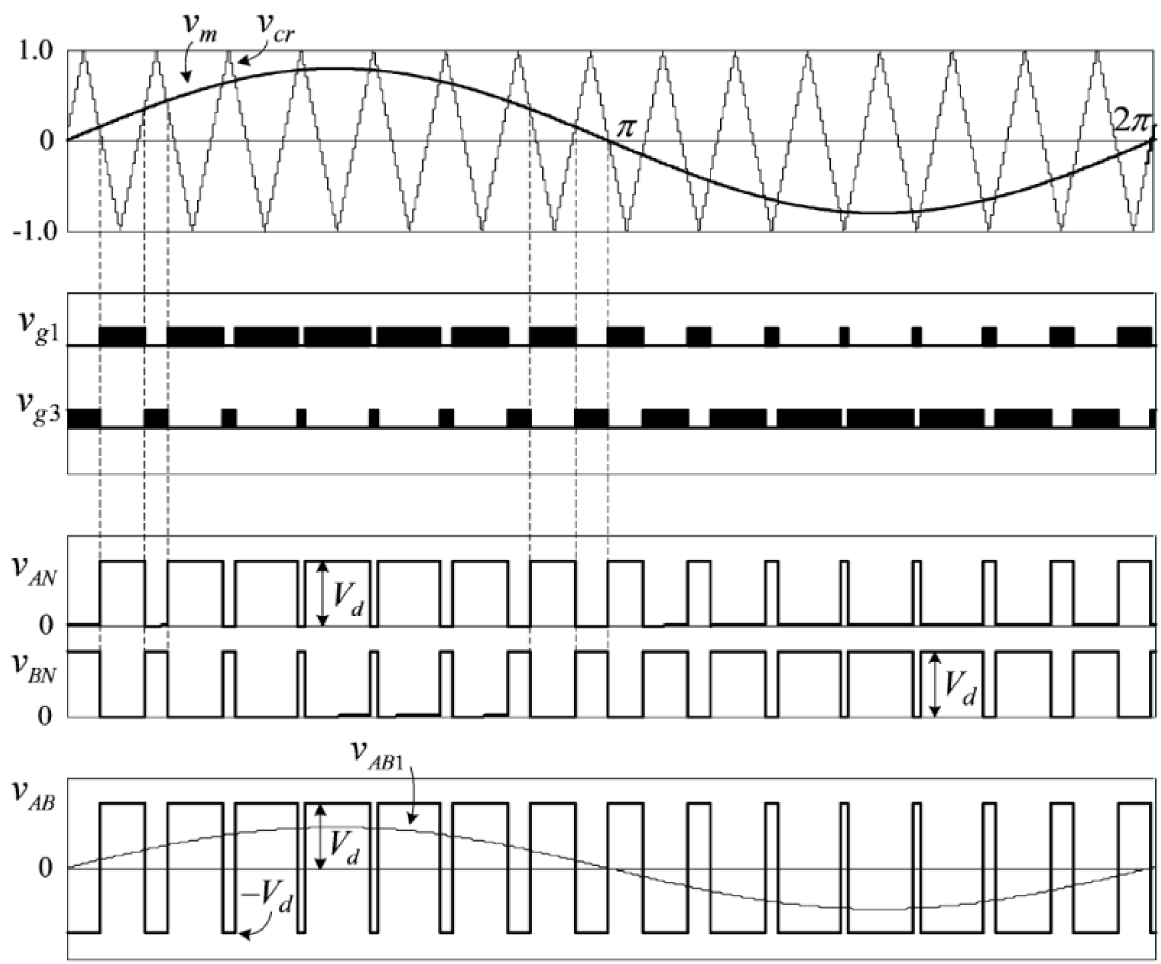

Figure 3.4: Waveforms of Bipolar Modulation Scheme

3.6 CONCLUSION

This chapter focuses on control methodologies essential for the optimal performance of a Hybrid Renewable Energy System (HRES). It covers MPPT control using the Perturbation and Observation (P&O) method to maximize PV panel output by dynamically adjusting the duty cycle. Buck-Boost Converter Control is discussed for managing battery charging and discharging to maintain a stable DC-link voltage, adapting to PV power fluctuations and load demands. The controlLoads function allocates power to loads based on available PV power and battery state of charge, ensuring efficient energy use and prioritizing battery charging when necessary. Additionally, Pulse Width Modulation (PWM) is explained, focusing on bipolar PWM inverters for effective DC to AC power conversion using sinusoidal and triangular wave comparisons to produce stable AC output. These strategies collectively optimize power production, manage energy storage, and ensure stable power conversion, enhancing the HRES's efficiency and reliability .

Chapter 4

Results and Discussion

4.1 Introduction

In this chapter, we present and discuss the simulation results, emphasizing the application of the Energy Management System (EMS) to two distinct scenarios. These scenarios incorporate variations in irradiance levels, photovoltaic (PV) power output, and the state of charge (SOC) of the battery. The primary aim is to assess the accuracy and effectiveness of the energy management strategy implemented in the system, which is controlled using MATLAB functions. The tests were performed within the MATLAB/Simulink simulation environment.

4.2 Methodology

In addition to the MATLAB function introduced in the previous chapter, which accepts inputs such as m and the State of Charge (SOC) of the battery to determine system states, MATLAB Simulink was employed for simulation purposes. Simulink facilitated the integration of these MATLAB functions into a comprehensive simulation environment. This approach allowed for the graphical modeling and simulation of the entire PV and battery standalone hybrid system, enabling detailed analysis and optimization of system performance under various operational conditions. By utilizing MATLAB Simulink, the thesis not only modeled the behavior of individual components but also simulated their interactions to enhance the understanding and reliability of the system design.

4.3 Application

The system comprises various components, including renewable energy resources in the form of a Photovoltaic (PV) system (Solar Array), an Energy Storage System (ESS), three-phase loads, power electronics devices (inverters and converters), an energy management function and we utilize five loads in total: two principal loads, which always operate, and three secondary loads, which operate when needed. The PV model includes a 3.4 kW Solar Array with 8 series modules and 2 parallel strings, as depicted in the I-V and P-V characteristics in Figure 4.1. Detailed PV characteristics are provided in the Appendix. The ESS model features a battery pack with a voltage of 120V and a rated capacity of 250Ah. The state of charge (SOC) of the battery varies in each simulation.

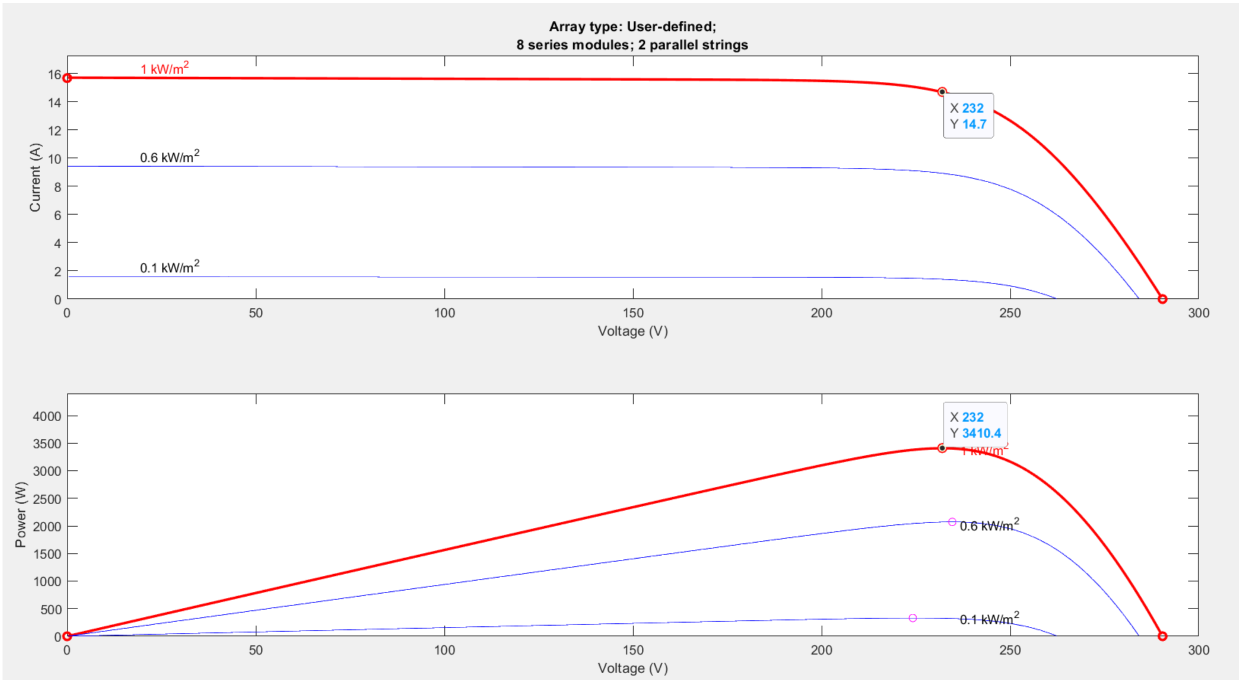

Figure 4.1: PV array V-P and I-V characteristics.

4.4 Simulation of the Scenarios

In this simulation, we are analysing our system under two distinct scenarios based on the state of charge (SOC) of the battery. The first scenario examines the system when the SOC is greater than 30% and the second scenario check the system when the SOC is less than 30%.

4.4.1 First Scenario (SOC greater than 30%)

This situation typically represents a well-charged state. We will discuss how varying levels of irradiance affect the system's ability to utilize solar energy especially the loads . The irradiance is initially set at 1000 $\frac{w}{m^2}$ gradually decreases over time. The state of charge (SoC) is maintained at 70%. The principal loads have an active power rating of 1 kilowatt each, while the secondary loads are rated at 500 watts of active power each. The irradiance levels are shown in Figure 4.2.

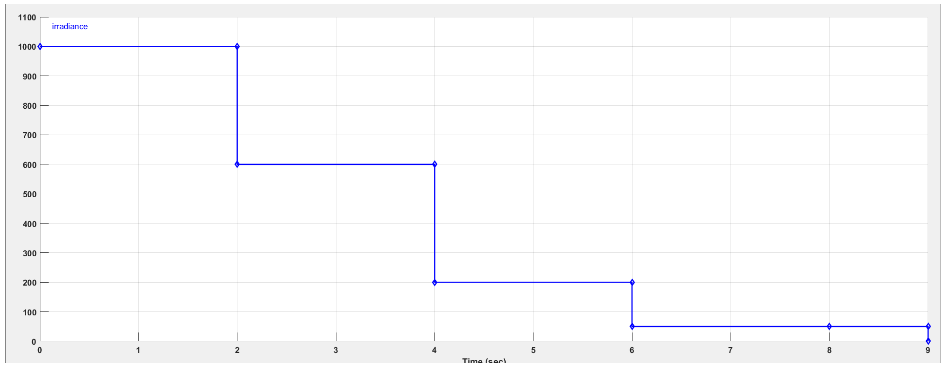

Figure 4.2: Irradiance levels #1

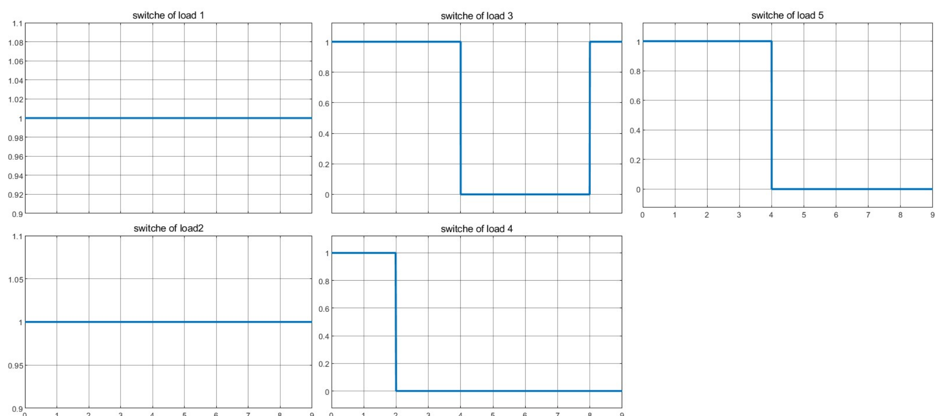

Figure 4.3: Loads switches #1

The status of load switches over time is presented in the following graphs:

- **Switch of Load 1:** Remained ON throughout the simulation.
- **Switch of Load 2:** Remained ON throughout the simulation.
- **Switch of Load 3:** Turned OFF at 4 seconds and back ON at 8 seconds.
- **Switch of Load 4**: Turned OFF at 2 seconds and remained OFF.
- **Switch of Load 5**: Turned OFF at 4 seconds and remained OFF.

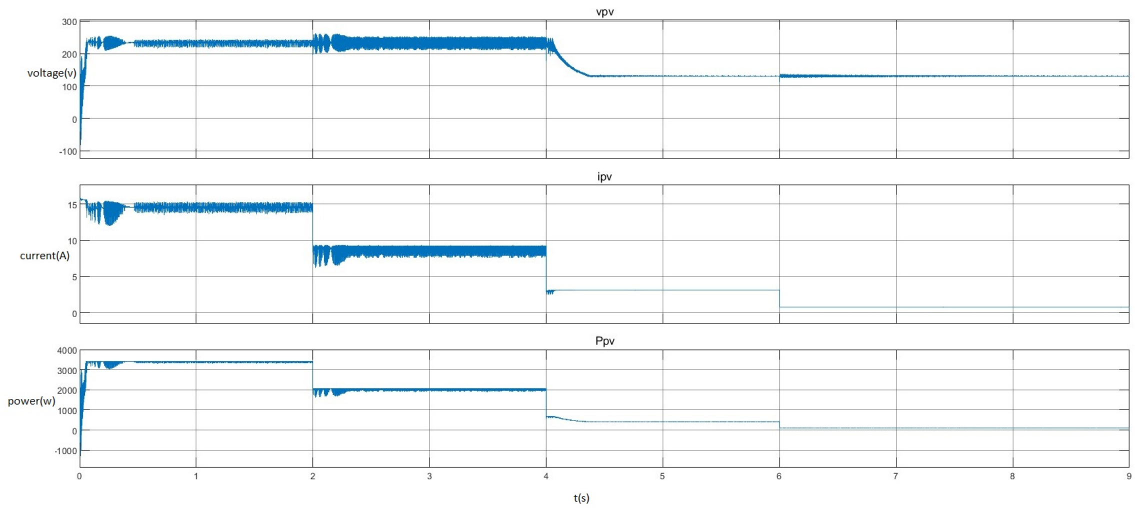

Figure 4.4: PV voltage, current and power 1

Observations:

- **PV Voltage:** Initially stable at around 230V during high irradiance periods. However, as the irradiance decreases to 400 W/m^2, there is a notable drop in the PV voltage. This decrease is due to the Maximum Power Point Tracking (MPPT) controller, which may not effectively track the maximum power point at low irradiance levels.
- **PV Current:** the current is directly proportional to the irradiance.
- **PV Power:** Directly proportional to the product of Vpv and Ipv and to the irradiance decreases.

Discussion:

- From 0 to 2 second: The irradiance level is at its peak (1000 W/m^2), resulting in maximum power generation from the PV system. This is reflected in the high Vpv, Ipv and Ppv values.
- From 2 to 4 second: The irradiance drops to 600 W/m^2. The PV current show a decrease, leading to a corresponding drop in PV power.
- From 4 to 6 second: With irradiance further reducing to 200 W/m^2, the PV current continue to decline, and the PV voltage shows a sharp decline due to low irradiance.
- From 6 to 9 second: The irradiance remains very low (50 W/m^2). The PV voltage stay constant and the current and the power decreases.

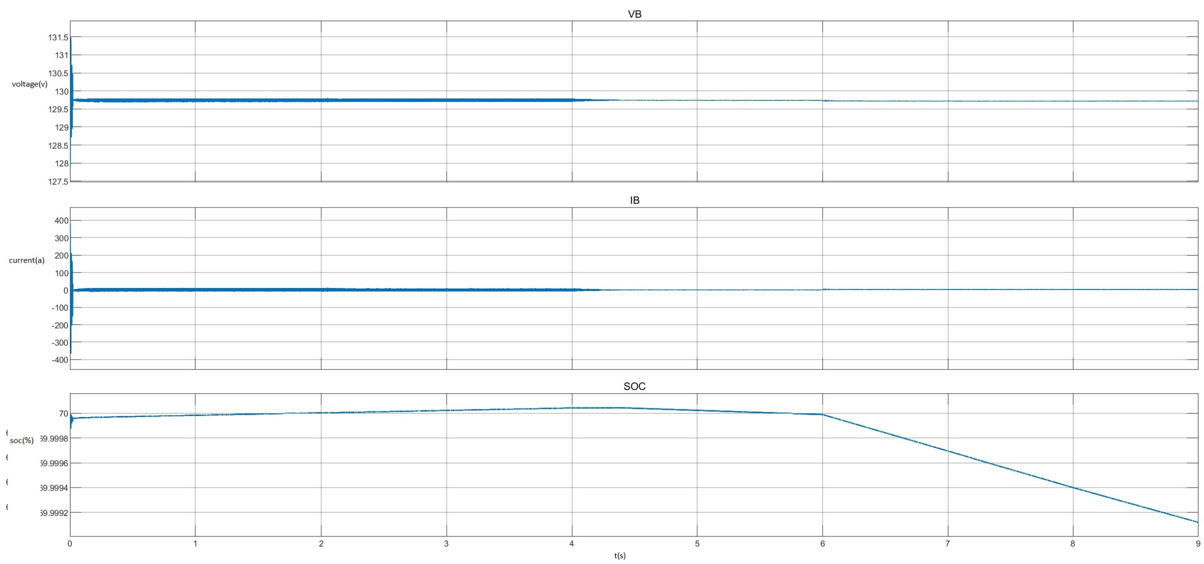

Figure 4.5: Battery voltage, current and state of charge 1

Voltage (VB)
Observations:

- The battery voltage remains almost constant at around 129.5V throughout the time interval.
- There are no significant fluctuations or drops in the voltage.

Discussion:

- The consistent voltage suggests that the battery is well-maintained and operating within a stable range.
- The stable voltage during load switching events, as observed in the previous data, indicates that the battery is effectively buffering the system against transient loads and ensuring continuous power supply.

Current (IB):
Observations:

- The current starts at a high value around 100A and then stabilizes close to 0A for most of the time interval.
- There is a brief period where the current becomes negative, indicating discharge.

Discussion:

- The initial high current aligns with the time when the PV system was generating high power output, indicating battery charging.
- The stabilization near 0A corresponds to periods of balanced power, where PV generation matches the load demand.
- The negative current observed when the loads were switched on indicates that the battery was discharging to meet the additional power requirements, compensating for the reduced PV power output due to lower irradiance or increased load.

State of Charge (SOC):
Observations:

- The SOC starts at around 70% and shows a slight increase initially, indicating charging.
- After reaching 4.5 Seconds, the SOC gradually decreases, indicating discharge.

Discussion:

- The initial increase in SOC corresponds to the high irradiance period, where excess PV power is used to charge the battery.
- The gradual decrease in SOC corresponds to the periods when the irradiance is decreasing, This shows that the battery is effectively discharging to support the loads when PV power is insufficient.
- The SOC remains relatively high throughout, indicating that the system has a good reserve of stored energy to handle load variations and periods of low irradiance.

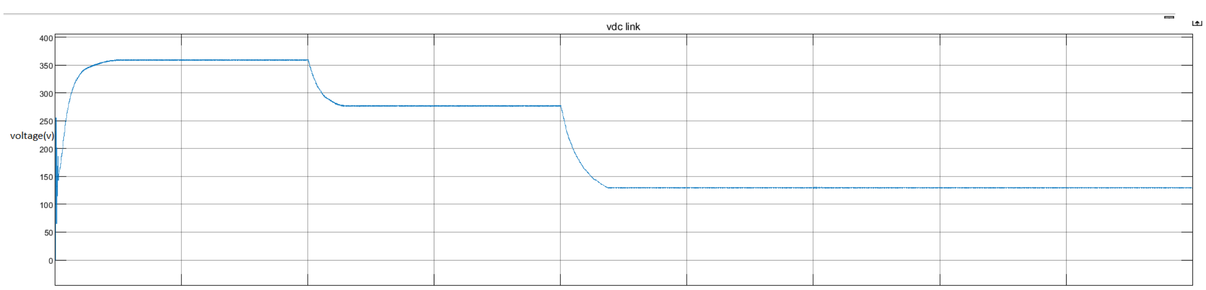

Figure 4.6: Voltage DC link 1

Results from VDC Link Plot:

Initial Increase: The DC link voltage initially increases rapidly from 0 to around 350V. Stable Region: The voltage stabilizes and remains steady at around 350V for a period. First Drop: There is a sudden drop in the DC link voltage from 350V to approximately 250V. Stable Region Again: The voltage stabilizes again at around 250V for a period. Second Drop: Another sudden drop occurs, bringing the voltage down from 250V to around 150V. Final Stabilization: The voltage then stabilizes around 130V and remains constant

Discussion:

The voltage drop in the first time is due to the duty cycle of the boost converter changed when the irradiance changed and the second drop is still due to the duty of boost changed and due to low irradiance caused the MMPT miss track the PV voltage . The ability to stabilize at lower voltage levels means that the battery system is compensating for these changes by discharging.

4.4.2 Second Scenario(SOC less than 30%)

Here, the battery is in a relatively discharged state, requiring careful management to ensure energy availability and system stability. We analyze how changes in irradiance impact the energy capture and storage processes, and the implications for overall system performance.

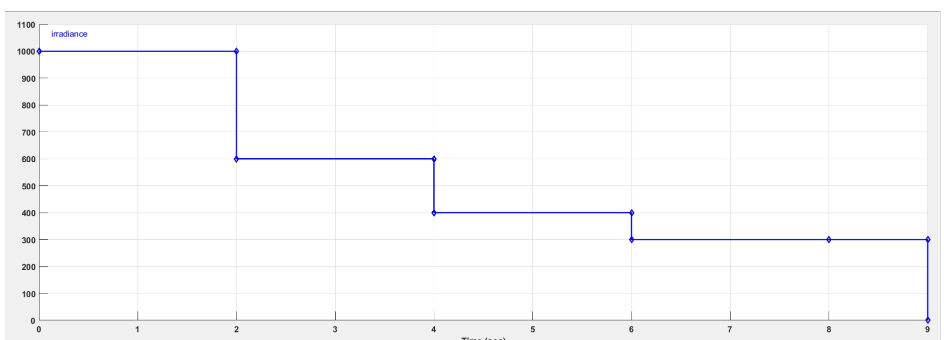

Figure 4.7: Irradiance levels #2

The irradiance profile shows a stepwise reduction over time, starting from 1000 W/m^2 and gradually decreasing to 300 W/m^2. This indicates the varying solar energy input to the PV system over the simulation period. The distinct steps provide a clear indication of how the PV system would perform under different levels of solar radiation.

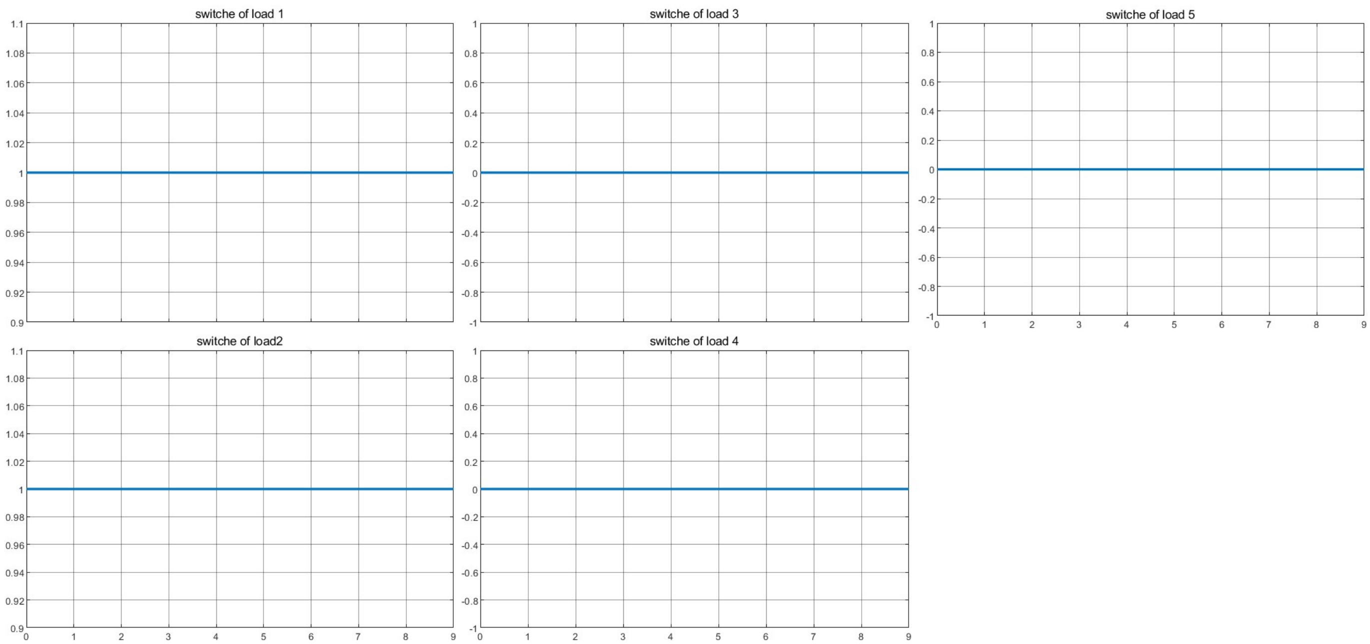

Figure 4.8: Loads switches #2

The graphs for the switches of the loads show the state of each load switch over time. The principal loads (load 1 and load 2) remain on throughout the simulation period, while the other loads (load 3, load 4, and load 5) remain off. We have set the control strategy such that only the principal loads are switched on when the battery SOC is less than 30%.

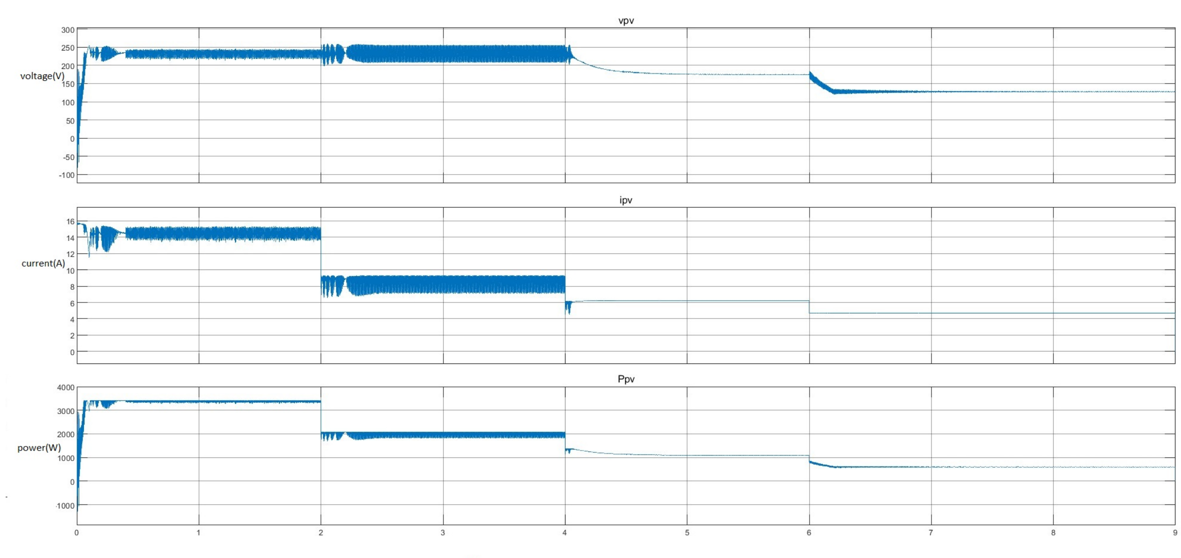

Figure 4.9: PV voltage, current and power 2

The graphs depict the behavior of the PV system's voltage, current, and power during the simulation period.

- **PV Voltage:** Initially stable at around 230V during high irradiance periods. However, as the irradiance decreases to 400 W/m², there is a notable drop in the PV voltage. This decrease is due to the Maximum Power Point Tracking (MPPT) controller, which may not effectively track the maximum power point at low irradiance levels.
- **PV Current:** the current is directly proportional to the irradiance.
- **PV Power:** Directly proportional to the product of Vpv and Ipv and to the irradiance decreases.

Discussion:

- At the start, with high irradiance, the PV system achieves high voltage, current, and power levels. The MPPT effectively tracks the maximum power point, ensuring optimal performance.
- As the irradiance decreases in steps, the PV system's current and power output decrease correspondingly. Each transition period shows a clear adjustment in the system's electrical parameters to match the reduced solar energy input.
- During lower irradiance levels, the significant drop in PV voltage indicates that The P&O method can struggle to accurately track the maximum power point (MPP) under low irradiance conditions. This suggests that the MPPT algorithm might need improvement to better handle low irradiance conditions.

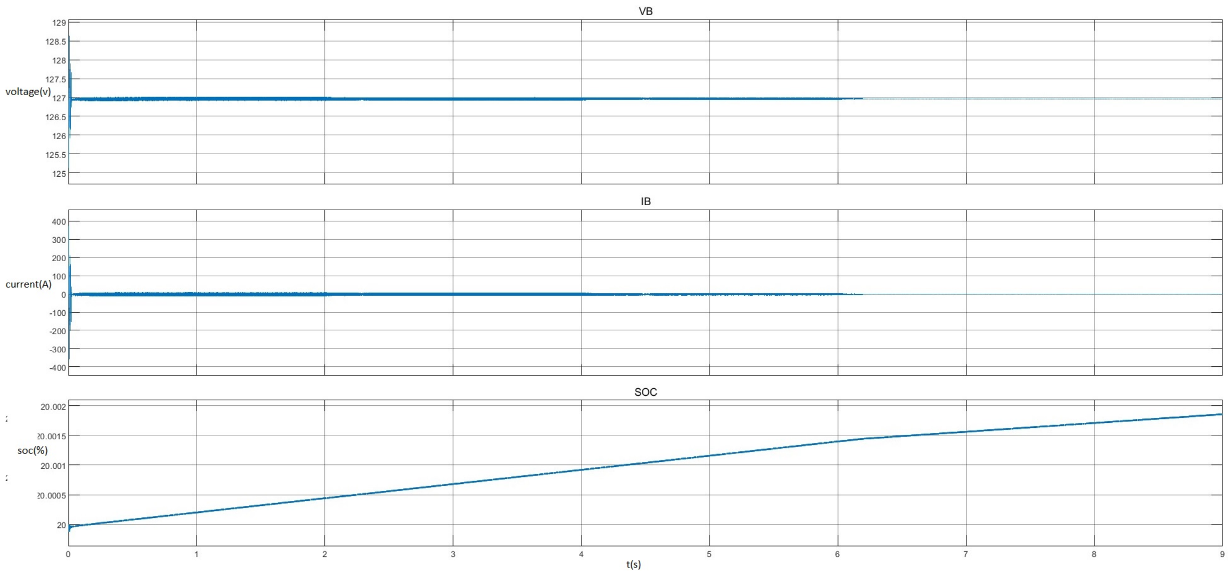

Figure 4.10: Battery voltage, current and state of charge 2

Voltage (Vb)
Observations:

- The battery voltage remains relatively stable throughout the simulation period, hovering around 127V.
- There are no significant fluctuations or drops in the voltage.

Discussion:

- The consistent voltage suggests that the battery control system is effectively regulating the battery voltage, ensuring stable operation.
- The stable voltage during the entire period indicates that the battery is effectively buffering the system.

Current (Ib):
Observations:

- The battery current small negative value, indicating charging activity.

Discussion:

- Given that the control function is set to charge the battery when the SOC is less than 30%, the negative value in current indicates that the system is effectively maintaining the battery in a charged state.

State of Charge (SOC):
Observation:

- The state of charge of the battery shows a gradual increase from 20%, indicating slow charging process.

Discussion:

- The gradual increase in SOC reflects the control function's directive to charge the battery when the SOC is below 30%. The slow rate of increase could be attributed to the limited excess power available for charging after meeting the load demand.

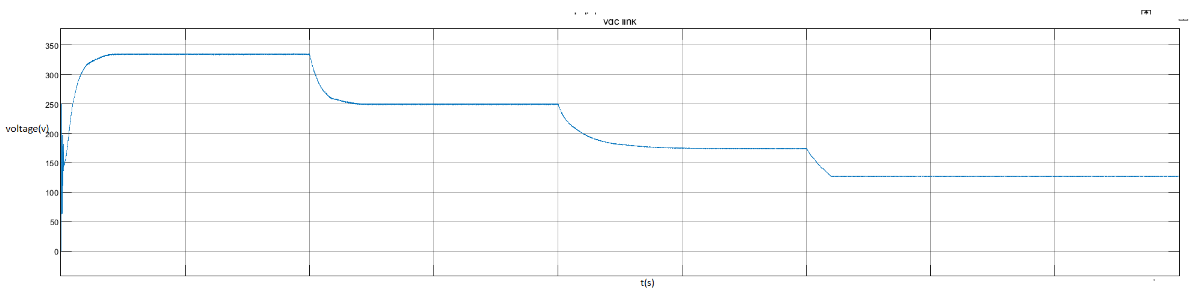

Figure 4.11: DC link voltage 2

Results from VDC Link Plot:

The initial value of the DC bus voltage rises rapidly to around 350V at the beginning (approximately 0.5 seconds). There is a steady phase where the DC bus voltage is maintained at around 350V for a certain period. Several drops in the DC bus voltage can be observed at different intervals (around 2.5 seconds, 4.5 seconds, and 6.5 seconds), each stabilizing at a lower voltage level before rising again slightly and then stabilizing. The final stable value of the DC bus voltage is around 130V.

Discussion:

As we have seen in the previous scenario, the the initial rise in DC bus voltage indicates the system's ability to quickly stabilize the DC bus when the PV generation starts. The step changes in irradiance levels are reflected in the changes in the DC bus voltage. This indicates that the system is responsive to changes in PV output due to varying irradiance. The drops in the DC bus voltage is due to the sudden drop in PV output.

4.5 Conclusion

In conclusion, the simulation results demonstrate that the Energy Management System (EMS) effectively manages the standalone hybrid PV and battery system under varying irradiance conditions and states of charge (SOC). When the SOC is above 30%, the system performs robustly, maintaining stable power output in each period and efficiently shifting between charging and discharging states to support the loads. In contrast, with an SOC below 30%, the system continues to operate reliably, though with reduced PV power generation and notable drops in DC link voltage during low irradiance periods, indicating potential areas for MPPT algorithm improvement. Overall, the EMS proves capable of balancing supply and demand, ensuring system stability and reliability, thereby validating the implemented energy management strategy for standalone hybrid applications.

General Conclusion

The conclusion of this thesis encapsulates the critical elements of energy management in PV and battery standalone hybrid systems, reaffirming the significance of integrating renewable energy sources with efficient storage solutions. Through a structured approach that combines theoretical insights, methodological precision, advanced control strategies, and empirical validation, this research contributes to the advancement of sustainable energy systems.

The findings underscore the importance of accurate modeling to predict system behavior under various conditions, the necessity of robust control mechanisms to optimize energy flow, and the practical implications of implementing such systems in real-world scenarios. By addressing the challenges associated with the intermittent nature of solar power, this thesis highlights the potential of hybrid systems to provide reliable and sustainable energy solutions.

Ultimately, this research aims to support the growth of renewable energy technologies, helping to move towards more sustainable energy practices. The insights from this study are expected to guide future improvements in our hybrid energy system, leading to more efficient and reliable renewable energy setups. Future work could focus on exploring additional scenarios, such as varying geographic locations and load profiles, to better understand the system's adaptability. Improving control functions and Maximum Power Point Tracking (MPPT) algorithms could significantly enhance energy capture and system efficiency. Additionally, connecting to the grid to stabilize the DC link voltage could make the energy supply more reliable and stable. By focusing on these areas, future research can make our system better suited for a wider range of uses and conditions, ensuring they meet the growing needs for sustainable energy solutions.

Appendix

The characteristics of the pv panel is shown in Figure A.1

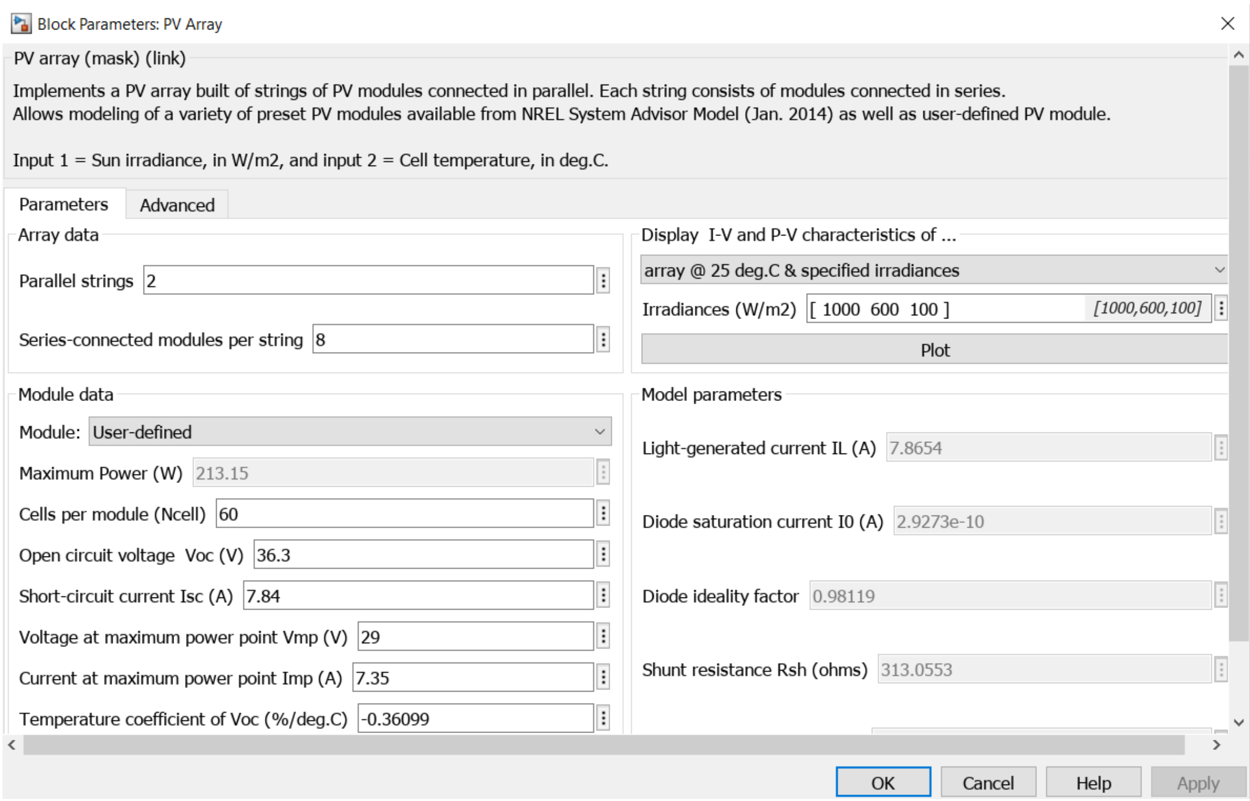

Figure 4.12: PV characteristics

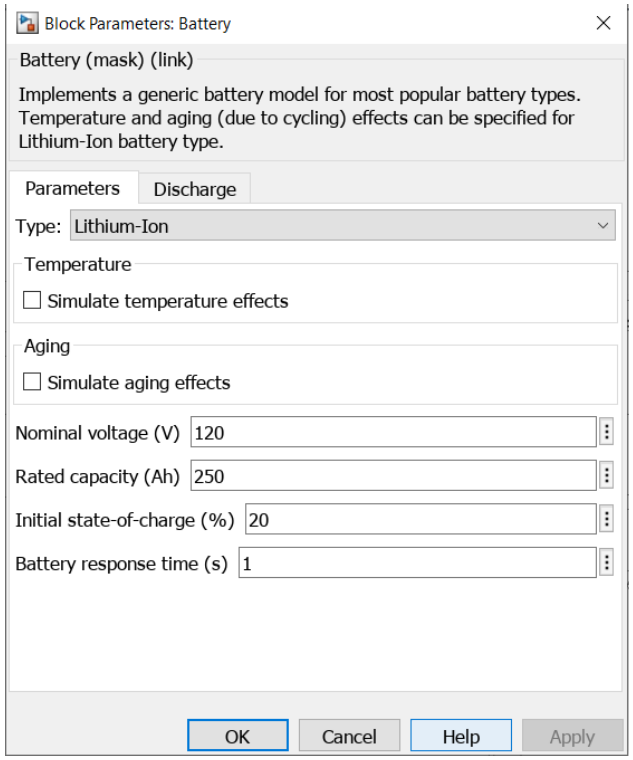

Figure 4.13: Battery pack characteristics.

```
function [v1, v2, v3, v4, v5] = controlLoads(m, SoC)

    SoC_threshold = 30;

    if SoC >= SoC_threshold
        if m == 5
            v1 = 1;
            v2 = 1;
            v3 = 1;
            v4 = 1;
            v5 = 1;
        elseif m == 4
            v1 = 1;
            v2 = 1;
            v3 = 1;
            v4 = 0;
            v5 = 1;
        elseif m == 3
```

```
            v1 = 1;
            v2 = 1;
            v3 = 0;
            v4 = 0;
            v5 = 0;
        elseif m == 2
            v1 = 1;
            v2 = 1;
            v3 = 0;
            v4 = 0;
            v5 = 0;
        else
            v1 = 1;
            v2 = 1;
            v3 = 1;
            v4 = 0;
            v5 = 0;
        end
    else
        v1 = 1;
        v2 = 1;
        v3 = 0;
        v4 = 0;
        v5 = 0;
    end
end
```

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