PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

University Amar Telidji- Laghouat

DOMAIN: Science and Technology

FIELD: Electrical Engineering

Faculty of Technology

Department of Electrical Engineering

OPTION: Electrical Power System

Master's Dissertation

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Theme

Control strategy for a Standalone PV System with Battery-Supercapacitor Hybrid Energy Storage Under Cloudy Days

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Academic Year: 2024-2025

ملخص: تشكل تقلبات الإشعاع الشمسي في الظروف الغائمة تحديًا كبيرًا لموثوقية أنظمة الطاقة الكهروضوئية (PV). تبحث هذه الدراسة في أنظمة التخزين الهجينة للطاقة (HESS)، التي تجمع بين السعة العالية للطاقة في البطاريات والكثافة العالية للطاقة الفورية في المكثفات الفائقة، كحل للمنشآت الكهروضوئية المستقلة. تتبع الدراسة نهجًا منهجيًا يبدأ بأساس نظري حول تقنيات الطاقة الكهروضوئية والتخزين، يليه تطوير نماذج رياضية لمكونات النظام. تأخذ هذه النماذج في الاعتبار العوامل البيئية وتدمج تقنيات تتبع نقطة القدرة القصوى (MPPT). تُجرى محاكاة موسعة لتقييم التوصيلات السلبية وشبه النشطة لأنظمة HESS تحت ظروف مناخية متغيرة، باستخدام استراتيجيات تحكم محسّنة لإدارة تدفق الطاقة، وتقليل إجهاد البطارية، والحد من دورات الشحن والتفريغ غير الضرورية، وإطالة عمر البطارية. تُظهر النتائج أن نظام التخزين الهجين المصمم بشكل جيد يُحسّن بشكل كبير الأداء الديناميكي وموثوقية أنظمة PV أثناء تقلبات الإشعاع الشمسي، مع تعزيز عمر مكونات التخزين. تسهم هذه الدراسة في تطوير استراتيجيات ذكية لإدارة الطاقة، وهي ضرورية لأنظمة الطاقة المتجددة المستقلة والمرنة في إطار التحول نحو الطاقة النظيفة.

الكلمات المفتاحية: الطاقة المتجددة، نظام الطاقة الكهروضوئية (PV)، نظام هجين بطارية–مكثف فائق، تخزين الطاقة، تقلبات الطاقة الشمسية، عمر البطارية،

Abstract: Fluctuations in solar irradiance under cloudy conditions pose a significant challenge to the reliability of photovoltaic (PV) systems. This study investigates hybrid energy storage systems (HESS), which combine the high energy capacity of batteries with the high-power density of supercapacitors, as a solution for standalone PV installations. The study adopts a structured approach, beginning with a theoretical foundation on PV and energy storage technologies, followed by the development of mathematical models for system components. These models account for environmental factors and incorporate maximum power point tracking (MPPT) techniques. Extensive simulations assess passive and semi-active HESS topologies under varying weather conditions, employing optimized control strategies to manage power flow, reduce battery stress, minimize unnecessary cycling, and extend battery lifespan. The results demonstrate that a well-designed hybrid storage system significantly enhances the dynamic performance and reliability of PV systems during solar fluctuations while improving the longevity of the storage components. This work contributes to the development of intelligent energy management strategies, which are essential for resilient and autonomous renewable energy systems in the transition to clean energy.

Key words: Renewable Energy, PV system, Hybrid Battery-Supercapacitor System, Energy Storage, Solar Energy Fluctuations, Battery Lifespan.

Résumé : Les fluctuations de l'irradiance solaire sous des conditions nuageuses représentent un défi majeur pour la fiabilité des systèmes photovoltaïques (PV). Cette étudie les systèmes de stockage d'énergie hybrides (HESS), qui combinent la grande capacité énergétique des batteries à la forte densité de puissance des supercondensateurs, comme solution pour les installations PV autonomes. L'étude adopte une approche structurée, en commençant par une base théorique sur les technologies photovoltaïques et de stockage, suivie du développement de modèles mathématiques des composants du système. Ces modèles prennent en compte les facteurs environnementaux et intègrent des techniques de poursuite du point de puissance maximale (MPPT). Des simulations approfondies évaluent les topologies HESS passives et semi-actives dans des conditions météorologiques variables, en utilisant des stratégies de contrôle optimisées pour gérer le flux d'énergie, réduire le stress des batteries, limiter les cycles inutiles et prolonger leur durée de vie. Les résultats montrent qu'un système de stockage hybride bien conçu améliore de manière significative les performances dynamiques et la fiabilité des systèmes PV en cas de fluctuations solaires, tout en prolongeant la durée de vie des composants de stockage. Ce travail contribue au développement de stratégies intelligentes de gestion de l'énergie, essentielles pour des systèmes d'énergie renouvelable résilients et autonomes dans la transition vers une énergie propre.

Mots clés : Énergie Renouvelable, Système Photovoltaïque (PV), Système Hybride Batterie-Supercondensateur, Stockage D'énergie, Fluctuations de l'Energie Solaire, Durée de Vie de la Batterie.

Dedication

I dedicate this thesis to my beloved family, whose unwavering love, support, and encouragement have been the foundation of my journey.

To my dear parents—your sacrifices, wisdom, and constant belief in my potential have shaped who I am today. Your strength, patience, and tireless efforts to provide me with the best opportunities in life have been my greatest source of inspiration. Without your guidance and prayers, this achievement would not have been possible.

To my wonderful sisters, thank you for being my pillars of strength, for always cheering me on, and for reminding me of my worth during moments of doubt. Your affection, care, and unwavering belief in me have uplifted me throughout every challenge.

To my close friends, who stood by me through the ups and downs of this academic journey, your encouragement, thoughtful conversations, and shared laughter helped me stay motivated and focused.

To my mentors and teachers, your guidance, insight, and belief in my work have been invaluable. You pushed me to think critically and pursue excellence.

This work is a tribute to all of you. Your presence in my life has not only made this achievement possible but has also enriched my personal and academic growth in ways I will cherish forever.

Ikram

Dedication

I dedicate this work to my beloved family, whose unwavering support, encouragement, and sacrifices have been the foundation of my academic journey.

To my parents, for their endless love and belief in me.

To my teachers and mentors, for guiding me with wisdom and patience.

And to all my friends and colleagues, who shared this path with me—thank you for the motivation and companionship.

This achievement is as much yours as it is mine.

Salah

Acknowledgment

First and foremost, I am deeply grateful to **God Almighty** for granting me the strength, patience, and wisdom to complete this thesis. Without His guidance and blessings, none of this would have been possible.

I would like to express my sincere gratitude to my supervisor**, Dr. Youcef Oubbati**, for his continuous support, valuable guidance, and encouragement throughout the development of this work. His expertise and insightful advice have played a crucial role in this research.

I also wish to thank my co-supervisor, **Dr. Halmous Abdelkader**, for his support, helpful suggestions, and availability during every stage of this project.

My heartfelt thanks go to the members of the jury, **Pr. Chettih Saliha** and **Pr. Salem Arif**, for their time, thoughtful evaluation, and valuable feedback. A special note of thanks to **Pr. Salem Arif**, president of the jury, for his kind attention and consideration.

Finally, I would like to express my appreciation to all the professors and academic staff who contributed to my education and personal growth throughout my studies.

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Nomenclature

Abbreviations

PV – Photovoltaic

HESS – Hybrid Energy Storage System

MPPT – Maximum Power Point Tracking

P&O – Perturb and Observe

ESS – Energy Storage System

SOC – State of Charge

BESS – Battery Energy Storage System

DC – Direct Current

AC – Alternating Current

SC – Supercapacitor

IGBT – Insulated Gate Bipolar Transistor

PWM – Pulse Width Modulation

Symbols

V_{oc}– Open-circuit voltage

I_{sc} – Short-circuit current

V_{mpp} – voltage at maximum power point

I_{mpp} – current at maximum power point

P_{max} – Maximum power

V_{PV} – PV array voltage

I_{PV} – PV array current

E – Battery open-circuit voltage

V_{BESS} – Battery terminal voltage

i_{BESS} – Battery current

C_{SC} – Capacitance of supercapacitor

V_{SC} – Voltage across supercapacitor

W_{ESS}– Energy stored in the ESS

D – Duty cycle

q – Electron charge

k – Boltzmann constant

T – Temperature (Kelvin)

A – Diode ideality factor

R_i – Internal resistance of battery

L – Inductance

R – Resistance

C_{PV} – PV output filter capacitance

General Introduction

Global energy transitions increasingly rely on solar photovoltaic (PV) technology as a cornerstone of sustainable electricity generation. The compelling advantages of PV systems—modularity, minimal environmental footprint, and continually decreasing costs—have accelerated their adoption in both grid-connected and standalone applications. Yet the inherent variability of solar irradiance, especially during cloudy periods, remains a fundamental challenge to maintaining reliable power output.

Hybrid energy storage systems (HESS) present an elegant solution to this variability by combining complementary storage technologies. Battery systems offer high energy capacity ideal for extended storage needs, while supercapacitors provide superior power density for managing rapid fluctuations. This technological synergy enhances overall system stability, responsiveness, and durability when properly integrated. Critical to maximizing these benefits is the development of sophisticated control and energy management strategies that optimize the interaction between these storage components, minimizing battery stress while extending system lifespan [1].

Problematic

Despite the increasing deployment of photovoltaic (PV) systems as a renewable energy source, their inherent intermittency, especially under variable weather conditions like clouds, poses a critical challenge to maintaining a stable and reliable power supply. This variability can lead to power fluctuations that affect the performance and lifetime of connected loads and reduce the overall efficiency of the energy system. Traditional battery storage systems, while useful for energy buffering, are often limited in their ability to respond quickly to rapid power changes, and their lifespan can be significantly reduced under frequent charge-discharge cycles.

To address this, hybrid energy storage systems (HESS) that combine batteries with supercapacitors are gaining attention. Supercapacitors are capable of absorbing and delivering high bursts of power over short periods, making them ideal for handling fast transients, while batteries serve as the primary energy reservoir. However, the integration of these two technologies introduces new challenges in terms of system architecture, energy management, and control strategy.

The central question this memoir seeks to answer is:

How can a hybrid energy storage system combining batteries and supercapacitors be effectively modeled, controlled, and integrated with a photovoltaic source to ensure a stable and efficient energy supply under variable irradiance conditions, such as those encountered on cloudy days?

This study aims to address this problem through detailed modeling, simulation, and control of a hybrid PV-HESS system, focusing on optimizing power flow, protecting components, and maintaining system performance in real-world conditions.

Objectives of this dissertation

The main objectives of this dissertation are presented as follows:

- To develop mathematical models for photovoltaic (PV) systems and hybrid energy storage systems (HESS) using batteries and supercapacitors.
- To consider environmental factors and system limitations in simulation scenarios.
- To implement Maximum Power Point Tracking (MPPT) techniques, particularly the Perturb and Observe (P&O) method.
- To design intelligent control strategies for managing power flow between the battery and the supercapacitor.
- To reduce battery stress and extend battery lifespan.
- To simulate and evaluate system performance under realistic conditions, especially during rapid weather changes.
- To compare passive and semi-active HESS topologies.
- To evaluate system efficiency, reliability, and the impact on battery degradation.
- To demonstrate how effective hybrid storage control improves the stability, responsiveness, and longevity of off-grid PV systems.

Dissertation outlines

This Master's dissertation systematically explores the integration of hybrid storage with photovoltaic systems through three interconnected chapters:

Chapter One: establishes the fundamental framework by examining photovoltaic and energy storage technologies, their operational principles, key components, and comparative advantages in renewable energy applications.

Chapter Two: develops comprehensive mathematical models for each system element—the PV generator, battery storage, supercapacitors, and power electronic converters—with particular attention to environmental influence factors and maximum power point tracking methodologies.

Chapter Three: presents detailed simulation analyses and control strategy implementations for PV-HESS integration under variable weather conditions, demonstrating how the control approach significantly enhances system reliability, efficiency, and longevity even during challenging cloudy periods.

Through rigorous modeling, analysis, and simulation, this work demonstrates how strategically designed hybrid storage solutions can transform conventional PV installations into highly resilient and autonomous power systems—a critical advancement for accelerating the global transition to sustainable energy infrastructure

Chapter 1: Photovoltaic and Hybrid Storage Generality

1.1 Introduction

Photovoltaic (PV) energy is generated by converting sunlight directly into electricity using photovoltaic cells, typically made from crystalline silicon. This technology is widely adopted due to its efficiency, reliability, and ongoing advancements. The photovoltaic effect—discovered in 1839 by Edmond Becquerel and later explained by Albert Einstein—forms the foundation of PV energy conversion. Despite its many advantages, solar energy is inherently intermittent, with output varying due to time of day, weather, and location. To ensure a stable and reliable power supply, especially in off-grid systems, effective energy storage is essential. Hybrid energy storage systems (HESS), which integrate batteries and supercapacitors, offer a promising solution. Batteries provide high energy density for long-term storage but have limited lifespans and slower response times. Supercapacitors, in contrast, deliver quick energy bursts and longer cycle life but lower energy capacity. This chapter explores PV energy principles and highlights hybrid storage solutions that enhance system efficiency and reliability.

1.2 Historical

The French physicist Edmond Becquerel first described the photovoltaic effect in 1839, and Einstein explained its mechanisms in 1912. However, it remained a scientific curiosity confined to laboratories until the 1950s. Becquerel discovered that certain materials generate a small amount of electricity when exposed to light. This effect was studied in solids such as selenium by Heinrich Hertz as early as the 1870s. With efficiencies around 1%, selenium was quickly adopted by photographers as a light meter [1].

Rapid progress was made in the 1950s by teams at Bell Laboratories, who manufactured the first crystalline silicon cell with an efficiency of 4% using the Czochralski process. The semiconductor industry played a significant role in the development of solar cells.

The size of PV cells followed the evolution of wafer dimensions in the integrated circuit industry, increasing from 5.08 cm in the early 1970s to 7.62 cm by the late 1970s and reaching 10.16 cm in the early 1980s. This trend changed with the discovery of multicrystalline ingot growth in parallelepiped shapes, which produced square wafers of 10 cm per side. Today, these wafers commonly reach sizes of 12.5 to 15 cm per side [2].

1.3 Photovoltaic solar energy

Photovoltaic energy is based on the photoelectric effect to create a continuous electric current from electromagnetic radiation. This light source can be natural (sun) or artificial (a light bulb). Photovoltaic energy is captured by photovoltaic cells, an electronic component that produces electricity when exposed to light. Several cells can be connected to form a photovoltaic solar module or a photovoltaic panel [3]. The cell is composed of two types of silicon crystals called "doped," one doped "N" and the other doped "P." Doping creates an imbalance between the two layers, one being deficient and the other in excess. The excess electrons will then be brought to circulate between the two layers to find a place. When photons (solar energy) pass through the cell, they cause the movement of electrons from both the N and P layers, leaving their respective zones. This agitation of electrons is the very definition of electricity. The addition of the reactions of all the cells in the solar panel therefore constitutes the raw electricity provided by the panel [3].

1.4 Solar radiation

The Earth's surface receives a significant amount of energy on the order of 180.10^6 GW despite the enormous distance between the sun and the earth (150.10^6 Km), which is why solar energy presents itself well as an alternative to other energy sources as shown in Figure 1.1.

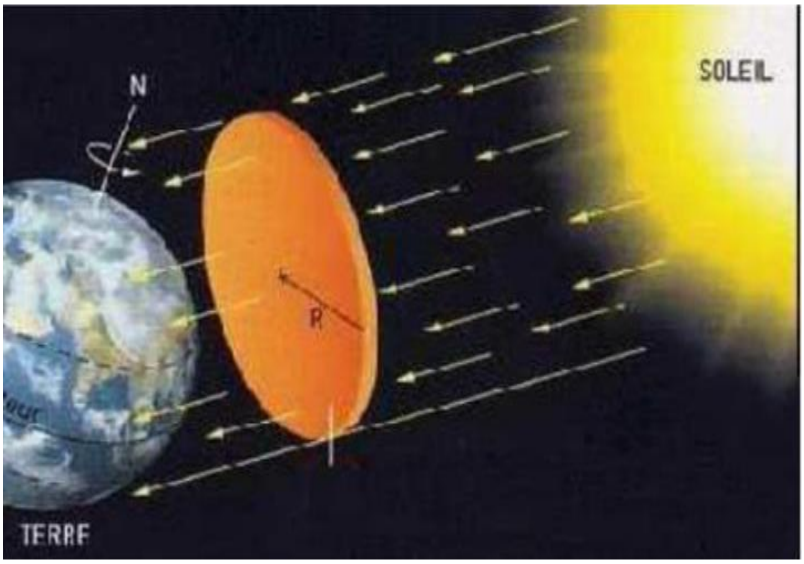


Figure1.1: Solar radiation [4].

This amount of energy will leave its surface in the form of electromagnetic radiation with a wavelength ranging from 0.22 to 10 µm, the energy associated with this solar radiation is approximately broken down as follows:

- 9% in the ultraviolet band (<0.4µm).
- 47% in the visible band (0.4 to 0.8 µm).
- 44% in the infrared band (> 0.8µm).

Over the past ten years, this spectrum has been standardized by the International Organization for Standardization (ISO 9845-1:1992) and the American Society for Testing and Materials (ASTM E 892-87:1992), setting the standard flux at 1000 W/m². This energy is defined as a solar parameter that has a variable value depending on the season, the time of day, the geographical location of the site, and the weather conditions (dust, humidity, etc.) [5].

Figure 1.2 shows a typical solar radiation spectrum and the spectral response of a silicon solar cell. This spectral response or spectral sensitivity defines the range of the radiation at which the cell functions most effectively and influences its efficiency under different radiation conditions. It should be noted that these cells respond primarily in the visible spectrum and the near infrared [6].

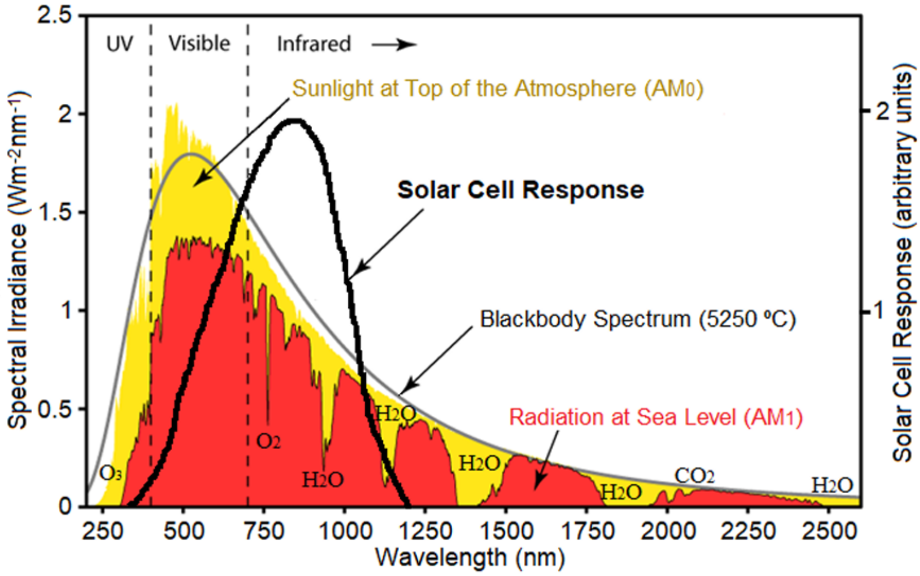


Figure 1.2: Spectral response of a cell (PV) [6].

Note that Figure 1.2 shows not only the spectral distribution of the extraterrestrial solar radiation, with AM0 (AM is the Air Mass coefficient), but also the radiation at sea level with sun directly overhead (0º), with AM1 and a 5250ºC blackbody spectrum. It should be noted that the emission spectrum of the sun can be considered like that of a blackbody with a temperature of approximately 5800 Kelvin. The yellow areas in Figure 1.2 show the energy absorbed by gases present in air, including water vapor, carbon dioxide, ozone and other greenhouse gases [6].

1.5 Different types of solar radiation

a. Direct radiation

Direct radiation is the radiation incident on a given plane coming from a small solid angle centered on the solar disk; it arrives in a straight line and in clear weather.

b. Diffuse radiation

Direct radiation is the radiation incident on a given plane coming from a small solid angle centered on the solar disk; it arrives in a straight line and in clear weather.

c. Global radiation

Diffuse radiation results from the diffraction of light by atmospheric molecules and its refraction by the ground, reaching us from the entire celestial vault.

Global radiation (G) is the sum of diffuse and direct radiation [7].

1.5.1. The PV module

The photovoltaic cell, also known as a solar cell, is the building block of photovoltaic modules. photovoltaic. A photovoltaic panel is made up of several modules, these the latter being composed of several cells in a series to obtain the desired voltage.

The operating principle of a photovoltaic cell consists of a conversion of light energy (solar) into electrical energy: this is the photovoltaic effect, one of the electrical properties of semiconductors as shown in Figure 1.3 [8].

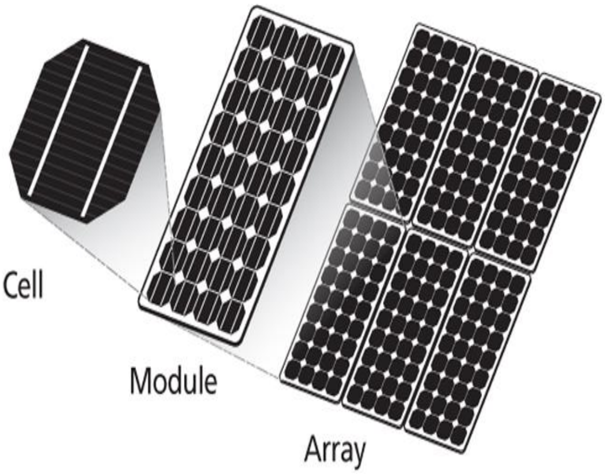


Figure 1.3: Photovoltaic module [9].

1.5.2. Characteristics of a module

A photovoltaic (PV) module is composed of multiple solar cells connected in series and/or parallel to produce a desired voltage and current. The electrical characteristics of a PV module are typically represented by its current-voltage (I-V) curve. This curve reflects how the current output varies with voltage under specific conditions of irradiance and temperature, key parameters include:

- The peak power PC: Maximum electrical power that the module can provide under standard conditions (25°C and an illumination of 1000W/m²).

- Open-circuit voltage V_{oc}: Voltage across the module terminals in the absence of any current, under "full sun" illumination.

- Short-circuit current ISC: Current delivered by a module in short circuit for "full sun" illumination. It is the highest current value generated by a module for zero voltage $V_{pv} = 0$.

- Optimum operating point(U_m, I_m): When the peak power is maximum in full sunlight, $P_m = U_m * I_m$.

- Efficiency: Ratio of the optimal electrical power to the incident radiation power.

- From factor: Ratio between the optimal power Pm and the maximum power the cell can have: $V_{oc} * I_{cc}$ [10].

1.5.3. The photovoltaic panel

The photovoltaic panel or (solar field) consists of photovoltaic modules interconnected in series and/or in parallel to produce the required power. These modules are mounted on a metal frame that supports the solar array at a specific angle of inclination. The most crucial component of any PV installation is the PV module, which consists of interconnected solar cells. These modules are interconnected to form panels and arrays (fields) to meet different levels of energy needs, as shown in Figure 1.4 [10].

Figure 1.4: Photovoltaic panels.

1.5.4. The photovoltaic field

The collection of panels arranged in parallel and series to increase voltage and current is known as the photovoltaic field. We begin by dividing the nominal voltage to be obtained by the voltage at a panel's maximum power point to calculate how many panels to employ in series and parallel [12].

1.5.5. Advantages and disadvantages of photovoltaic energy

Photovoltaic (PV) energy has become one of the most promising renewable energy sources due to its ability to convert sunlight directly into electricity. While it offers numerous environmental and economic benefits, it also comes with certain limitations that need to be considered. Understanding the main advantages and disadvantages of PV energy is essential for evaluating its role in current and future energy systems [13].

1.5.5.1. The advantages

- First, high reliability

- It does not have any moving parts
- Which makes it particularly suitable for isolated regions.

- The modular nature of photovoltaic panels allows for simple installation and adaptability to various energy needs. The systems can be sized for very high-power applications.

- Their operating costs are very low due to reduced maintenance, and they require neither fuel, nor transportation, nor highly specialized personnel.
- Photovoltaic technology has ecological qualities because the finished product is non-polluting, silent, and does not cause any disruption to the environment, except for the occupation of space for large-scale installations.

1.5.5.2. The disadvantages

- The manufacturing of the photovoltaic module involves high technology and requires high-cost investments.
- The actual conversion efficiency of a module is low (the theoretical limit for a crystal-line silicon cell is 28%).
- Photovoltaic generators are only competitive with diesel generators for low energy demands in isolated areas.
- When the storage of electrical energy in chemical form (battery) is necessary, the cost of the generator increases [13].

1.5.6. The photovoltaic generator

The fundamental component of photovoltaic modules is the photovoltaic cell, sometimes referred to as a solar cell. To obtain the required voltage, a solar panel is constructed of many modules, each of which is made up of multiple cells connected in series. The photo-voltaic effect, one of the electrical characteristics of semiconductors, is the process by which light energy (solar) is converted into electrical energy and forms the basis of a photovoltaic cell's operation.

Solar cells with area (10*10) cm^2 or (15.6*15.6) cm^2 are the fundamental building block of PV modules. Modules are connected in series or parallel to form a larger unit called a panel, many panels connected together are called array, as shown in Figure 1.5. Photovoltaic PV applications are divided into two kinds: grid-connected system and standalone system (no connection to the utility grid and with battery for storage or called off-grid system) [14].

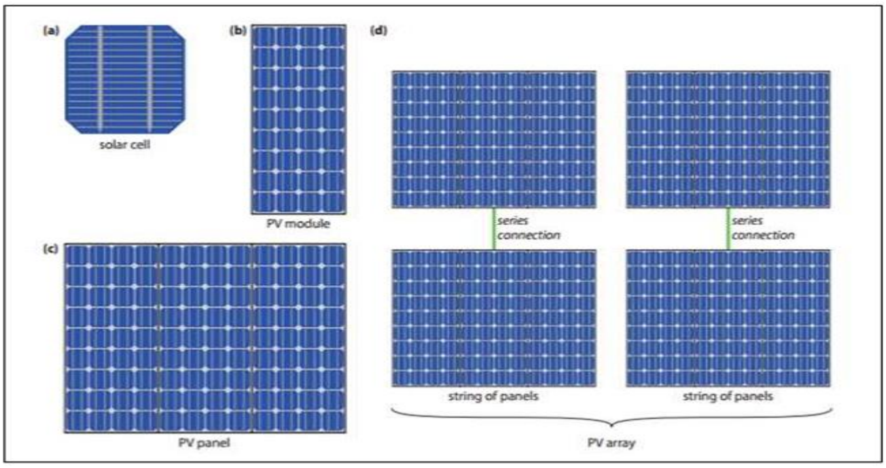


Figure 1.5: Cell, module, panel, and PV field [15].

1.5.7. The photovoltaic cell

Photovoltaic cells are optoelectronic components. They are made using semiconductor materials, that is, materials with intermediate properties between conductors and insulators. Photovoltaic cells are made of semiconductors based on silicon (Si), cadmium sulfide (CdS), or cadmium telluride (CdTe). The most used material for so-called photovoltaic solar cells, so far, especially for terrestrial ones, remains silicon (Si) in various forms (crystalline, multicrystalline, amorphous, thin film, etc.) due to its low cost [16].

1.6. Different technologies

Photovoltaic effects are implemented using a variety of technologies. The research and development stage are still ongoing for many. The two primary technologies that have been industrialized in large quantities thus far are thin-film silicon based on amorphous silicon, or CIS, and mono or polycrystalline silicon, which accounts for over 80% of global production, as shown in Figure. 1.6.

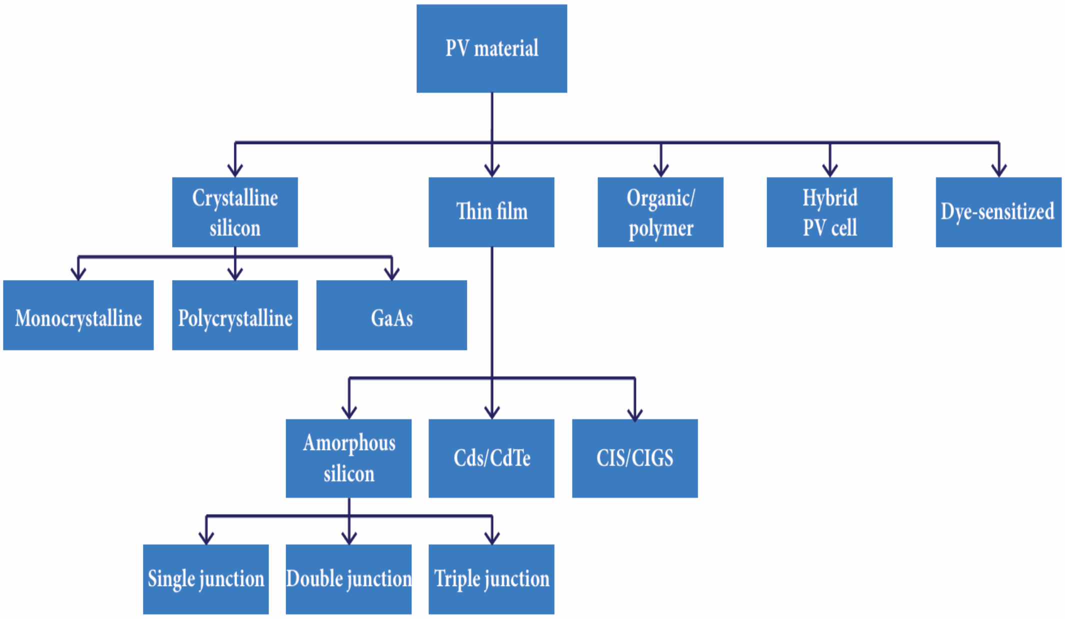


Figure 1.6: Classification of photovoltaic cell based on PV material [17].

1.6.1. Main types of cells

Various semiconductors can be used to create photovoltaic cells. Currently, silicon is the most used semiconductor material in photovoltaic cells, accounting for the majority of PV cell manufacturing worldwide. It is a very stable, non-toxic, and abundant substance. Three categories of photovoltaic cells can be identified based on their characteristics:

a. Monocrystalline silicon

Solar panels composed of silicon condensed into a single crystal are known as monocrystalline cells. Although their production process is intricate and energy-intensive, their efficiency ranges from 12 to 16%, as shown in Figure 1.7 [17, 18].

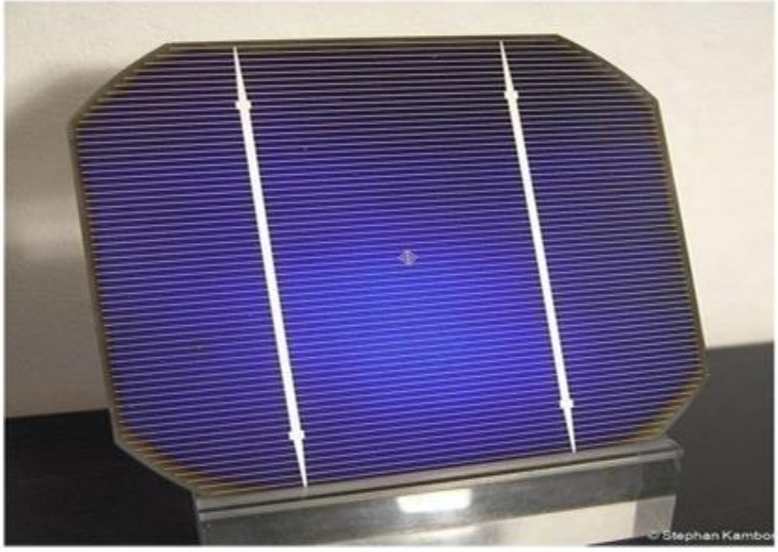


Figure 1.7: Monocrystalline [17].

✓ **Advantages**

- The panels' electrical efficiency ranges from 12 to 16 percent STC.
- Panel power range: 5 to 150Wc
- Range of illumination: 100–1000 W/m²
- Use: all high- and medium-power outdoor applications (e.g., relays, housing, marking, telecoms).

✓ **Disadvantages**

- The first generation of solar cells is a drawback.
- A labor-intensive and challenging production process, which makes it highly costly.
- A pure crystal requires a lot of energy to produce.
- Inadequate performance in low ligh.

b. Polycrystalline silicon

A silicon block that has crystallized into several distinct crystals is used to create polycrystalline cells. They have a somewhat lower production cost than monocrystalline cells and an average efficiency of 11–13% As can be seen in Figure 1.8 [17].

Figure 1.8: Polycrystalline Silicon [17].

- ✓ **Advantage:**

- The panels' electrical efficiency is 11–13% STC.
- Panel power range: 5 to 150Wc
- Range of illumination: 200–1000W/m2.
- Used in the same way as crystalline silicon.
- Modified for mass manufacturing.

- ✓ **Disadvantage**

- As a disadvantage A drawback is that it performs less efficiently than monocrystalline in low-light conditions [18].

c. Amorphous silicon

Very thin layers of silicon are placed to a glass, flexible plastic, or metal substrate to create amorphous cells. Their efficiency ranged from 6 to 10% at first, but technology is advancing quickly. functions well in dim or diffused lighting, including artificial lighting with 20–3000 lux, even in cloudy conditions, as demonstrated in Figure 1.9 [17].

Figure 1.9 : Amorphous Silicon [17].

✓ **Advantage**

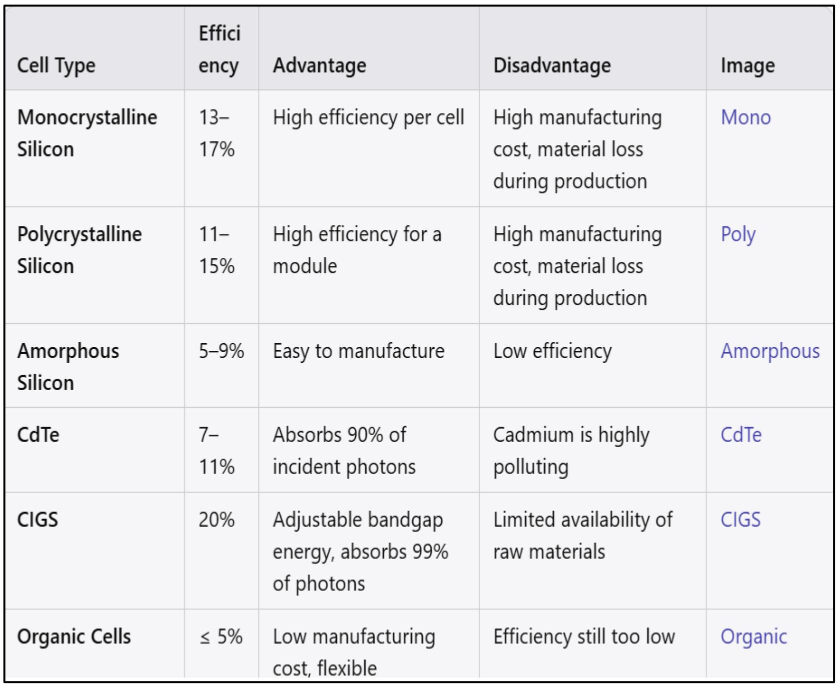
- Electrical efficiency of the panels: 5-7% STC (up to 9% for "multi-junction" panels).
- Illumination range: 20 lux (indoor) to 1000 W/m2 (outdoor).
- Usage: professional and consumer electronics (watches, calculators...), low-powe
- Electronics outdoors, semi-transparent windows.
- A little cheaper than other technologies.
- They work with low light even in overcast weather.

✓ **Disadvantages**

- Low yield in full sun, from 5% to 7%.
- Need to cover larger surfaces than when using crystalline silicon.
- Performance decreases over time during the initial exposure to natural light (3-6 months), then stabilizes (10 to 20% depending on the junction structure) [18].

In Table 1.1 below, we summarize the different performances of the technologies mentioned previously [18].

Table 1.1: Performance of different photovoltaic cell technologies [18].



Cell Type	Efficiency	Advantage	Disadvantage	Image
Monocrystalline Silicon	13–17%	High efficiency per cell	High manufacturing cost, material loss during production	Mono
Polycrystalline Silicon	11–15%	High efficiency for a module	High manufacturing cost, material loss during production	Poly
Amorphous Silicon	5–9%	Easy to manufacture	Low efficiency	Amorphous
CdTe	7–11%	Absorbs 90% of incident photons	Cadmium is highly polluting	CdTe
CIGS	20%	Adjustable bandgap energy, absorbs 99% of photons	Limited availability of raw materials	CIGS
Organic Cells	≤ 5%	Low manufacturing cost, flexible	Efficiency still too low	Organic

1.6.2. Operating principle of the photovoltaic cell

In Figure 1.10, the photovoltaic cell's working principle is demonstrated. Two thin layers of semiconductors, one composed of an N-type semiconductor and the other of a P-type, doped differently, making up the most basic structure of a photovoltaic cell. The cell generates electricity at the intersection of these two levels. The photovoltaic cell's heart is represented by this junction, also known as the PN junction.

When the photovoltaic cell is exposed to sunlight, an incident photon in the P-N junction causes one electron to be knocked out, resulting in the creation of a free electron-hole pair. The N-doped layer experiences an accumulation of electrons under the influence of the electric field, whereas the P-doped layer experiences an accumulation of holes. The photovoltaic effect is the result of this interaction, which causes a difference in the distribution of charges and an electrical potential difference between the cell's two layers. Consequently, by connecting the junction terminals to an external circuit, an electric current can flow [19].

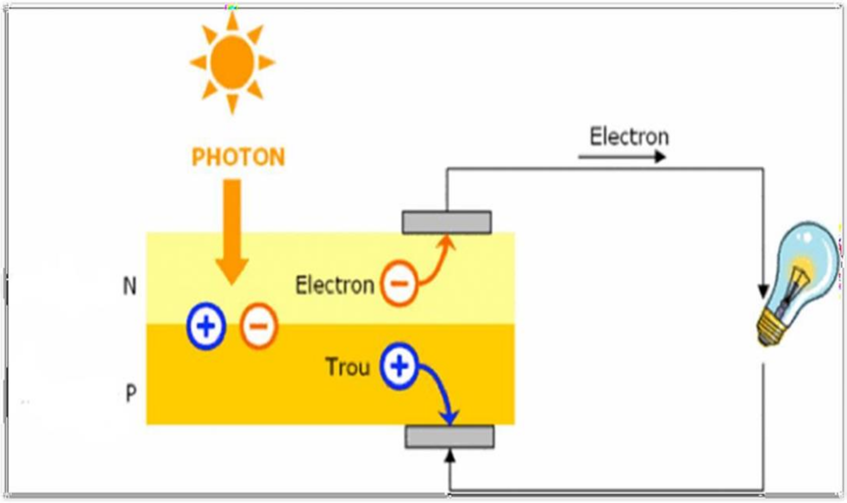


Figure 1.10: Operating principle of a photovoltaic cell [20].

1.7. Series and parallel connection of photovoltaic cells

The series connection: In a series arrangement, the cells are traversed by the same current, and the resulting characteristic of the series arrangement is obtained by adding the voltages at a given current. Figure 1.11 shows the resulting characteristic obtained by connecting ns identical cells in series [21].

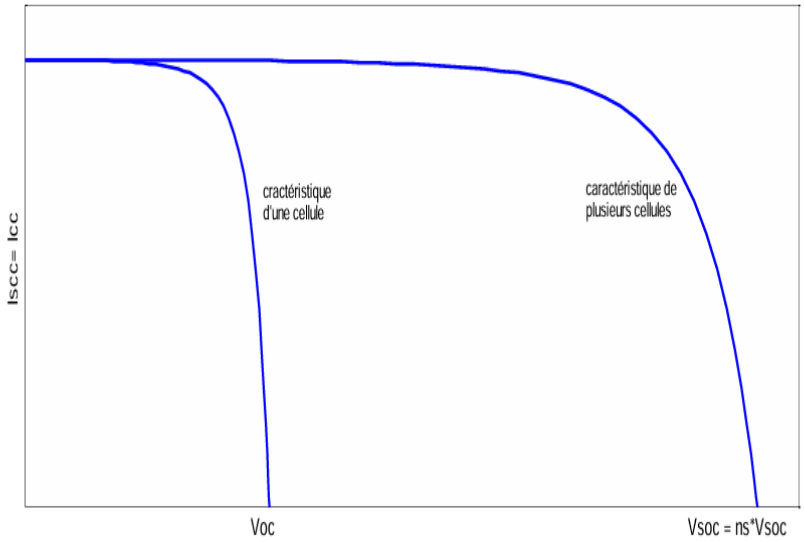


Figure 1.11: Resulting characteristic of a series grouping of ns identical cells [22].

Parallel connection: The characteristics of a parallel cell connection are identical to those of a series cell connection. When cells are coupled in parallel, they are all exposed to the same voltage. The characteristic of the grouping is then determined by adding the currents at a specific voltage, Figure 1.12 shows the result.

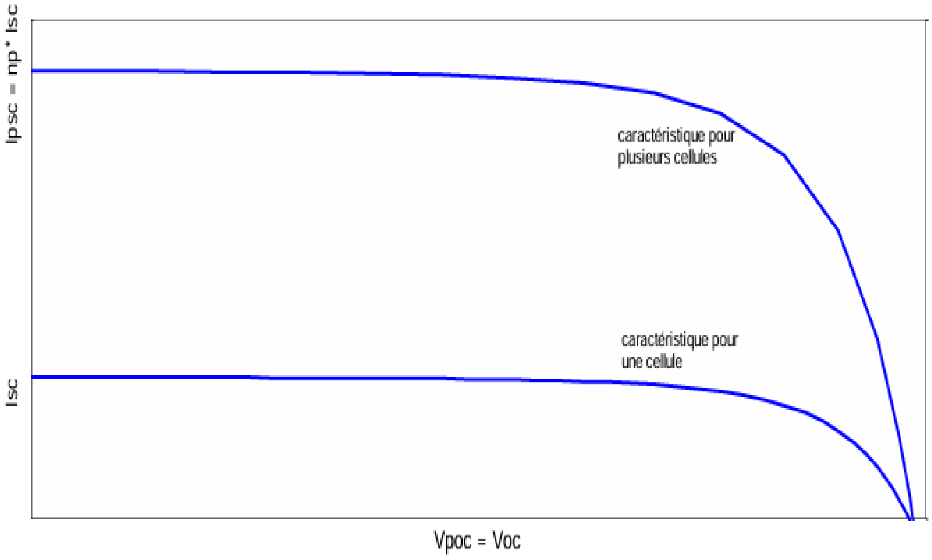


Figure 1.12: Resulting characteristics of a parallel grouping of np identical cells [23].

1.8. Hybrid energy systems

A portion of the energy used by hybrid systems comes from one or more extra sources that are not connected to the electrical distribution networks. The photovoltaic generator is coupled with either a wind turbine, a fuel generator, or both at the same time with energy storage batteries. For applications requiring a steady power supply at a relatively high level, such a system turns out to be a solid option [24].

1.9. The structure of a photovoltaic system

A photovoltaic system is a power supply system that uses photovoltaics to generate electricity; these systems typically have the following components:

- The photovoltaic field is made up of several modules that are arranged and connected in parallel and series to capture solar energy and transform it into low-voltage direct current.
- An accumulator is used to store the energy generated by the generator and make electric current available at night or on overcast days.
- An electronic device called a charge regulator keeps track of batteries' charge levels to prevent overcharging and deep draining.
- An MPPT-controlled converter is an electronic device that ensures the system always operates at maximum power.
- An electronic device known as an inverter makes sure that the input direct current voltage is converted into the output alternating current voltage.
- Charge: usage (consumer) [25].

1.9.1. Advantages and disadvantages of photovoltaic systems

Photovoltaic systems have many advantages and disadvantages, which are [26]:

✓ **Advantages:**

- They are non-polluting with no discernible emissions or odors.
- They can be autonomous systems that run dependably for long stretches of time without oversight.
- They do not need any connection to another energy source or fuel supply.
- They can be combined with other energy sources to increase the reliability of the system.
- They are resilient to severe weather, including ice and snow.
- Their fuel is plentiful and free, and they don't use any fossil fuels.
- High reliability due to the installation's lack of moving parts, which makes it ideal for remote locations and explains why spacecraft employs it.
- Installation of the modular solar panel system can be tailored to meet different energy requirements; the systems can be sized for milliwatt to megawatt applications.
- Photovoltaic technology has ecological qualities because it is non-polluting, silent, and does not cause any disruption to the environment.
- They have a long lifespan.

- The costs and risks of transporting fossil fuels are eliminated.

✓ **Disadvantages:**

- High technology is used in the production of solar modules, which drives up the cost.
- The actual efficiency of a photovoltaic module is around 10 to 15%.
- They rely on the weather for support.
- Since the photovoltaic generator's energy is low voltage (less than 30 V) and continuous, an inverter is required to transform it.
- Many devices sold on the market operate with 230 V alternating current.

1.10. Hybrid storage (battery and supercapacitor)

Electricity must be converted into another type of energy (chemical, thermal, potential, mechanical, etc.) because it is difficult to store. Electrical energy storage is one of the elements of sustainable growth in the future. There are numerous energy storage techniques that fall into one of two groups as represented in Figure 1.13 [27].

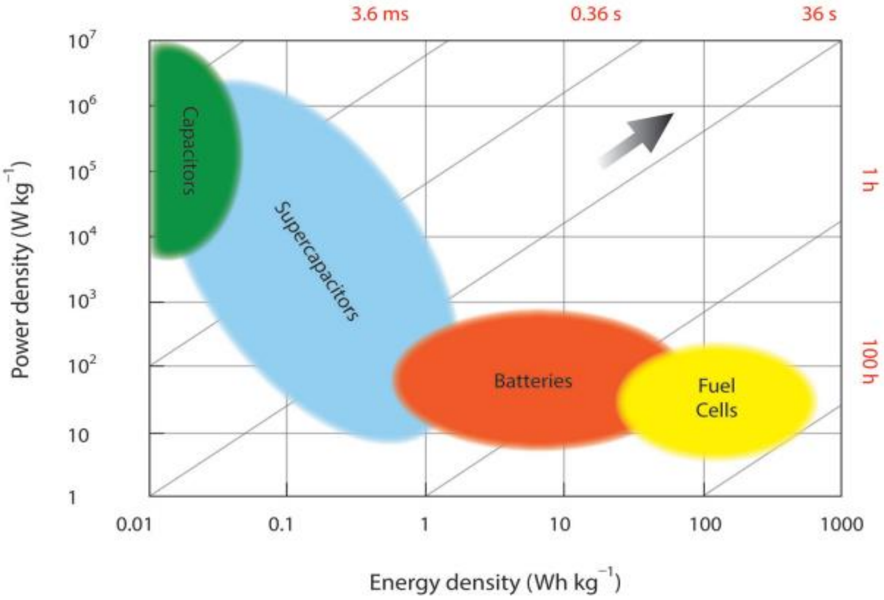


Figure 1.13: Ragone diagram comparing various energy storage systems [28]

• **Long-term storage:** Long-term storage refers to storage techniques where a storage-discharge cycle lasts anywhere from a few hours to many days or even months.

• **Supercapacitors for short-term storage:** (batteries) Short-term storage is defined as storage techniques where a storage-discharge cycle lasts anywhere from a few fractions of a second to many hours.

1.11. Batteries

A battery or electrochemical accumulator is a system that allows the conversion of electrical energy into chemical potential energy during the charging phase and the conversion of chemical potential energy into electrical energy during discharge. It is the chemical modification of the electrolyte that allows this energy to be stored or released.

Each battery is made up of a collection of electrochemical cells that can store electrical energy in chemical form and then release some of it later because the reactions involved are reversible. These reactions include oxidation and reduction (also known as redox reactions, which are the loss or gain of one or more electrons) at the electrodes, while current flows in the electrolyte as ions and in the battery-connected circuit as electrons [29].

1.11.1. Schematic principle of battery operation

Figure 1.14 illustrates the basic operating principle of a battery. It consists of two electrodes—one positive and one negative—immersed in an electrolyte. The positive electrode (cathode) attracts negatively charged ions, while the negative electrode (anode) attracts positively charged ions. A separator allows ion flow but prevents direct contact between the electrodes. During operation, electrons flow from the negative electrode to the positive electrode through an external circuit, powering any connected device. Simultaneously, ions move through the electrolyte to maintain charge balance. This electrochemical process enables the battery to store and supply electrical energy.

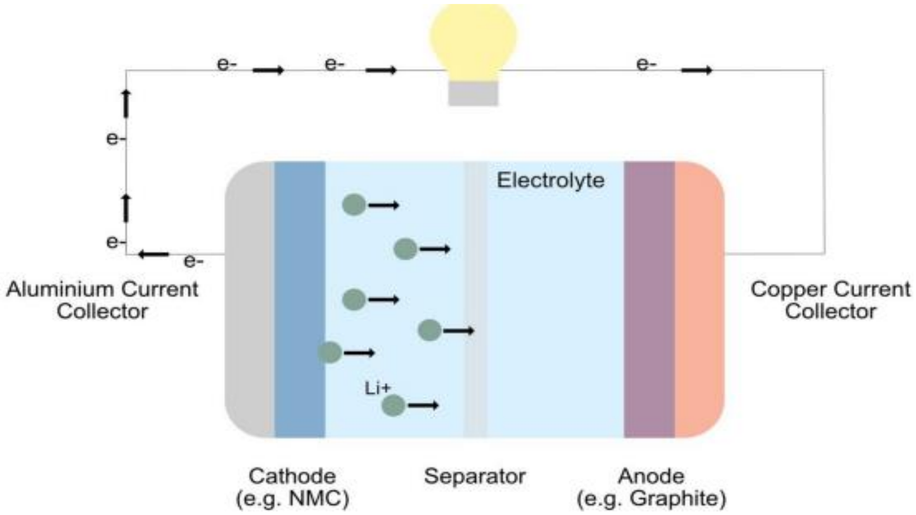


Figure 1.14: Operation of a battery [30].

There are different types of batteries, we can mention:

- Lead-acid battery
- The nickel-cadmium battery
- The nickel chloride sodium battery
- The lithium-ion battery
- The zinc-air battery

1.11.2. General characteristics of batteries

The batteries intended for photovoltaic installations must have the following qualities:

- To be robust have good charge and discharge efficiency
- To have a low internal resistance
- Have a low self-discharge rate
- Reduced maintenance
- To have a large reserve of electrolyte
- To have a long lifespan
- To be suitable for Cycles (by cycle, we mean the discharge of the battery, regardless of the depth of discharge, followed by a recharge)

In this work, our choice is focused on lead-acid batteries due to the advantages they offer [30]:

- The price is cheaper than other types of batteries.
- They are solid.
- able to supply high currents
- Without memory effect.

1.12. Supercapacitor

By polarizing an electrolytic solution, a supercapacitor—also known as a super-capacity or double-layer capacitor—stores energy electrostatically. Hermann Von Helmholtz's 1853 discovery of the capacitance phenomenon marks the beginning of this component's history. In the 1970s, NEC began marketing the first supercapacitors under the moniker "super-capacitors». High surface capacities can be attained with supercapacitors, leading to extremely high-capacity values. Supercapacitors are hence possible supplemental storage components [31].

1.12.1 Structure and operation of supercapacitors

The basic structure of a supercapacitor consists of aluminum current collectors, electrodes generally made of activated carbon impregnated in a zero organic or aqueous electrolyte. A separator is interposed between the two electrodes to isolate them as illustrate in Figure 1.15. The assembly of the entire unit is carried out as for conventional capacitors [32].

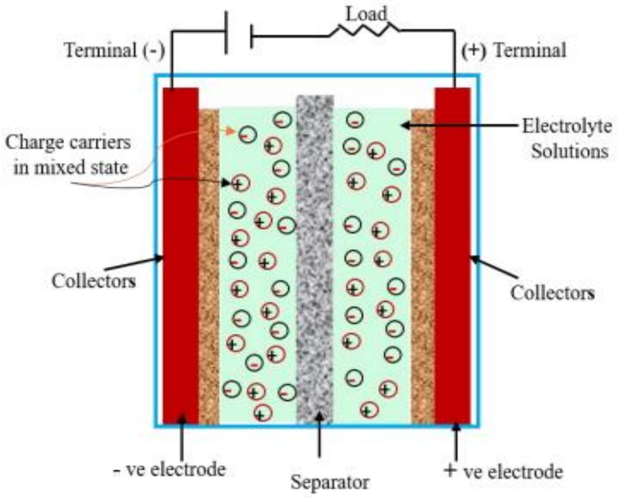


Figure 1.15 : Structure of a supercapacitor [32].

A supercapacitor can be represented by two capacities indicative of the stored charges connected through a resistance associated with the electrolyte as Figure 1.16 represented [33].

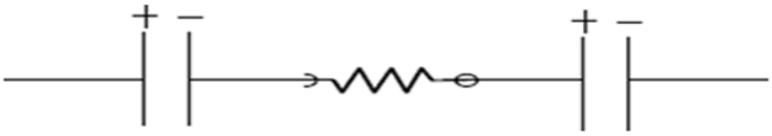


Figure 1.16 : Representative diagram of a supercapacitor [33].

1.12.2 Operating principle of supercapacitors

The creation of an electrochemical double layer at the interface between an electrolyte and a highly specific surface area polarizable electrode is the fundamental working concept of supercapacitors. Charges are electrostatically stored at the two electrode-electrolyte interfaces when a voltage difference is applied across the device's terminals. The four states of the component (discharged, charging, charged, and discharging) can be used to deconstruct the operating principle [34]:

A) State in charge

When a potential difference is applied across the terminals of the supercapacitor, the distribution of charges at the two interfaces will be modified. One of them passes through its zero-charge potential while the other sees the accumulation of charges increase. There is therefore an increase in potential, as we show in Figure 1.17.

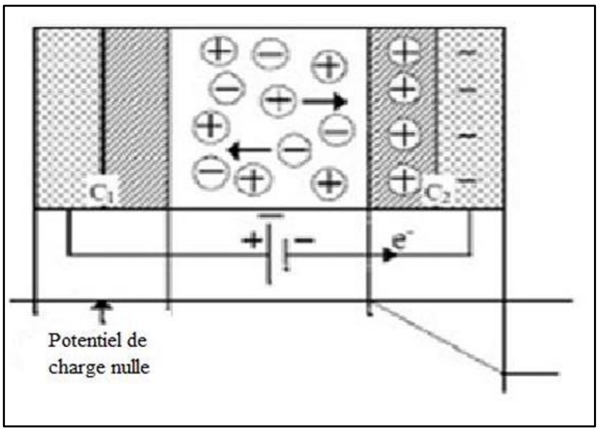


Figure 1.17: Headed load [34].

B) Discharged state:

In the discharged state and without any power supply, a charge accumulation spontaneously occurs at the electrode/electrolyte interface on both the electrode side (qel) and the electrolyte side (qion). Qel and qion are respectively the charges of electronic and ionic nature per unit area.

The condition of electro neutrality imposes qel = - qion. A potential, called the abandonment potential, then appears at each interface; the sign and amplitude of this potential are specific to each electrode/electrolyte pair.

This accumulation of charges corresponds to the electrochemical double layer (its thickness is a few nanometers), Figure 1.18 summarizes that.

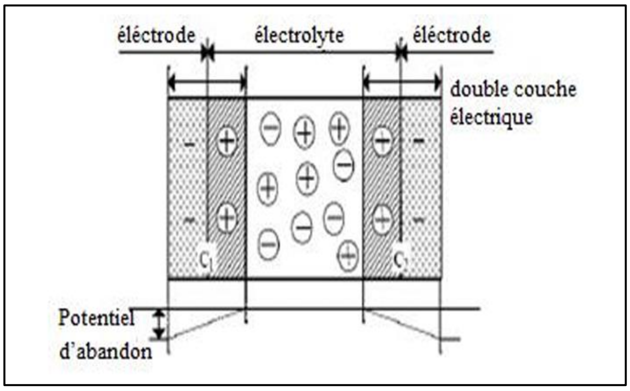


Figure 1.18: Discharged state [34].

1.12.3. Advantages and disadvantages [35]:

- ✓ **Advantages:**

- A longer charge/discharge life cycle than chemical batteries without deterioration in properties.
- High power density (2000-4000W/kg) corresponds to 10 times that of high-power lithium-ion batteries and 100 times that of conventional capacitors.
- High frequency energy collecting capability (regenerative breaking): fast charging frequently damages batteries.
- High capacity (high energy that can be discharged quickly).
- ESR (equivalent series resistance) very low.
- extremely low leakage current (long-term charge maintenance).
- Stored energy greater than that of a conventional capacitor.
- Very fast charging.

- ✓ **Disadvantages:**

- Low specific energy (10 Wh/kg).
- Limited voltage range.
- Technology is less mature than that of batteries.
- More expensive than lead-acid batteries, which are currently quite affordable and practical.
- Specific energy is lower than that of batteries.

1.13 Comparison between batteries and supercapacitors:

Batteries and supercapacitors have extremely different electrical characteristics; we summarize them in the following table:

Table1.2 : Comparison between the battery and supercapacitors [36].

	Battery	**Supercapacitors**
Charging time t	1 hour < t < 5 hours	1s < t < 30s
Discharging time	0.3 hour < t < 3 hours	1s < t < 30s
Charge/discharge efficiency	between 70% and 85%	between 85% and 98%
Power density (W/kg)	$<10^3$	10^4
Energy density (Wh/kg)	between 10 and 100	between 1 and 10
Lifetime (number of cycles)	10^3	10^6

According to the data in the table above, the supercapacitor is a potential element for onboard energy storage as a source for high power demands for a few seconds. The supercapacitor has already found its place in cars for energy recovery and not just in electric vehicles. Indeed, supercapacitors are particularly effective in meeting this need. Capable of charging and discharging very quickly, the supercapacitor presents itself as an ultra-fast and reliable battery [37]. Figure 1.19 presents a comparative diagram illustrating the characteristics of different energy storage devices in terms of specific power (kW/kg) and specific energy (Wh/kg).

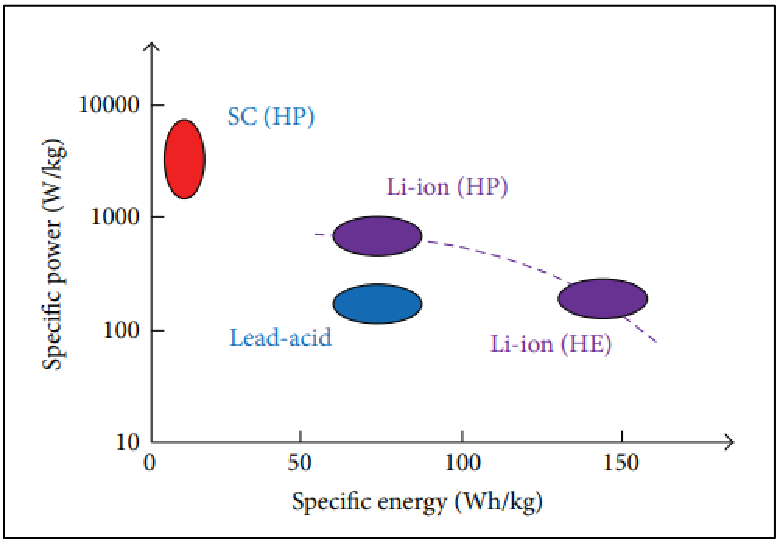


Figure 1.19: Comparative diagram of storage units [36].

1.14. Static converters

To optimize the power output of power sources, static converters transform the direct current supplied by batteries or solar panels into alternating current, or vice versa, or into another direct current [37, 38].

1.14.1. Chopper (DC/DC converter)

DC/DC converters are quite an important part of the conversion chain. They are widely used in connections to accumulator batteries, photovoltaic systems, wind turbines, and hybrid systems. These converters are used to adapt the input voltage of a system to the desired output voltage and can be of the step-down type "Buck", step-up type "Boost", or step-down-step-up type "Buck-Boost".

1.14.2. Series chopper (Buck converter)

A "Buck" converter allows you to convert a direct current voltage into a lower direct current voltage; it is a step-down converter.

1.14.3. Parallel chopper (Boost converter)

A "Boost" converter allows converting a DC input voltage into another DC output voltage, but with a higher value than the input. It is a voltage booster. It is used in PV systems to reduce the number of cells because it allows us to reach the desired voltage level [38].

1.14.4. Buck-Boost Converter

A "Buck-Boost" converter is a switching power supply that converts a direct current voltage into another direct current voltage of lower or higher value but with opposite polarity.

The output voltage is opposite in sign to the input voltage. When the switch (S) is in the (on) position, the current in the inductor increases, energy is stored, whereas, when the switch (S) turns to the (off) position, the voltage across the inductor (L) is reversed, the stored energy is transferred to the load (R) via the diode (D) [38].

1.15. Conclusion

In this chapter, we have provided a general overview of the technique for converting light energy into electrical energy based on photovoltaic cells. To do this, we presented the different types of photovoltaic systems and the functioning of the elements belonging to the conversion chain of this system, including the hybrid storage we used, specifically batteries and supercapacitors. For the proper functioning and utilization of this energy, we have also introduced an energy management system, where the sizing and operation of the components of the overall system must consider load variations. For this purpose, we study and model the conversion and storage chain as well as the evaluation and control of the entire system in the following chapters.

Chapter 2: Modeling of Different Parts of the Studied System

2.1 Introduction

The growing global energy demand and the need to reduce carbon emissions have increased interest in renewable energy sources. Among these, the photovoltaic (PV) generator stands out as a promising solution due to its availability, modularity, and low environmental impact. However, its efficiency is significantly influenced by environmental conditions such as solar irradiation, temperature, and partial shading, as well as by the energy management strategies employed.

This chapter begins by introducing the basic principles of the photovoltaic generator and its role in solar energy conversion. It then presents the main components of a PV system, focusing on their mathematical modeling and functional importance. Special attention is given to the photovoltaic cell, whose electrical characteristics are analyzed to develop an accurate model for simulating real-world performance.

We also examine the implementation of Maximum Power Point Tracking (MPPT) algorithms, which are crucial for maximizing energy extraction from the PV system. Additionally, we discuss the integration of energy storage elements—specifically batteries and supercapacitors—and present models that describe their interaction with the PV generator. Finally, the influence of varying climatic conditions on PV panel performance is analyzed to assess their impact on system efficiency and reliability.

2.2 Electrical model of a photovoltaic generator

Photovoltaic (PV) cells are the fundamental building blocks of solar energy systems, responsible for converting solar radiation directly into electrical energy via the photovoltaic effect. For accurate analysis and control of PV systems under varying environmental conditions, it is essential to adopt a mathematical model that effectively represents the electrical behavior of a PV cell. Among several modeling techniques, the single-diode equivalent circuit remains the most used due to its practical balance between simplicity and accuracy [39, 40] as show in Figure 2.1.

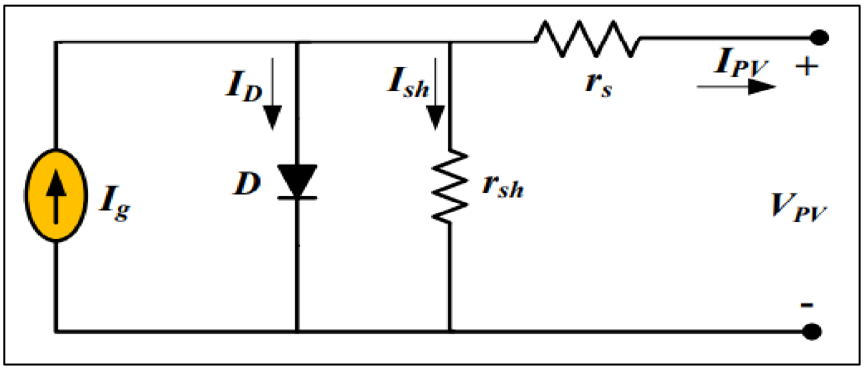


Figure 2.1: Equivalent circuit of PV cell [39].

In this model, the PV cell is represented by a current source corresponding to the photogenerated current (I_g), a diode that characterizes the nonlinear response of the p-n junction, a series resistance (r_s) accounting for ohmic losses, and a shunt resistance (r_{sh}) modeling leakage currents. The net output current (I_{PV}) from the PV cell is derived from the difference between the generated current and the sum of the diode and shunt currents, as shown in Equation (1):

$$I_{PV} = I_g - I_D - I_{sh} \tag{2.1}$$

The value I_g represents the illumination current, I_{sh} represents the shunt resistance current, and I_D represents the diode current.

Equation (2.1) forms the basis of the PV cell model by describing the fundamental current flow relationships. It is later expanded by incorporating the physical properties of the diode and resistances to fully describe how I_{PV} depends on external conditions such as temperature and irradiance.

The complete nonlinear behavior of the PV cell can be expressed using the following equation:

$$I_{PV} = n_p I_g - n_p I_o \left[exp \left(\frac{q\left(V_{PV} + \frac{I_{PV} r_s n_s}{n_p}\right)}{n_s n_c A k T} - 1 \right) \right] - \frac{V_{PV} + \frac{I_{PV} r_s n_s}{n_p}}{\frac{r_{sh} n_s}{n_p}} \tag{2.2}$$

where V_{PV} represents the PV array's output voltage, q has been the electron charge, T is the solar panel's temperature, n_p is the total number of PV panels in parallel, n_s is the number of PV arrays in series, n_c is the number of series-positioned PV cells, k symbolizes the Boltzmann constant, A is the diode's ideality factor, r_{sh} and r_s are the series and shunt resistance.

2.3 Battery Modeling

The mathematical model for the battery used in this study is based on a fundamental battery model that includes the State of Charge (SoC). The model is designed to precisely simulate the voltage behavior of a Battery Energy Storage System (BESS) under varying charging and discharging conditions, while accounting for the multiple factors that affect the battery's performance, as illustrated in Figure 2.2 [41, 42].

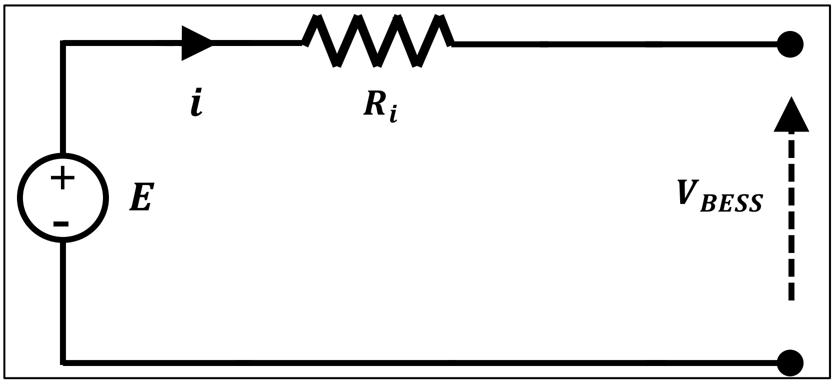


Figure 2.2: The simplified circuit diagram of battery model [41].

As seen in the following equations, the battery is defined as a controlled voltage source with specific resistance:

$$E = E_0 - \frac{P_v C_{BESS}}{C_{BESS} - \int_0^t i\,dt} + A exp\left(-B \int_0^t i_{BESS} dt\right) \tag{2.3}$$

$$V_{BESS} = E - R_i i_{BESS} \tag{2.4}$$

Where:

- E represents the battery's open-circuit voltage, which is the voltage present across the battery terminals when no current is flowing.
- E_0 defines the no-load voltage of the battery, which is the voltage when the battery is fully charged, and no load is applied.
- P_v represents the polarization voltage, which is related to the battery's State of Charge (SoC) and accounts for the electrochemical phenomena occurring within the battery during charging and discharging processes.
- C_{BESS} is the battery's capacity, which determines the amount of charge it can store.
- The integral term $\int_0^t i dt$ illustrates the charge drawn and supplied by the battery over time, where i represents the battery current and t represents time.
- B defines the exponential zone time constant inverse, which is related to the time constant of the transient voltage response.
- i_{BESS} symbolizes the battery current, which can be either positive (during discharge) or negative (during charge).

- V_{BESS} describes the actual battery voltage, which is the voltage observed across the battery terminals when current is flowing.
- R_i is the internal resistance of the battery, which accounts for the voltage drop caused by the flow of current through the battery's internal components.

This mathematical model considers several factors that impact the battery's voltage behaviour, such as the state of charge, internal resistance, transient voltage effects, and the charge drawn or supplied over time. By precisely modelling these elements, the equations offer a realistic depiction of the battery's performance, which is crucial for optimizing the operation and control of Battery Energy Storage Systems in diverse applications.

2.4 Supercapacitor modeling

The energy storage system (ESS) under consideration is known as a supercapacitor. This advanced form of energy storage comprises two electrodes separated by an electrolyte containing ionic channels or pores that allow for the free movement of ions between the electrodes. The fundamental operating principle of a supercapacitor relies on the electrostatic separation of charges, enabling rapid energy uptake and release. This type of ESS plays a vital role in modern energy systems due to its capability to support energy balance and maintain power quality, especially under dynamic and challenging operating conditions.

Unlike conventional energy storage devices such as batteries, supercapacitors offer a range of unique advantages. These include an exceptionally long cycle life, minimal maintenance requirements, compact form factors, fast charge and discharge rates, and high-power density. Additionally, they are relatively easy to integrate into existing electrical infrastructure without requiring complex modifications. Because of their superior performance characteristics, supercapacitors are particularly well-suited for high-power engineering applications where rapid energy delivery is critical [42].

Due to their ability to store and release energy quickly and efficiently, supercapacitors have gained widespread use in fields such as transportation, renewable energy systems, and industrial power management. The energy stored in a supercapacitor, denoted as W_{ESS} , can be calculated using the following equations.

$$W_{ESS} = \int P_{Sc} dt = P_{sc} t \tag{2.5}$$

where P_{Sc} represents the storage energy in the supercapacitor at the time t. The capacity size of a supercapacitor is depicted below.

$$W_{ESS} = \frac{1}{2} C_{Sc} V_{Sc}^2 \tag{2.6}$$

$$C_{Sc} = \frac{2 P_{Sc} t}{V_{Sc}^2} \tag{2.7}$$

where V_{Sc} indicates the voltage of the supercapacitor and C_{Sc} equals its capacity size.

2.5 Model of a boost converter

The voltage control techniques have different kinds of converters circuits that are used for increasing or decreasing DC voltage. These converters can be used in PV systems to modify the DC voltage that is generated from PV arrays [43]. One of these converters that will be used here is DC/ DC boost converter. It is used to modify the PV voltage by controlling the switching operation of a semiconductor insulated gate bipolar transistor (IGBT) through the pulse width modulation (PWM) generator from the MPPT control unit. The ratio between the switches' operation on and of time with a constant frequency is called a duty cycle. In Figure 2.3 shows the main components of the boost converter circuit with the output parameters of DC current and voltage as following [44].

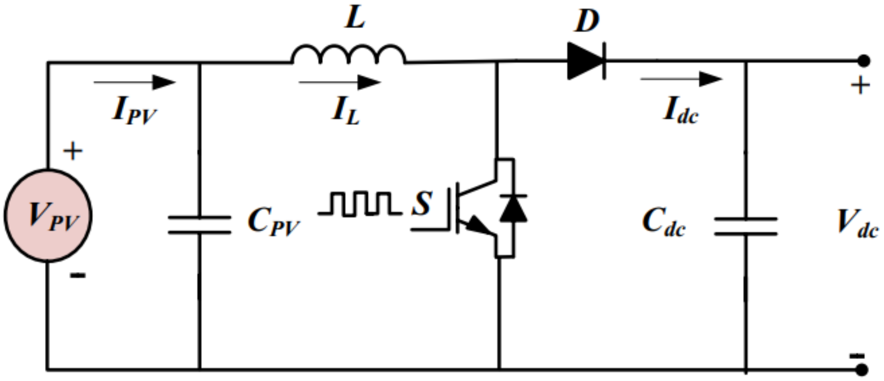


Figure 2.3: Circuit diagram of the DC/DC boost converter [39].

$$V_{DC} = \frac{V_{PV}}{1 - D} \tag{2.8}$$

The main two modes operation of boost converter are constructed through IGBT switch, when the switch signal S is ON, the value of D equals 1 at which the diode has an inverse polarity so the current will fow through inductor to store energy. Also, when switch signal S is OFF, the value equals 0 and the diode changes its polarity, at which the magnetic feld will be discharged to DC link and the induced voltage polarity will be reversed as the following.

$$\frac{dI_L}{dt} = \frac{1}{L}(V_{pv} - RL_L - (1 - D)V_{dc}) \tag{2.9}$$

$$\frac{dV_{PV}}{dt} = \frac{1}{C_{PV}}(I_{PV} - \frac{I_{dc}}{1 - D}) \tag{2.10}$$

$$I_{dc} = I_L(1 - D) \tag{2.11}$$

where C_{PV} is the filter capacitor I dc is the output current of converter circuit, I_L is the inductor current, R and L are the internal resistance and inductance of the inductor.

2.6 Model of bidirectional DC/DC converter

The DC microgrid model selects the battery energy storage unit as the main power supply, and the bus interface converter adopts a bidirectional DC–DC converter, as shown in Figure 2.4. This kind of converter is the most popular structure for low power applications at present. It has the characteristics of simple structure, convenient control, and high efficiency. When the power output by the distributed power source is excessive, the battery absorbs and stores it through the bidirectional DC–DC converter. When the power of the grid is insufficient, the battery energy storage unit discharges to maintain the power balance of the DC microgrid [45].

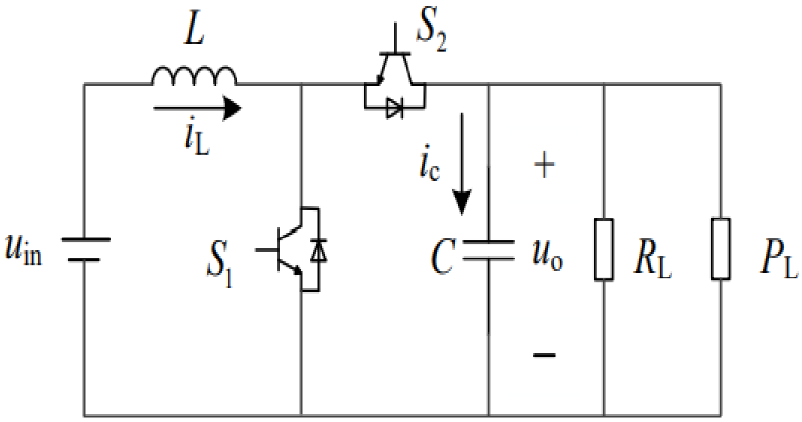


Figure 2.4: Model of bidirectional DC/DC converter [45].

In the Figure 2.4, u_{in} is the output voltage of the battery, i_L is the inductor current, and i_c is the capacitor current on the high-voltage side of the converter. u_o is the converter output voltage, R_L is the resistive load, and P_L is the constant power load in the DC microgrid.

The bidirectional DC/DC converter adopts the complementary PWM control method. When S1 is turned on, S2 is turned off, and when S2 is turned on, S1 is turned off, and the two switches operate at the same time. Compared with the independent PWM control method, the complementary PWM method does not require the logic unit to perform transition switching between the BUCK and BOOST circuits, which improves the work efficiency, and the system responds faster. From reference [46], the state-space averaging model of the circuit is as follows

$$\begin{cases} C\dfrac{du_o}{\mathrm{dt}} = ui_L - \dfrac{P_L}{u_o} - \dfrac{u_o}{R_L} \\ L\dfrac{di_L}{\mathrm{dt}} = u_{\mathrm{in}} - uu_o \end{cases} \tag{2.12}$$

where, u is the duty cycle of switch S2

2.7 Maximum power point tracking (MPPT) in photovoltaic Systems

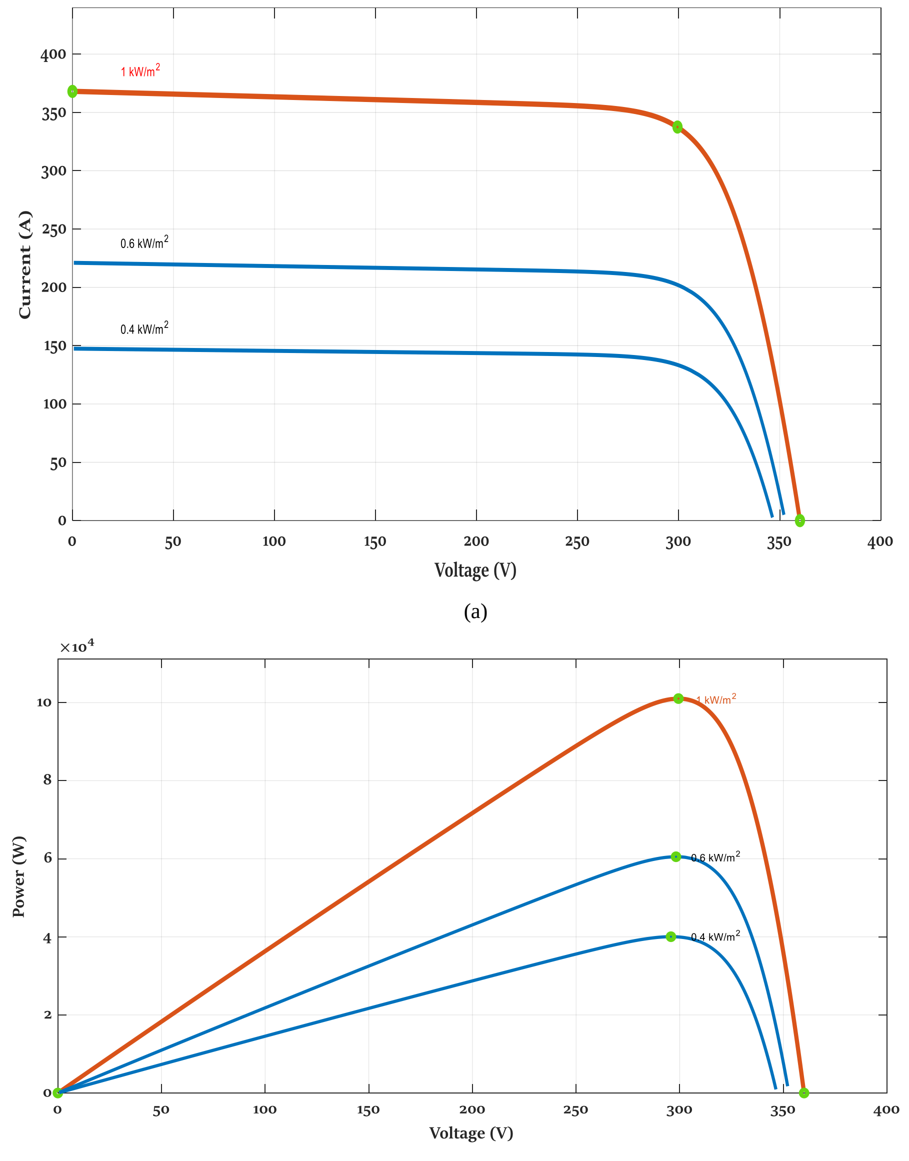
Photovoltaic (PV) systems generate power by converting sunlight into electricity using solar panels. The efficiency of PV systems heavily depends on their ability to operate at the Maximum Power Point (MPP), where the product of current and voltage is maximized.

However, due to varying environmental conditions such as solar irradiance and temperature, the MPP changes dynamically. Maximum Power Point Tracking (MPPT) techniques are employed to ensure that the PV system operates optimally under all conditions [47].

2.7.1 Principle of MPPT

The power output of a solar panel is a nonlinear function of both voltage and current, as shown in the power-voltage (P-V) and current-voltage (I-V) characteristics in Figure 2.5. At any given time, there is a unique operating point—the MPP—at which the panel delivers its maximum power.

Operating the PV system at this point requires continuous adjustment of the system's operating voltage or current [48].



(a)

(b)

Figure 2.5: (a) I-V and (b) P-V characteristics of a solar cell at different levels of irradiation with constant temperature (25°) [49].

2.7.2 MPPT Techniques

Solar power systems use Maximum Power Point Tracking (MPPT) techniques to operate at peak efficiency. The Perturb and Observe (P&O) method makes small voltage adjustments and observes power changes. If power increases, it continues in the same direction; otherwise, it reverses. While simple and popular, this technique tends to oscillate around the optimal point. Incremental Conductance (IC) offers better accuracy by calculating the derivative of power with respect to voltage. When this value equals zero, the maximum power point is reached. This method performs better in rapidly changing conditions but requires more complex calculations. The Constant Voltage technique maintains the system at a fixed voltage near the expected maximum power point. Though simple, it's less effective when environmental conditions vary. Modern Artificial Intelligence approaches using machine learning, fuzzy logic, and neural networks adapt better to dynamic environments, achieving higher efficiency. However, they demand significant computational resources and training data. Each technique balances simplicity, accuracy, and performance differently. The optimal choice depends on specific system requirements and operating conditions [50], Figure 2.6 explains the existing MPPT techniques.

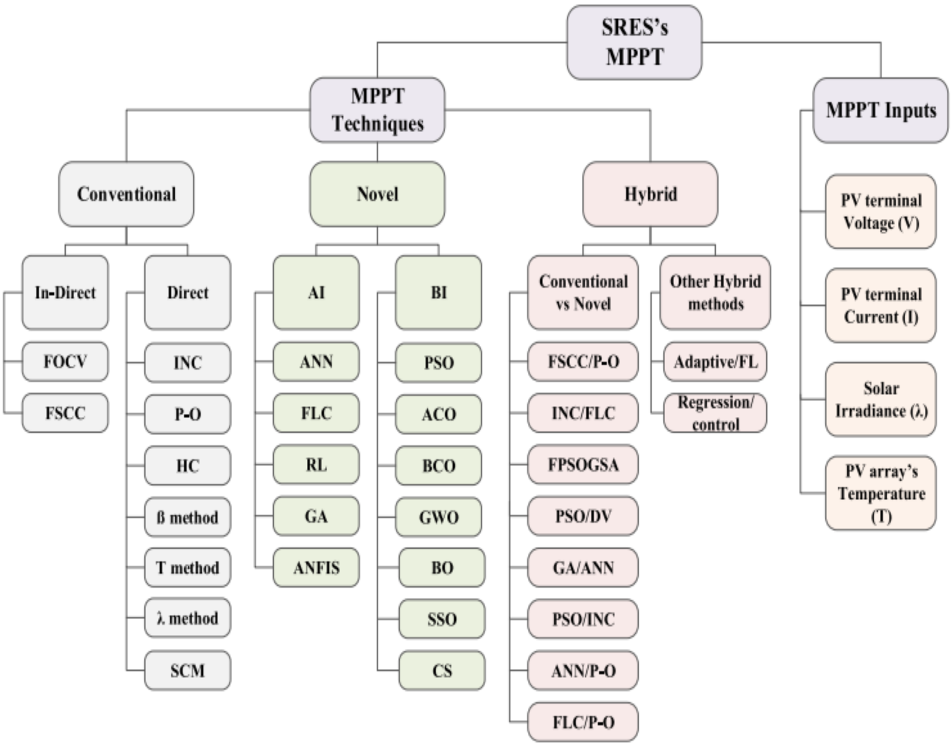


Figure 2.6: Flowchart of the existing MPPT techniques and MPPT input variables [50].

2.7.3 P&O MPPT algorithm

The algorithm of P&O is a widely used technique as a type of MPPT in power systems applications, where it is simple and easy to implementation characteristics. It explains the relation between the DC current and voltage of PV in the I–V characteristic curve and uses these parameters for power tracking. On the other hands, P&O illustrates the relation between DC power and voltage of PV through the P–V characteristic curve. I–V and P–V characteristic curves of P&O method at a certain temperature 25 °C and a certain radiation 1000 W/m2 are shown in Figure 2.7.

The main points of I–V curve are V_{OC} open circuit voltage, I_{sc} is the short circuit current that has a maximum value if V_{OC} =zero, V_{mpp} is DC voltage at MPP and I_{mpp} is the current of the MPP. In P–V curve P_{max} and V_{mpp} are the maximum values of output PV power and voltage at MPP.

This tracking method mainly depends on a frequent perturbation of (increasing or decreasing) voltage or current values then compare the new measured power with the previous perturbation value.

The sweeping for characteristic curve at the left side of MPP the perturbations values are ($\Delta P>0$ and $\Delta V>0$), the power is tracked by reducing its value to reach MPP. On the other hand, at the right side of MPP, the perturbations are ($\Delta P<0$ and $\Delta V>0$), so power value is tracked by increasing its value until MPP.

The flowchart of P&O algorithm is shown in Figure 2.8. First, I_{pv}(n) and V_{pv}(n) of PV array are measured and multiplied to calculate the output power P_{pv} (n) depending on sample time. For any change in the PV system operating condition occurs, P&O algorithm will compare the new measured values I_{pv} (n−1) and V_{pv}(n−1) and calculate perturbations values ΔP and ΔV.

The algorithm is programed for generating a unit of duty cycle D to increase or decrease the change in P_{PV}(n) to return to MPP. If the measured power is the same as reference value, the comparison between values will equal to zero and there is no change.

At left side of P–V curve ($\Delta P>0$), if check value of ΔV has a positive value, D will increase previous duty value.

If the perturbations value ΔV has a negative, D value will decrease previous calculated unit to track power to MPP. At right side of P–V curve ($\Delta P<0$), if ΔV has a positive value, D will decrement previous unit, but if ΔV has a negative, D value will increment previous calculated duty to track power again to MPP [51,52].

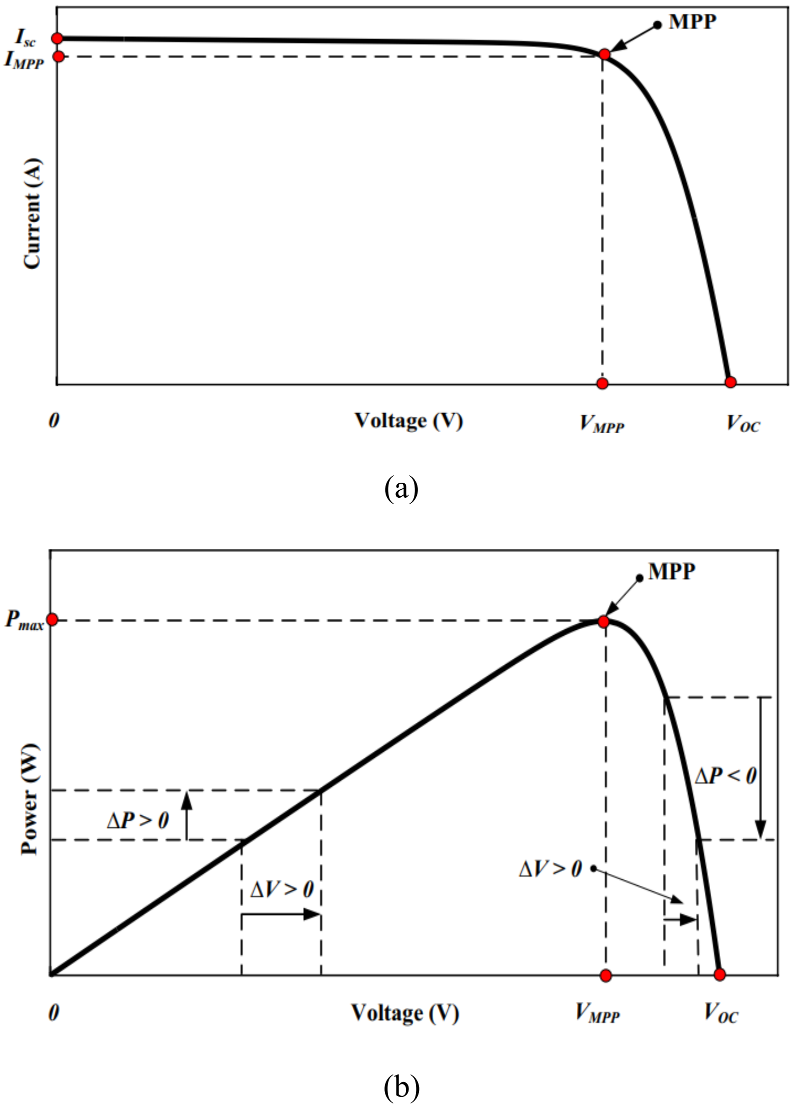


Figure 2.7: PV characteristic curves of P&O MPPT technique. (a) V–I curve, (b) P–V curve [39].

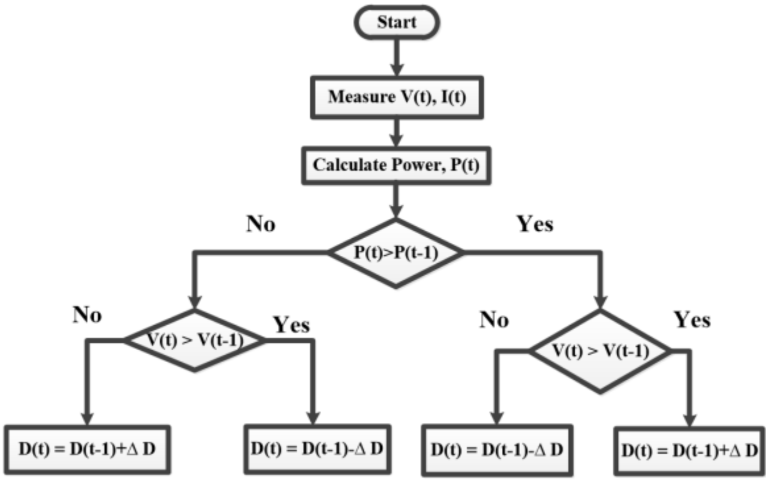


Figure 2.8: P&O MPPT algorithm [53].

2.8 Conclusion

In this chapter, we have developed models for each component of the photovoltaic conversion chain based on existing models in the literature (PV field, converters, MPPT, batteries, supercapacitor). Our goal was to ensure operation at or near the maximum power point (MPP) to minimize energy losses.

The simulations allowed us to evaluate the general behavior of all components in the studied system. The implementation of an MPPT regulator enabled the PV systems to operate at their highest efficiency. We observed that optimal utilization of a photovoltaic generator's characteristics requires energy adaptation through appropriate control techniques. For this purpose, we implemented the Perturb and Observe (P&O) MPPT control algorithm. In the next chapter, we will combine these components into one integrated system and propose our hybrid energy storage system technique to extend the lifespan of the battery in PV system.

Chapter 3: Simulation and Results

3.1. Introduction

In renewable energy systems, particularly photovoltaic (PV) installations, energy production is inherently intermittent due to environmental factors such as cloud cover, temperature variations, and diurnal cycles. To ensure a stable and reliable supply of power, energy storage systems (ESS) are often employed. However, traditional storage technologies, such as batteries alone, face challenges related to limited charge/discharge cycles, slow dynamic response, and degradation over time under high-frequency power fluctuations.

To address these limitations, the integration of hybrid energy storage systems (HESS)—typically combining batteries with supercapacitors—has gained significant attention. The supercapacitor, characterized by high power density and rapid charge/discharge capability, complements the high energy density and long-duration storage ability of the battery. Together, these two components form a synergistic system that can smooth out power fluctuations, enhance the reliability of the PV system, and prolong the lifespan of the battery. This chapter focuses on the simulation, and control strategies for a HESS under variable solar irradiance conditions, with an emphasis on both passive and semi-active configurations. The control objectives include maintaining DC bus voltage stability, optimizing battery usage, and ensuring efficient energy distribution.

3.2. PV System with and without MPPT (Test 01)

A standalone photovoltaic (PV) system converts solar energy directly into electrical energy to supply DC loads, often complemented by an energy storage system such as batteries or hybrid storage to ensure reliability during periods of low sunlight. Without a Maximum Power Point Tracking (MPPT) controller, the PV array operates at a voltage that is dictated by the connected load or the battery voltage. Since the I-V (current-voltage) characteristic of a PV module is nonlinear and highly sensitive to changes in irradiance and temperature, operating at a non-optimal point results in significant energy losses. Typically, the voltage of a battery or load is lower than the maximum power point voltage (V_{mpp}) of the PV array, leading to underutilization of the available solar energy.

In contrast, an MPPT controller uses algorithms such as Perturb and Observe (P&O) or Incremental Conductance to continuously track and maintain the PV array at its maximum power point. By adjusting the duty cycle of a DC-DC converter (usually a Boost converter), the MPPT ensures that the operating voltage of the PV modules always matches V_{mpp} . This dynamic adaptation maximizes the energy harvested from solar panels, increases the system's overall efficiency, and improves the autonomy of the energy supply, especially under varying weather conditions like cloud cover or temperature fluctuations.

In this test, we will evaluate the solar energy system both with and without the Maximum Power Point Tracking (MPPT) Perturb and Observe (P&O) algorithm to compare differences in energy production and system efficiency. Figure 3.1 illustrates the simulation of a standalone photovoltaic system operating without MPPT. The PV array, subjected to variable irradiance and temperature profiles (indicated by 'Irr' and 'T' input signals), connects directly to a DC-DC converter comprising an IGBT/Diode switching element, an inductor, and a passive filter. The converter operates with a constant duty cycle of 0.4 generated by a Pulse Width Modulation (PWM) generator block.

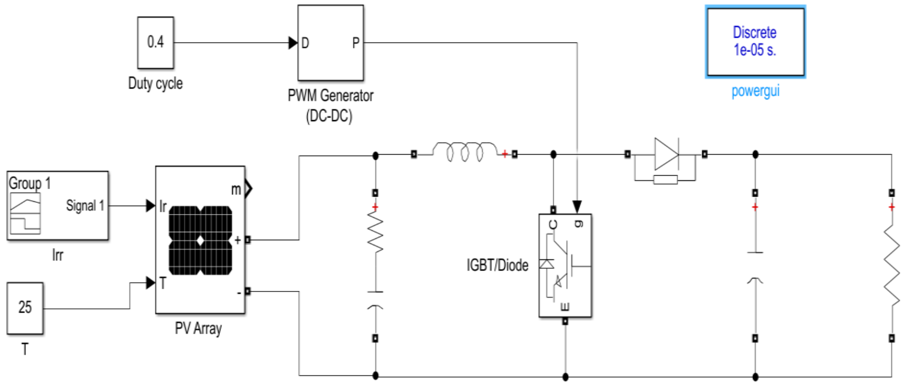
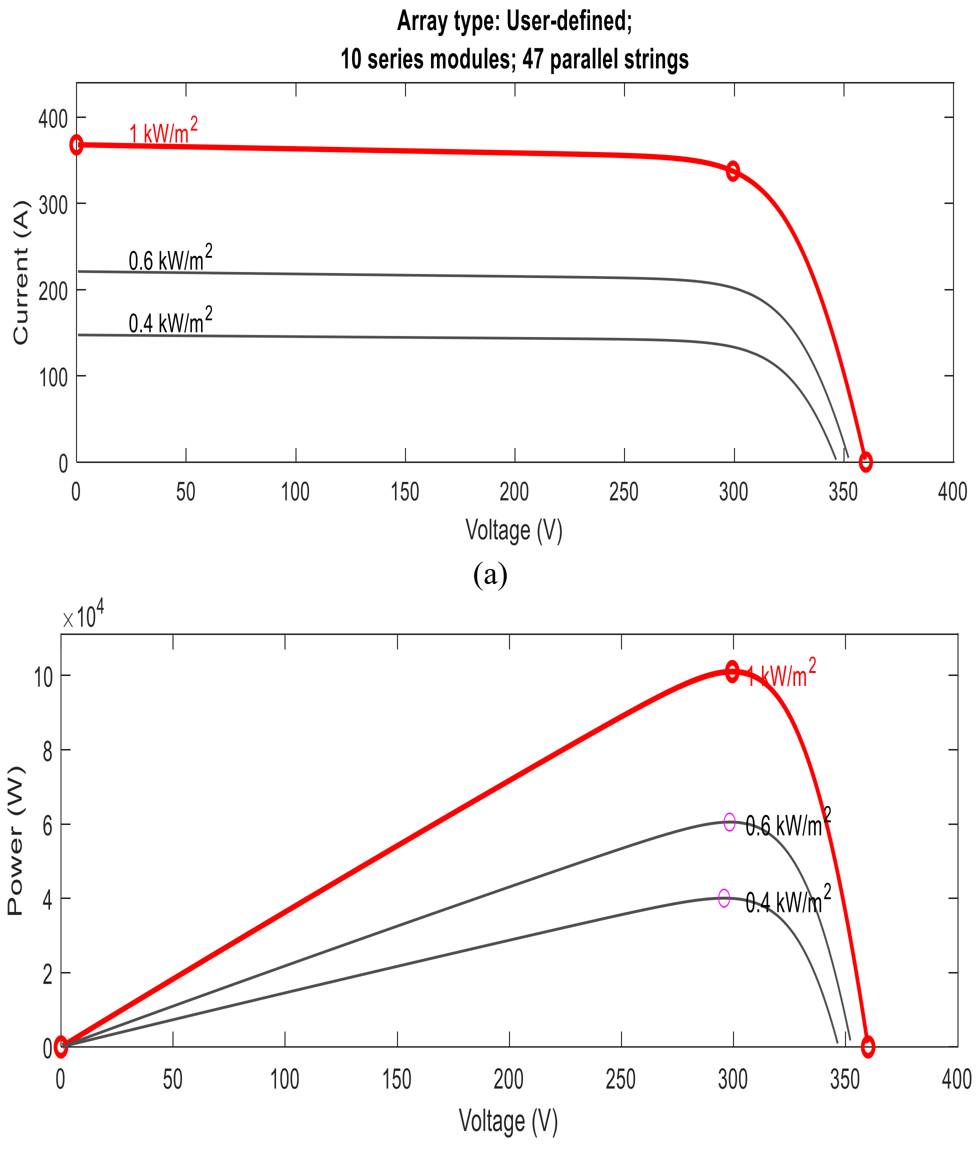


Figure 3.1: PV system without MPPT

This study applied ADVANCE POWER API-P215 photovoltaic module. This module delivers a maximum power output of 214.9692 W under standard test conditions, with an open-circuit voltage (V_{oc}) of 36 V and short-circuit current (I_{sh}) of 7.83 A. The module operates optimally at its maximum power point, characterized by a voltage (V_{mp}) of 29.94 V and current (I_{mp}) of 7.18 A. Our system configuration consists of 47 parallel strings (Np) with 10 modules in each series string (Ns), resulting in a total rated system capacity of 100 kW, as shown in Figure 3.2. These parameters are essential for understanding the system's performance expectations and for designing appropriate control strategies, including the MPPT algorithm implementation.



(a)

(b)

Figure 3.2: (a) I-V and (b) P-V characteristics of a solar cell at different levels of irradiation with constant temperature (25°).

The diagram in Figure 3.3 illustrates the simulation of a standalone photovoltaic system operating with a maximum power point tracking (MPPT) algorithm based on the Perturb and Observe (P&O) method. The PV array is subjected to variable irradiance and temperature profiles, as indicated by the "Irr" and "T" input signals. The output of the PV array is fed into a DC-DC boost converter, consisting of an IGBT/Diode switching element, an inductor, and a passive filter. The MPPT controller dynamically adjusts the duty cycle to maximize the power extracted from the PV array, and this duty cycle is used by a PWM (Pulse Width Modulation) generator to control the converter's switching operation, ensuring optimal system performance under changing environmental conditions.

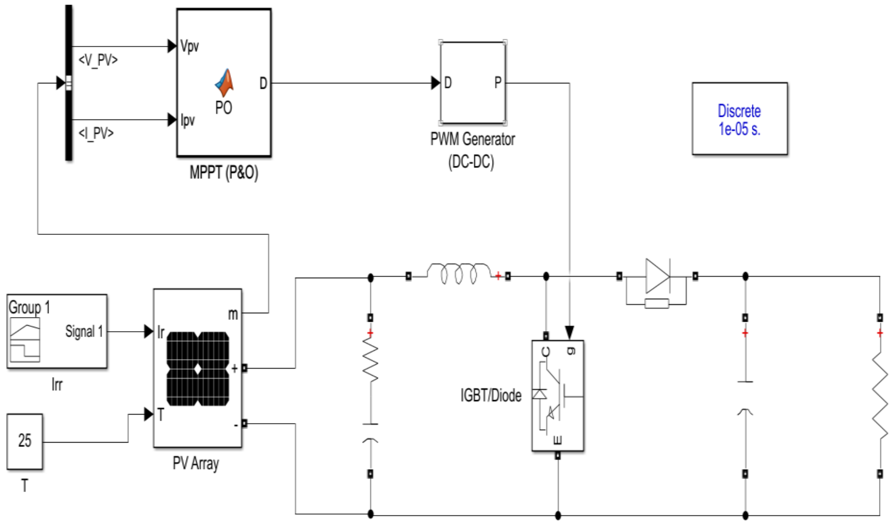


Figure 3.3: PV system with MPPT

3.3. Passive and semi-active connection of HESS (battery / supercapacitor) (Test 2)

Various HESS configurations combining batteries and supercapacitors have been proposed to maximize the strengths of each storage element. These systems aim to optimize energy and power management by leveraging the complementary characteristics of the components. Any HESS topology—existing or future—can be classified based on three main criteria: (1) the number of energy storage elements used, (2) the power-sharing strategy between them, and (3) the interfacing method [41], as illustrated in Figure 3.4.

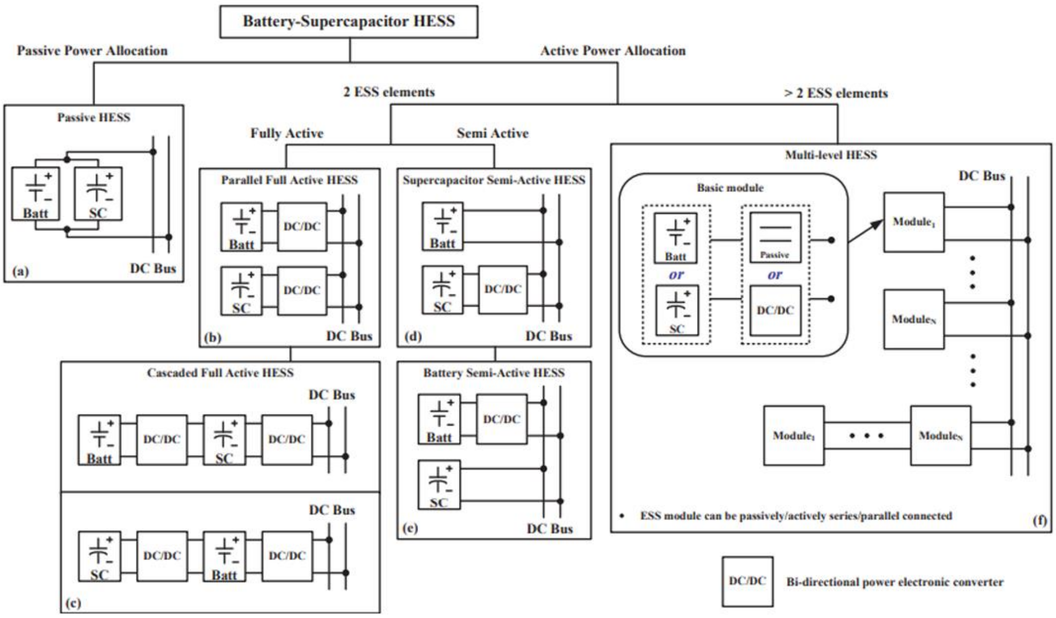


Figure 3.4: Classification of Battery-SC HESS Topologies [41].

3.4. Passive connection of HESS (battery / supercapacitor)

The passive connection is the simplest and most cost-effective method for integrating a hybrid energy storage system (HESS) into a microgrid (MG). As illustrated in Figure 3.5, this configuration directly connects the battery and supercapacitor to the DC bus without using any power converters. Consequently, ensuring proper voltage level matching between the HESS and the DC bus or connected load is critical.

In this setup, power sharing between the battery and supercapacitor depends on their internal impedances. During sudden power variations, the supercapacitor quickly compensates for transient demands due to its low internal impedance and fast response characteristics. However, the battery, having a slower voltage response, is less effective in such situations, making it difficult to manage the state of charge (SOC) and maintain DC bus voltage stability without power electronics.

Despite its simplicity and low cost, passive HESS topology is rarely used in MG applications due to several limitations:

- The terminal voltage of the HESS must precisely match the load and DC link voltage.
- Power sharing lacks flexibility and relies entirely on the internal impedance of the storage devices.
- Direct connection to the DC bus increases the risk of cascading failures during system faults.

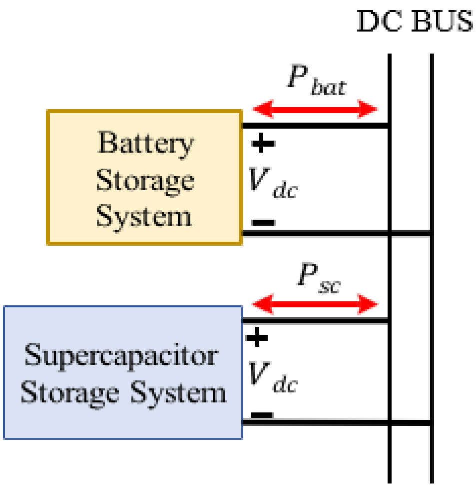


Figure 3.5: Passive connection of HESS.

3.5. Semi-active connection of HESS (battery / supercapacitor)

The semi-active connection is an enhanced version of the passive topology. In this configuration, one energy storage device (ESS) is connected directly to the DC bus, while the other is interfaced through a bidirectional DC/DC converter. This arrangement offers improved control and operational flexibility compared to the passive connection.

As shown in Figure 3.6 (a), a typical semi-active topology features a battery connected via a bidirectional converter, while the supercapacitor is directly connected to the DC bus. This setup allows for partial control of the battery's charging and discharging current, independent of sudden transients in load demand. Additionally, the DC bus voltage does not need to match the battery's terminal voltage, further easing design constraints.

However, since the supercapacitor is connected without a converter, its unregulated terminal voltage can introduce fluctuations in the DC bus, potentially affecting system stability and power quality. To mitigate these effects, a large-capacity supercapacitor often requires a solution that can be economically inefficient.

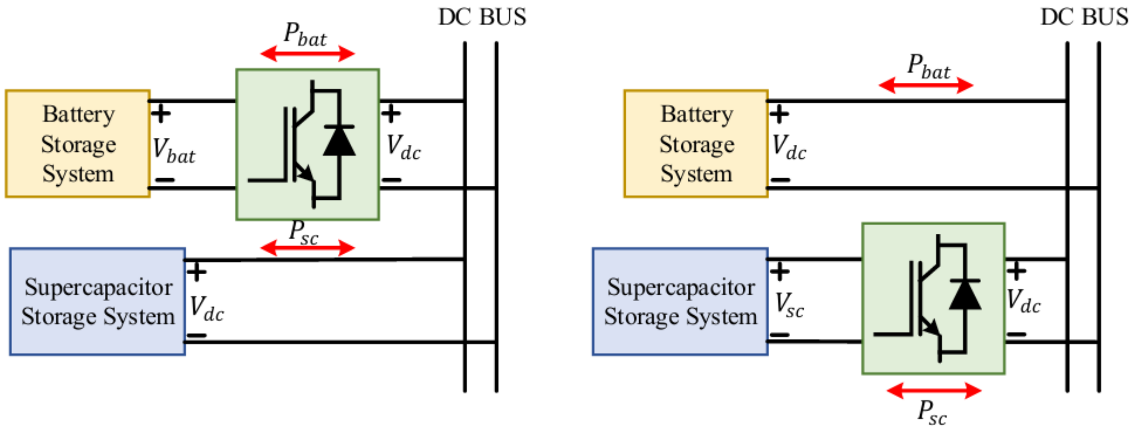


Figure 3.6 :(a) Battery semi-active topology. (b) SC semi-active topology.

Similarly, the supercapacitor semi-active topology, shown in Figure 3.6(b), consists of the battery being directly connected to the DC bus, while the supercapacitor (SC) is interfaced through a bidirectional DC/DC converter. This configuration allows the supercapacitor to operate over a wider voltage range, thereby improving its energy efficiency and responsiveness.

In this setup, the battery is responsible for maintaining a stable DC bus voltage. However, it is also exposed to sudden high current surges during faults or rapid load variations, which can accelerate battery degradation. While this topology provides greater flexibility than the passive connection, it is still not commonly used in microgrid applications due to several limitations:

- When the supercapacitor is directly connected to the DC bus, any disturbance in the system can cause voltage fluctuations, potentially affecting system stability.
- When the supercapacitor is connected through a DC/DC converter, the converter must be carefully designed to handle high-power transients, which increases system complexity and cost.

The simulation of the two cases of passive and semi-active connection of hybrid energy storage system shown in Figures 3.7-8.

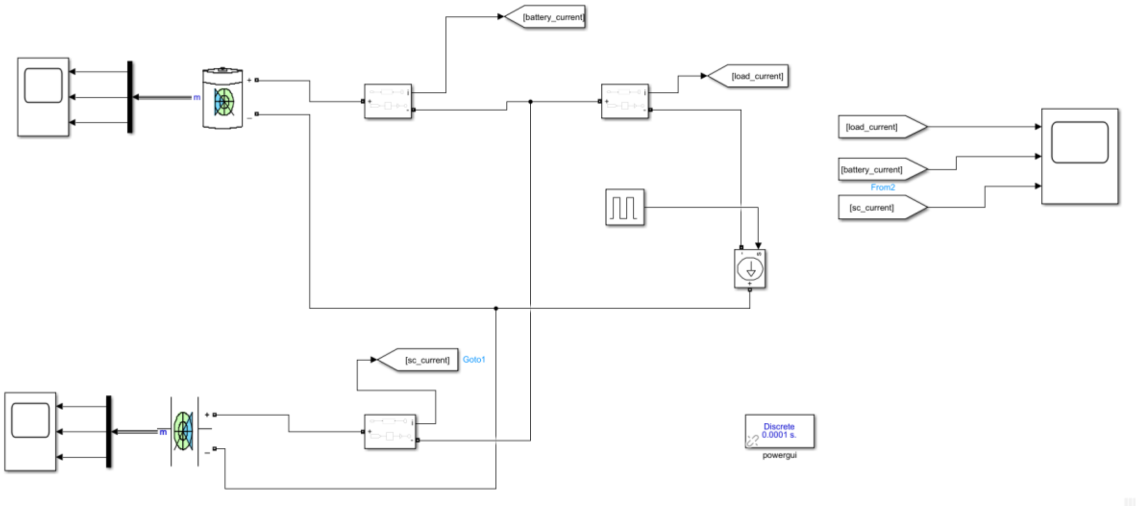


Figure 3.7: Simulink model Passive battery-supercapacitor HESS simulation.

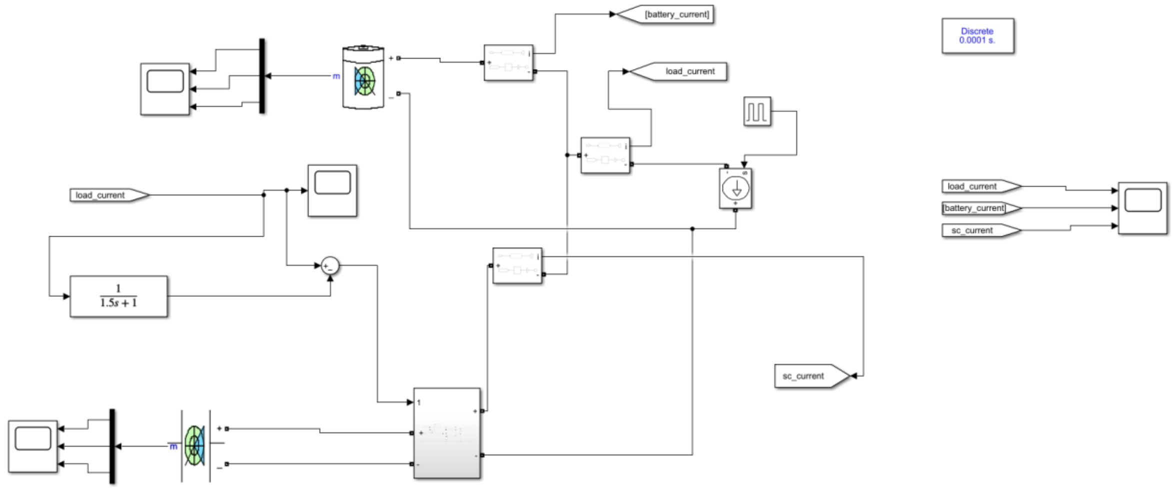


Figure 3.8: Simulink model of semi active control of SC and Battery

3.6 Photovoltaic systems under cloudy days with semi-active hybrid energy storage system (Test 3)

In this study, a hybrid energy storage system (HESS) was implemented to support a photovoltaic (PV) system supplying a constant load 50 kW. The HESS, comprising a 500 Ah battery and a 500 F supercapacitor, was designed to mitigate the impact of solar intermittency on battery degradation and extend its operational life.

To evaluate the effectiveness of active supercapacitor control, three different system configurations were developed and simulated. These configurations aim to assess how dynamic power sharing between the battery and supercapacitor affects battery longevity under variable solar conditions.

A realistic operating scenario was created by simulating partial shading, representative of a cloudy day, which resulted in fluctuations in solar irradiance. These fluctuations led to sudden drops in PV output power, forcing the battery to respond through rapid discharge cycles. Such deep discharge events are well-known contributors to accelerating battery aging and reducing lifespan.

The PV system was rated at 100 kW, continuously supplying a 50-kW load, and the experimental setups used to evaluate the HESS performance, the first setup illustrated in Figure 3.9.

System 1: A passive battery-only system without energy management controls.

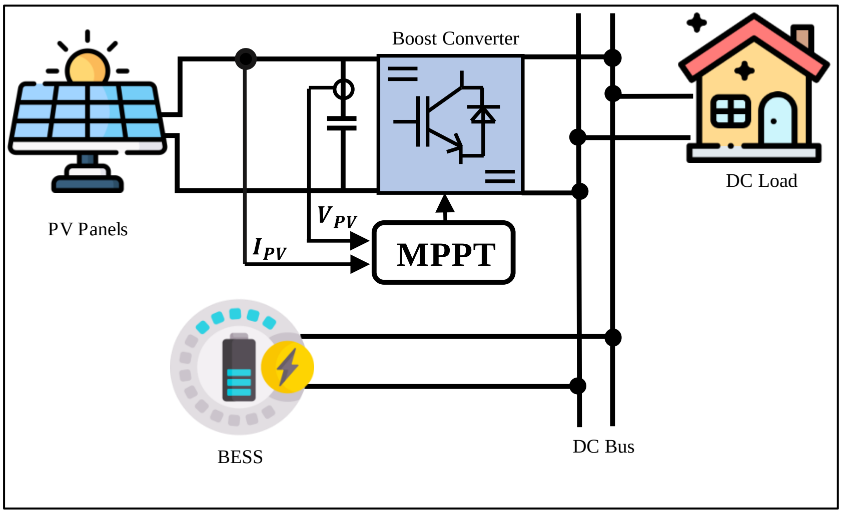


Figure 3.9: BESS passive connection with PV system and constant DC load [49].

System 2: A passive hybrid system with battery and supercapacitor connected in parallel, without control strategy as shown in Figure 3.10.

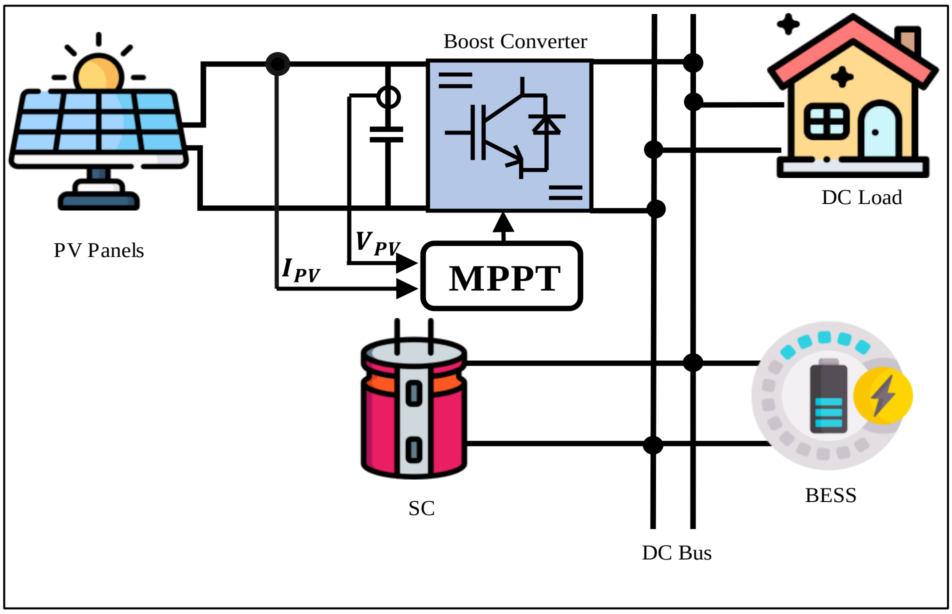


Figure 3.10: HESS battery-supercapacitor passive connection [49].

System 3: A semi-active hybrid energy storage system (HESS), with passive battery connection and active supercapacitor control, as shown in Figure 3.11.

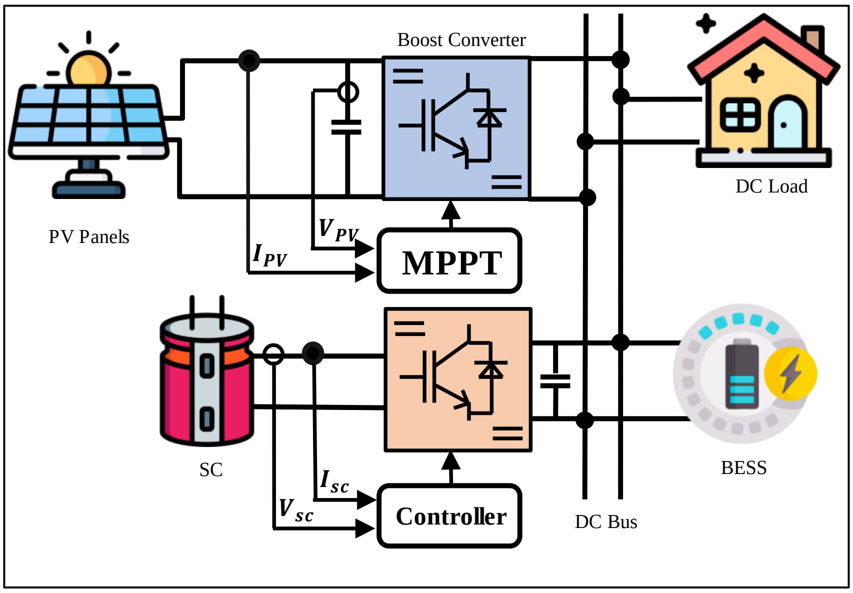


Figure 3.11: Semi-active connection of HESS [49].

The simulation of all three parts is clearly shown in the following Figures 3.12 to 3.14.

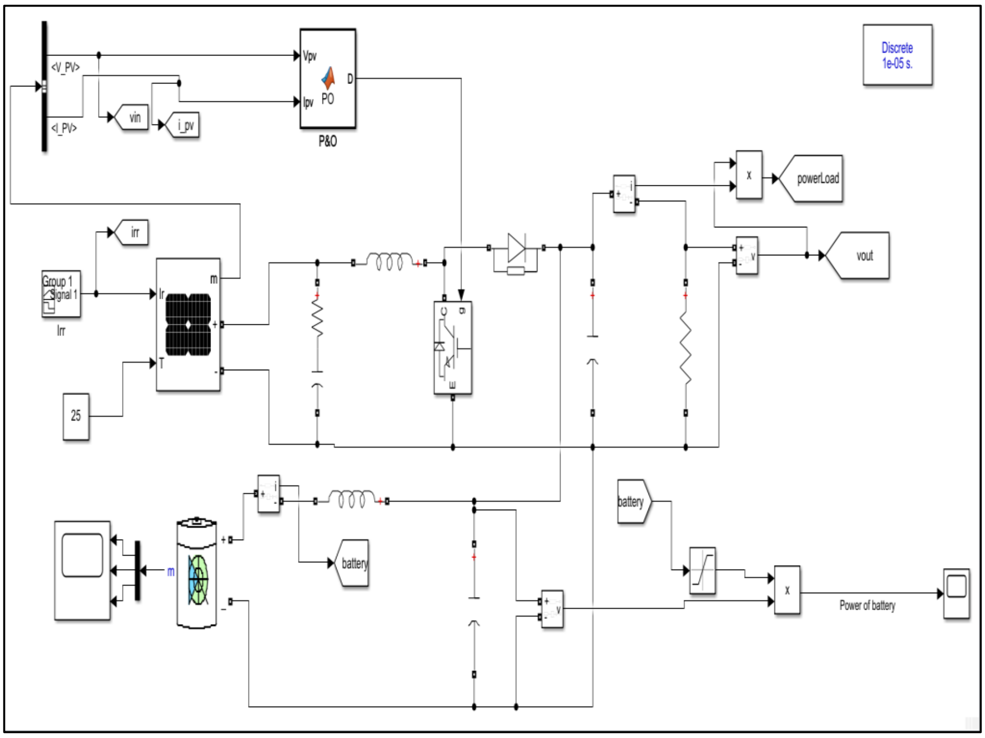


Figure 3.12: Simulink model of PV system with passive battery connection

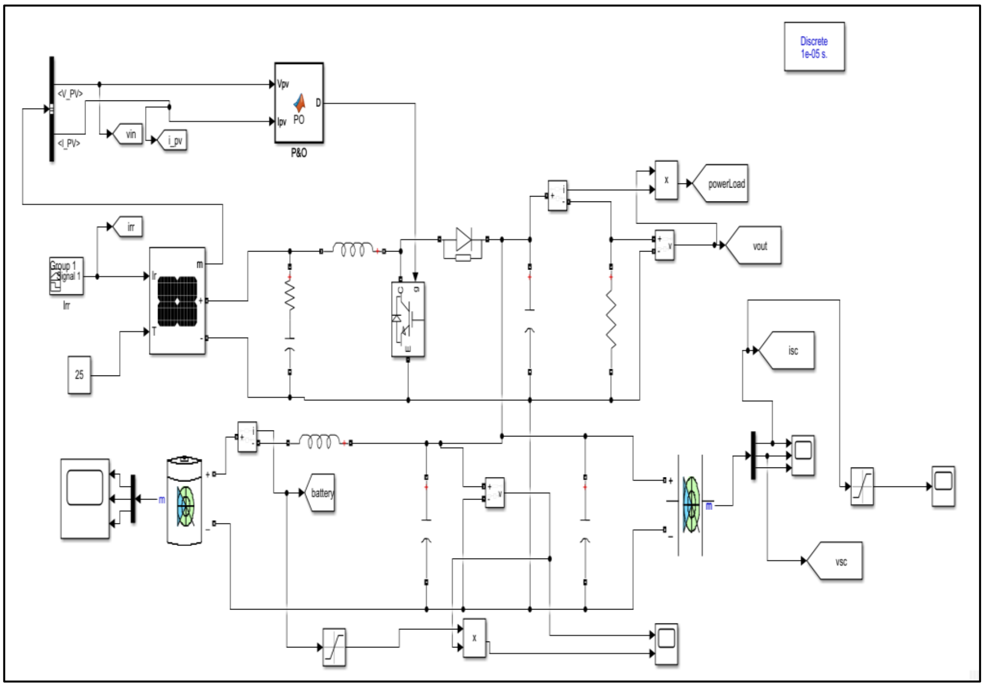


Figure 3.13: Simulink model of Passive hybrid system with battery and supercapacitor connected in parallel, without control strategy.

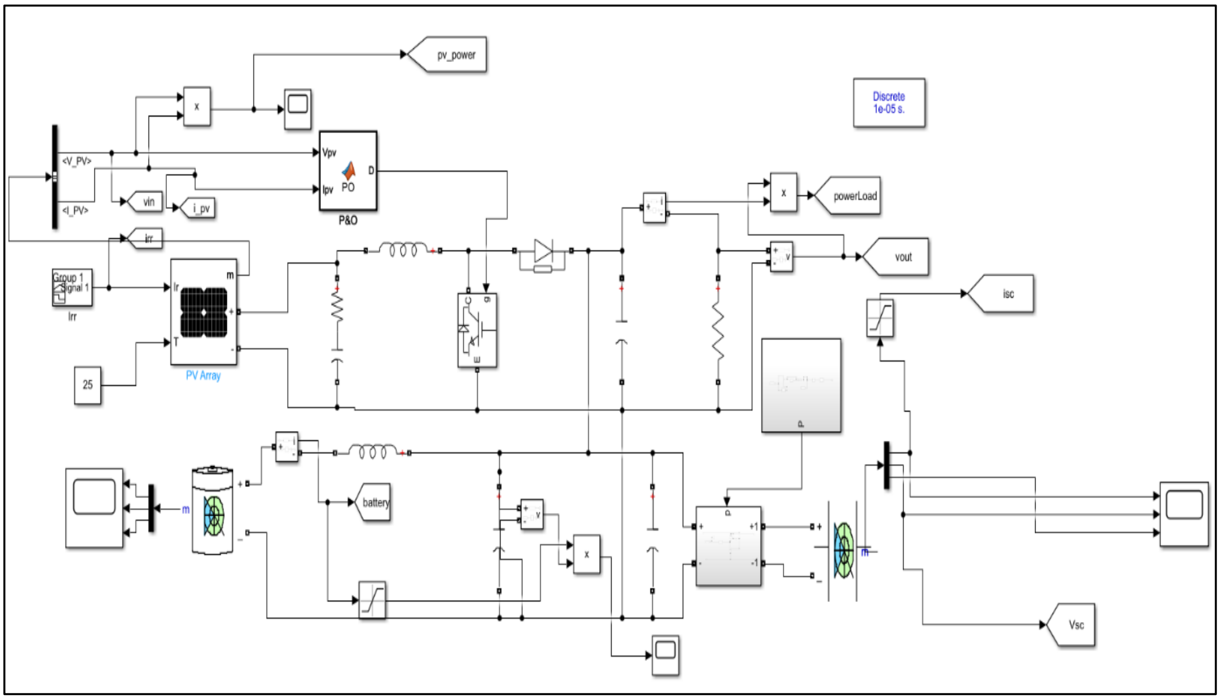


Figure 3.14: Simulink model of Semi-active hybrid energy storage system (HESS), with passive battery connection and active supercapacitor control.

Figure 3.15 illustrates the solar irradiance curve, which accurately represents a realistic cloudy day scenario. It shows sharp fluctuations in the energy production of the photovoltaic (PV) system, demonstrating the challenges posed by variable weather conditions

Figure 3.15 shows the variation of solar irradiance (in W/m²) over time (in seconds) during a simulation of a photovoltaic (PV) system under cloudy weather conditions.

On a cloudy day, the irradiance profile typically starts at 0 W/m² in the early morning, rises to a peak of around 1000 W/m² during midday, and gradually returns to 0 W/m² by evening, following the natural daily solar radiation trend. However, this general pattern is interrupted by sharp dips in irradiance, particularly noticeable between 9 and 18 seconds, which indicates the presence of intermittent cloud cover.

These rapid fluctuations result from clouds moving across the sun, causing temporary shading of the PV panels and leading to sudden reductions in the solar energy received. Such variations significantly impact the PV system’s performance, as the output power mirrors the irradiance instability. Without effective energy management, these power swings can trigger frequent charging and discharging cycles in the battery, which may shorten its operational life. This scenario emphasizes the importance of incorporating a fast-response energy storage element, such as a supercapacitor, to buffer these fluctuations and protect the battery. The simulated irradiance profile realistically reflects the challenges posed by a cloudy day, providing a valuable framework for evaluating the effectiveness of energy storage strategies in maintaining stable system performance.

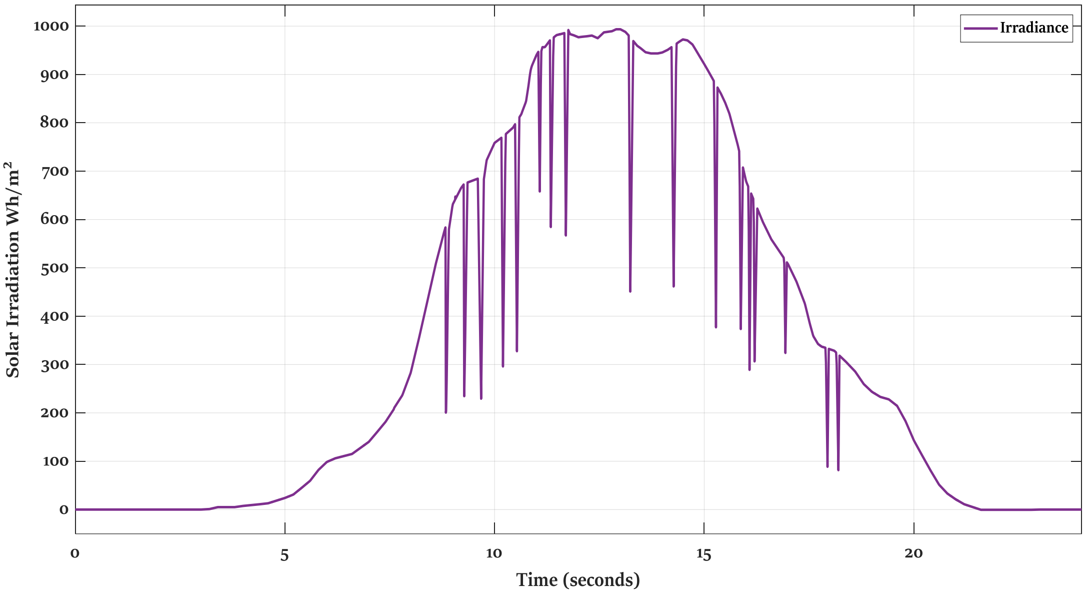


Figure 3.15: Solar irradiance profile under cloudy weather conditions.

This irradiance plot demonstrates the unpredictable nature of solar energy under cloudy conditions. The frequent and sudden dips in sunlight emphasize the importance of intelligent energy management systems, especially the role of supercapacitors in reducing stress on batteries and improving system reliability.

3.6.1. Control Approach of the Supercapacitor System

Figure 3.16 illustrates the control system for the supercapacitor, designed to calculate the reference current value required to prevent deep battery discharge caused by the intermittent nature of the photovoltaic (PV) system. The control system uses a proportional-integral (PI) controller with parameters $Kp = 800$ and $Ki = 0.01$ to ensure stable operation. This approach helps to manage the energy balance between the battery and supercapacitor, optimizing the overall performance of the system.

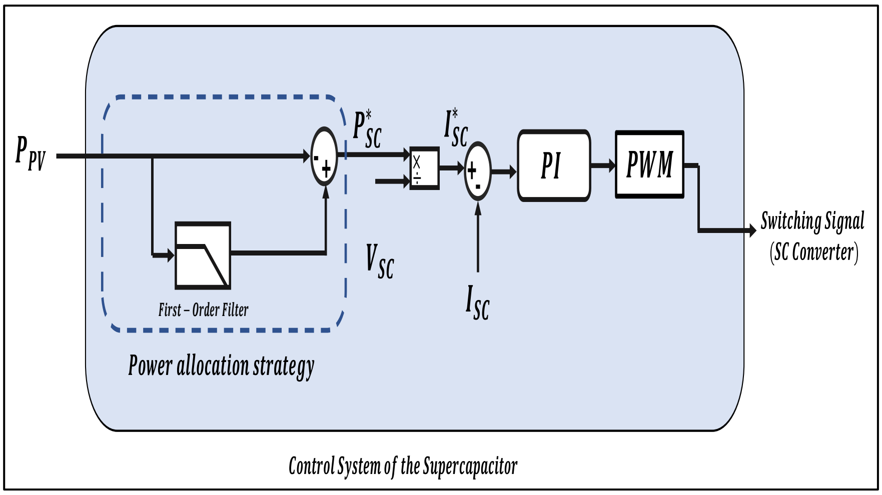


Figure 3.16: The control scheme of the supercapacitor [49].

3.7. Results and Discussion

The simulation results for the three tests are presented and compared in the following figures, providing an in-depth analysis of the performance and behavior of each configuration.

3.7.1. Test 1

The PV system with MPPT control provides a significantly higher and more stable output voltage and power compared to the system without MPPT, especially under varying irradiance conditions, the following curves shown that.

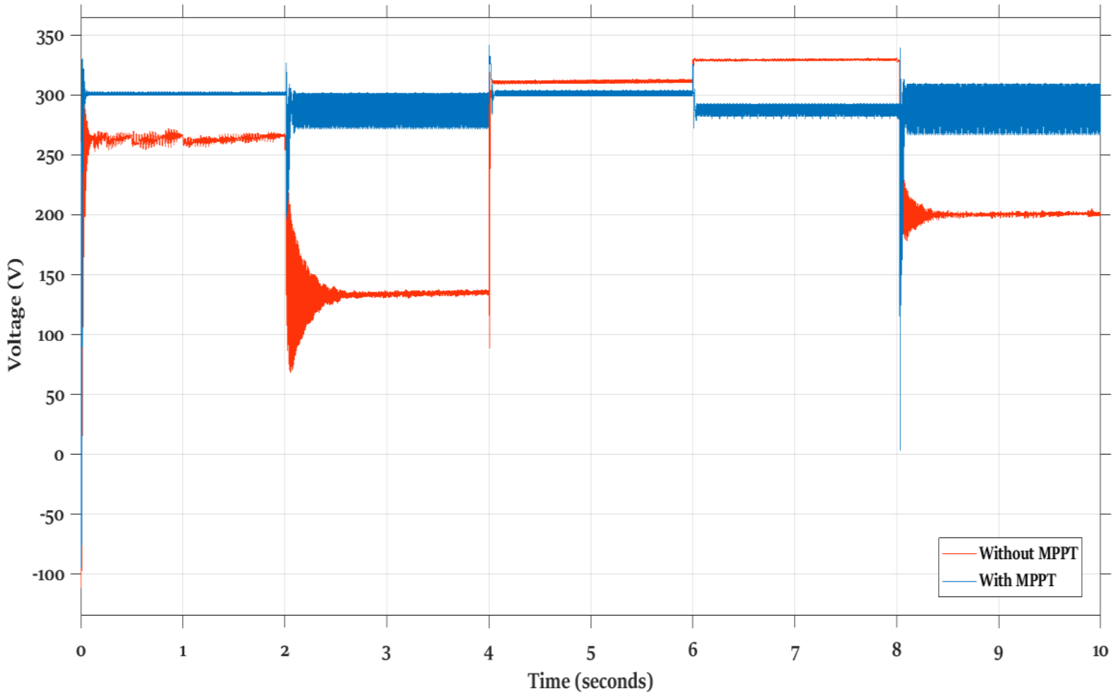


Figure 3.17: PV System Output Voltage with and Without MPPT.

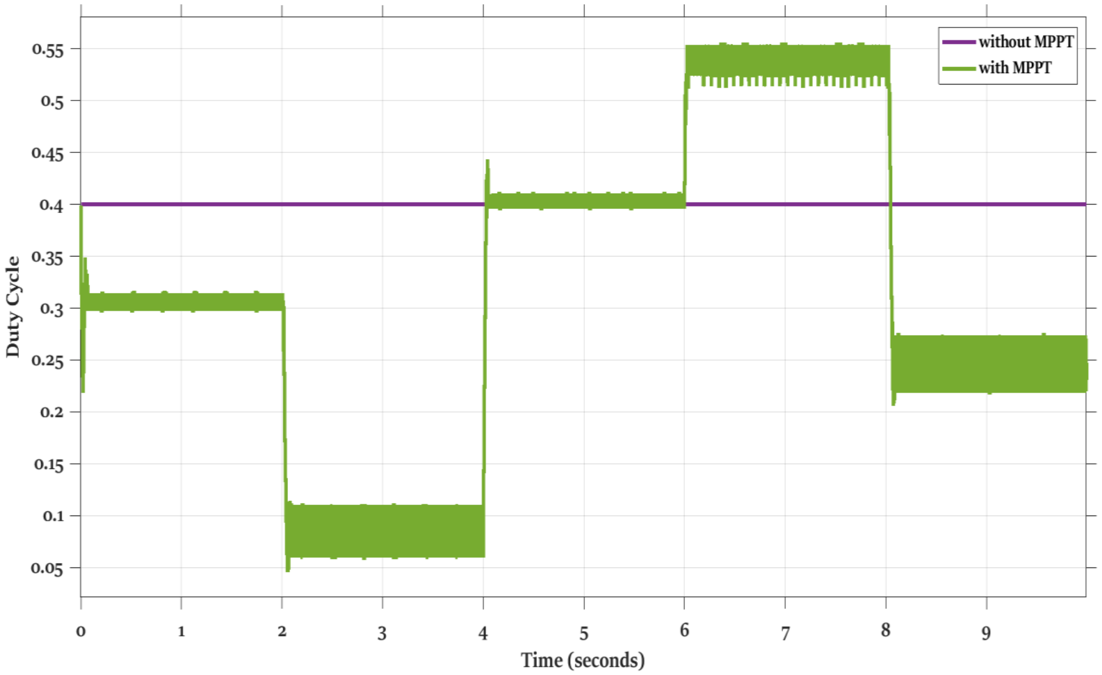


Figure 3.18: Comparison of the duty cycle variation with and without MPPT Control

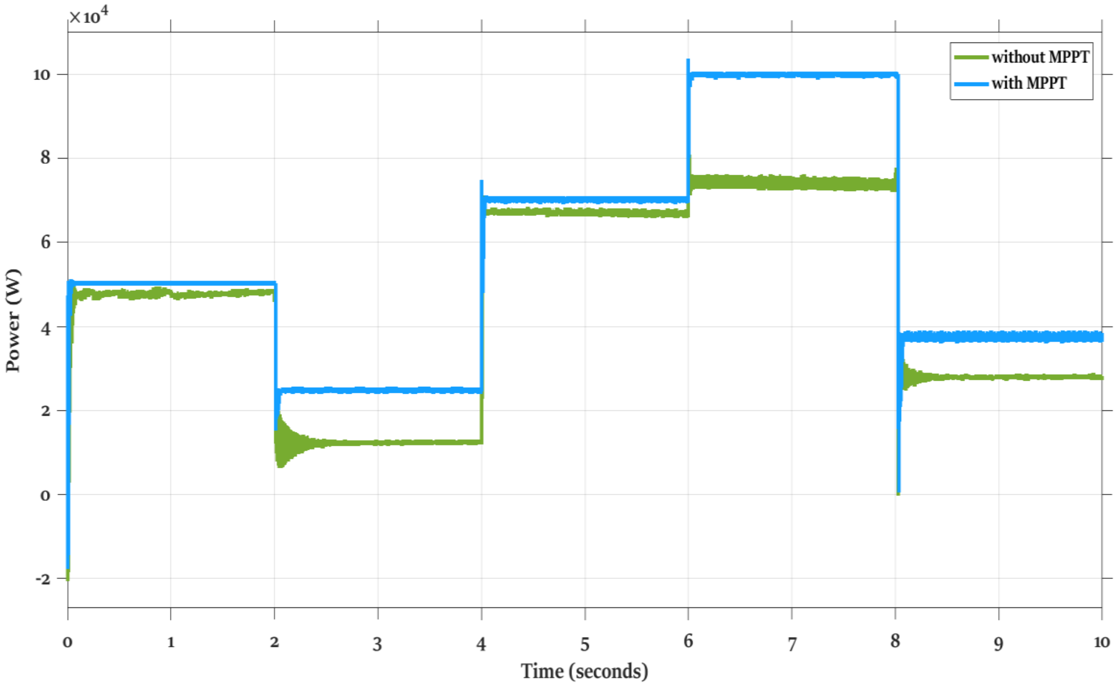


Figure 3.19: Power of PV system with and Without MPPT Control

The results demonstrate the effectiveness of using an MPPT algorithm in a standalone photovoltaic system. The voltage comparison Figure 3.17 shows that, without MPPT, the system output voltage is unstable and unable to maintain an optimal level when irradiance and temperature vary. Large fluctuations and voltage drops are observed, indicating inefficient energy extraction. In contrast, with MPPT, the system maintains a much more stable and higher output voltage, adapting quickly to environmental changes and maximizing energy capture.

Figure 3.18 of duty cycle comparison further supports these observations. Without MPPT, the duty cycle remains fixed at 0.4, regardless of changes in irradiance or temperature, which prevents the system from operating at its maximum power point under different conditions. With MPPT, the duty cycle dynamically adjusts in response to the environmental changes, allowing the boost converter to track the maximum power point continuously. This adaptive behavior ensures better performance, improved system efficiency, and more consistent power delivery.

Overall, the use of MPPT significantly enhances the photovoltaic system's response to variable conditions, leading to improved energy harvesting and system stability.

The system consistently extracts higher power compared to the case without MPPT as shown in Figure 3.19, even under sudden changes in environmental conditions. The response with MPPT is fast and stable, with minimal oscillations around the maximum power point. In contrast, without MPPT, the system operates at lower power levels and shows slower adaptation. Overall, MPPT significantly improves the efficiency and dynamic performance of the system.

This Table 3.1 presents the efficiency of the PV system when operating with and without a Maximum Power Point Tracking (MPPT) controller. Efficiency here refers to the ability of the system to extract the maximum possible power under varying conditions.

Table 3.1: Comparison of System Efficiency with and Without MPPT

	The efficiency
Without MPPT	80.84%
With MPPT	**99.47%**

From the Table 3.1, it is clear that the implementation of MPPT significantly improves the system’s efficiency. Without MPPT, the system reaches an efficiency of 80.84%, indicating substantial power losses due to the inability to adapt to changing conditions. However, when MPPT is applied, the efficiency increases dramatically to **99.47%,** demonstrating almost optimal power extraction. This highlights the critical role of MPPT algorithms in enhancing the performance and reliability of renewable energy systems, especially under dynamic environmental variations.

3.7.2. Test 2

After simulation of the two cases of passive and semi-active connection we obtain these results.

The simulation results presented in Figures 3.20 and 3.21 demonstrate the effectiveness of the semi-active hybrid energy storage system (HESS) in managing dynamic load demands by leveraging the complementary characteristics of a supercapacitor (SC) and a lead-acid battery. The total load current is successfully decomposed into low- and high-frequency components using a low-pass filter, with the SC actively controlled via a PI controller to respond to high-frequency transients, while the battery passively supports the smoother, low-frequency portion.

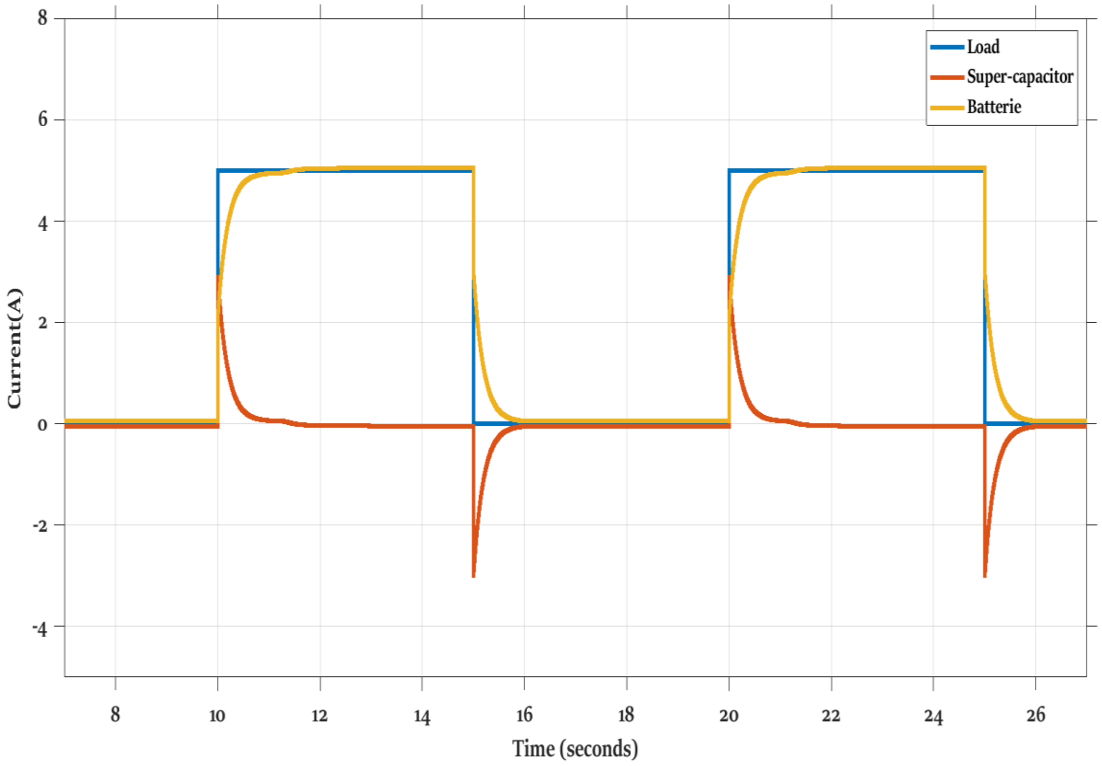


Figure 3.20: Power sharing curve for Battery and SC in passive connection.

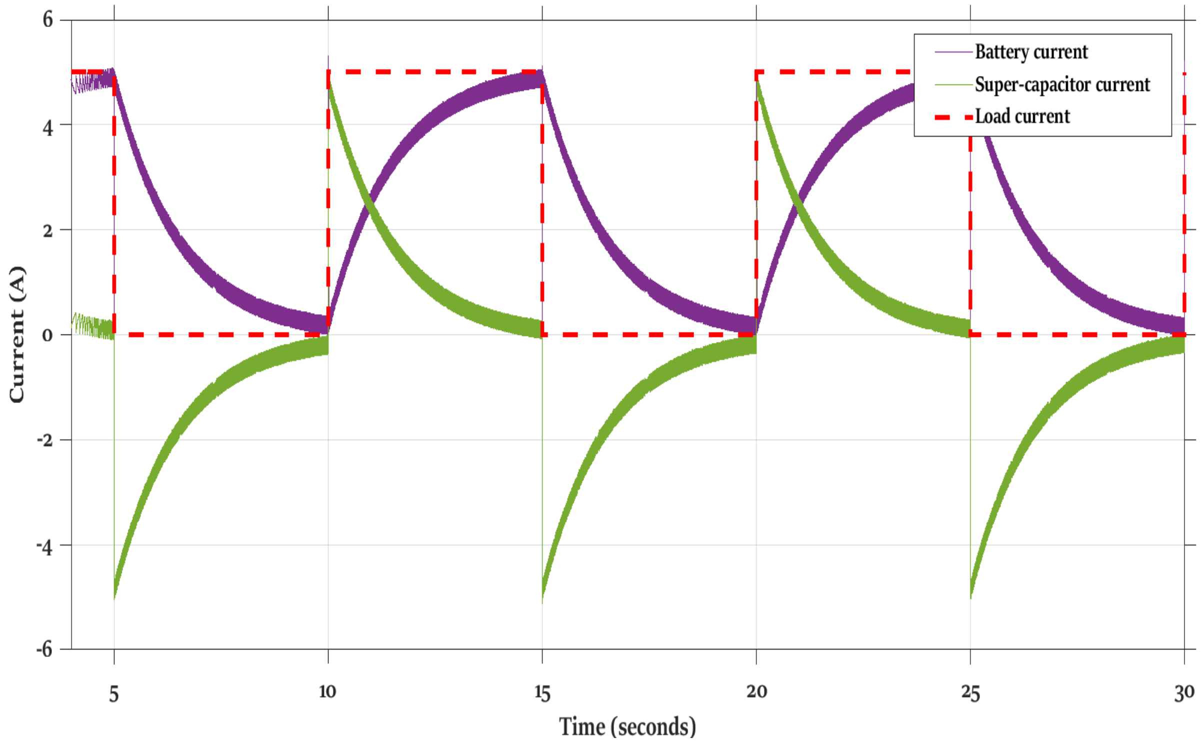


Figure 3.21: Power sharing curves for battery and SC in active connection.

This is evident in the current curves, where the SC handles rapid changes and sharp current spikes, while the battery exhibits a slower, more stable current profile. Such coordinated power sharing enhances the system's efficiency and dynamic response, minimizes battery stress, and improves the overall lifecycle of the energy storage components. The smooth transitions and precise current tracking also indicate that the control strategy, particularly the PI controller, is well-tuned and effective in regulating SC performance within the hybrid architecture.

3.7.3. Test 3

After simulating the three cases of passive battery connection, passive battery-SC connection and semi-active connection in PV system with load, we compared the results in the next figure.

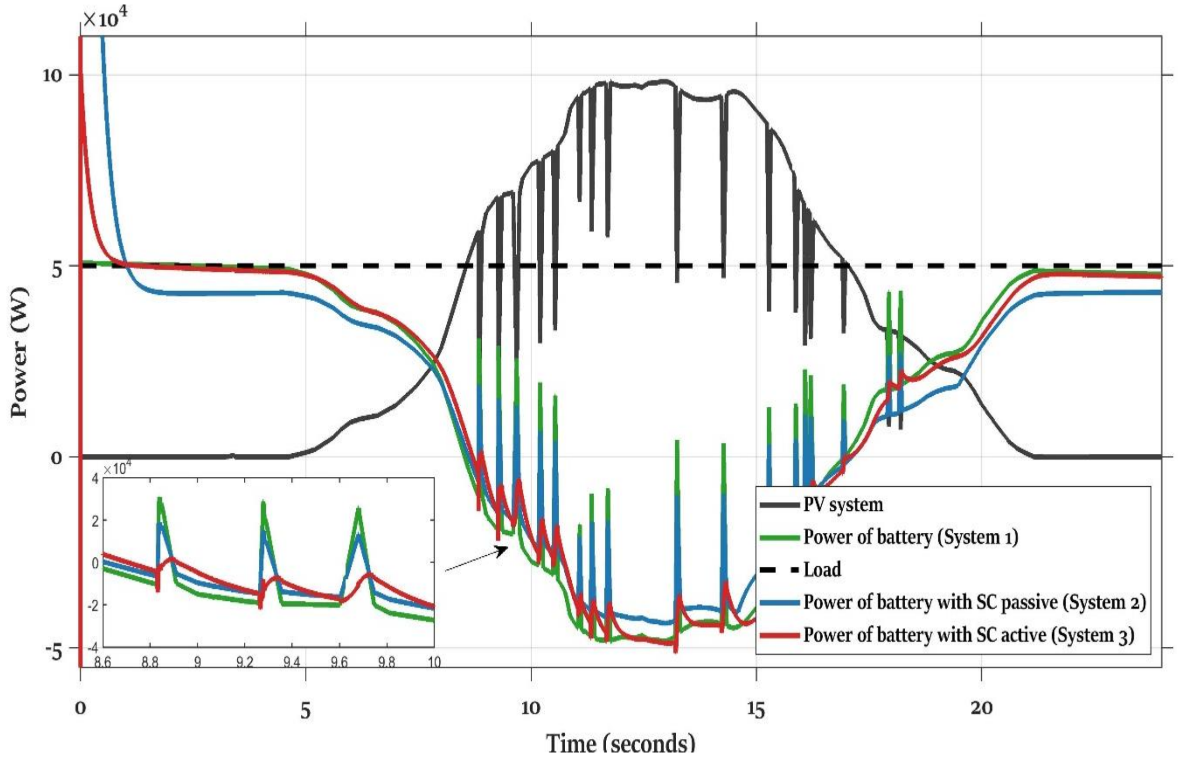


Figure 3.22: The curves of the power output of the PV system and battery for each system

Figures 3.22 and 3.23 illustrate the energy behavior of a solar system and battery under three different configurations. In the first configuration, the battery is passively connected to the PV system. Here, any drop in solar energy—such as during shading or cloudy conditions—results in a high battery discharge rate to maintain load supply. The second configuration adds a supercapacitor to the passive system. Although the battery still discharges rapidly during partial shading, the supercapacitor helps absorb some of the energy fluctuations, thereby reducing the frequency and intensity of battery cycling compared to the first setup. The third configuration introduces an actively controlled connection with the supercapacitor. This system offers better energy management and dynamic response, where the supercapacitor quickly reacts to sudden drops in solar generation. As a result, it effectively buffers short-term fluctuations, significantly reducing stress on the battery and helping to extend its lifespan.

Figure 3.23 compares the performance of the passive-supercapacitor system (System 2) with the semi-active system featuring control logic (System 3). The results show that the controlled supercapacitor in System 3 responds more effectively to power fluctuations, further minimizing unnecessary battery cycling. Overall, integrating a supercapacitor—especially with active control—proves highly beneficial in stabilizing PV system output, improving battery efficiency, and extending its operational life.

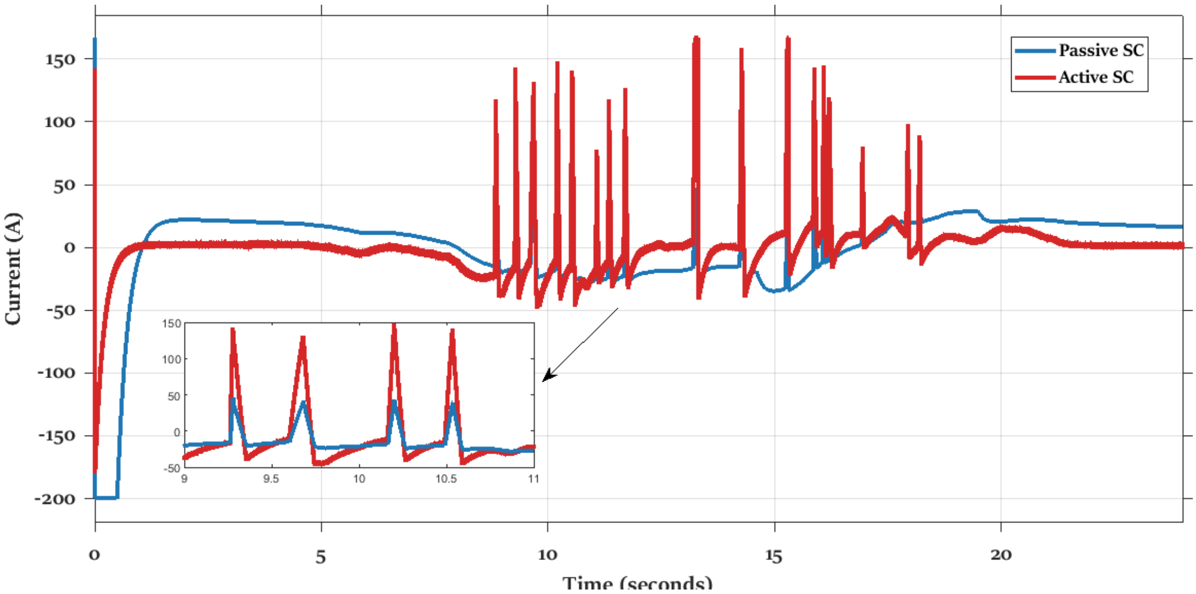


Figure 3.23: The curves of the power output of the Supercapacitor system for each system (System 2, System 3).

3.8. Conclusion

This chapter presented a detailed analysis of energy management in photovoltaic (PV) systems integrated with batteries and supercapacitors under varying operating conditions. Through simulation of three configurations, battery-only, battery with a passively connected supercapacitor, and battery with an actively controlled supercapacitor—the results clearly demonstrated the benefits of incorporating a supercapacitor, particularly with an active control strategy.

The passive battery system showed significant stress due to rapid and deep charge-discharge cycles in response to PV fluctuations, which can shorten battery life. The addition of a passively connected supercapacitor provided partial mitigation by absorbing some transient fluctuations. However, the best performance was observed in the actively controlled system, where the control loop enabled the supercapacitor to dynamically compensate for rapid energy variations, reducing the battery's workload and thereby improving system stability and extending battery lifespan.

These findings highlight the importance of intelligent energy management strategies and confirm that integrating supercapacitors with appropriate control mechanisms is a highly effective solution for enhancing the reliability, efficiency, and durability of hybrid PV-battery energy systems.

General Conclusion and Perspectives

This memoir has explored the integration of photovoltaic systems with hybrid energy storage technologies to improve energy reliability under varying irradiance conditions. In the first chapter, reviewing the fundamental principles and technologies underlying photovoltaic generation and energy storage, with emphasis on batteries and supercapacitors. The advantages of combining these storage elements into a hybrid system were highlighted, particularly in the context of autonomous PV installations.

The second chapter focusing on the detailed modeling of each system component. Electrical models for the PV generator, batteries, and supercapacitors were developed to better understand their dynamic behaviors. Power converters, crucial for interfacing these components, were also modeled, and the effects of meteorological parameters on system performance were analyzed. Additionally, Maximum Power Point Tracking (MPPT) techniques were introduced as essential tools for optimizing the energy yield of the PV system.

Finally, the third chapter presenting various simulation scenarios, including PV systems with and without MPPT, and different topologies of hybrid storage connection—passive and semi-active. Control strategies, including power allocation and PI-based current control, were implemented to manage the energy flow between PV, battery, and supercapacitor. Results demonstrated that the use of a hybrid storage system, particularly under cloudy conditions, significantly improves power stability and system responsiveness, validating the effectiveness of the proposed design and control approach.

In conclusion, this study confirms the vital role of hybrid energy storage in enhancing the performance and reliability of PV systems, especially in environments with fluctuating solar irradiance. Future work could extend to experimental validation and the integration of intelligent energy management systems based on artificial intelligence or adaptive control algorithms.

Perspectives

We all know that no work can cover all aspects and hypotheses completely. Therefore, we propose a set of points that could be further explored and give suggestions for developing the work:

- Develop intelligent energy management strategies
- Validate simulation results experimentally
- Extend the system to larger-scale applications
- Conduct detailed economic and environmental analysis
- Integrate additional renewable energy sources
- Explore emerging storage technologies, like lithium-sulfur batteries or solid-state supercapacitors, for improved performance.

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