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Entitled:

Photovoltaic pumping system control based on DC motor

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بسم الله الرحمن الرحيم

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Résumé:

Dans ce mémoire, un système de pompage photovoltaïque basé sur un moteur à courant continu a été étudié et modélisé. L'objectif principal était d'améliorer l'efficacité énergétique du système en utilisant des techniques de suivi du point de puissance maximale (MPPT), notamment les algorithmes Perturb & Observe (P&O) et Incremental Conductance (INC). Un modèle de simulation a été développé sous MATLAB/Simulink pour évaluer le comportement du système sous différentes conditions d'irradiation. Les résultats montrent que l'algorithme INC offre une meilleure précision et une réponse plus rapide que P&O, ce qui le rend plus adapté aux environnements dynamiques.

Mots-clés :pompe , systéme photovoltaïque , dc moteur

Abstract:

This thesis focuses on the modeling and control of a photovoltaic water pumping system using a separately excited DC motor. The main objective was to enhance system efficiency through Maximum Power Point Tracking (MPPT) techniques, specifically Perturb & Observe (P&O) and Incremental Conductance (INC) algorithms. A detailed simulation model was developed using MATLAB/Simulink to assess the system's performance under variable irradiance conditions. The results demonstrated that the INC algorithm achieved faster convergence and higher tracking accuracy compared to P&O, making it more suitable for dynamic environments.

Keywords: pump ,solar energy , direct current

ملخص:

في هذه المذكرة، تم دراسة وتصميم نظام ضخ كهروضوئي يعتمد على محرك تيار مستمر. تم التركيز على تحسين كفاءة النظام باستخدام تقنيات تتبع نقطة القدرة العظمى(MPPT) ، حيث تم تنفيذ خوارزميتي Perturb & Observe (P&O) و Incremental Conductance (INC). تم بناء نموذج محاكاة متكامل باستخدام برنامج MATLAB/Simulink ، وتم تحليل الأداء تحت ظروف إشعاعية متغيرة. أظهرت النتائج أن خوارزمية INC توفر دقة واستجابة أسرع مقارنة بـ P&O، مما يجعلها أكثر ملاءمة للأنظمة الديناميكية.

الكلمات المفتاحية :

مضخة ، طاقة شمسية ، تيار مستمر

تقدير

بسم الله الرحمن الرحيم

﴿ وَقلِ ٱعۡملوُا فسَيَرى ٱ ۖ عَملُكۡم وَرسُولهُ وَٱلۡمۡؤمِنوُنَ ﴾
سورة التوبة، الآية 105 —

At this pivotal moment of academic achievement, I pause with humility and gratitude to extend my heartfelt thanks to those who have supported and inspired me throughout this journey.

My utmost appreciation goes to my esteemed supervisor, ***Dr. ToumiJaafar****, whose insightful guidance, continuous encouragement, and deep knowledge have left a lasting impact on both this work and my academic development.*

His mentorship has been a compass that kept this thesis on the right path.

To my ***dear parents****, your endless love, prayers, and sacrifices have carried me forward even in the most challenging times. I am forever indebted to your unwavering belief in me.*

To my ***brothers and sisters****, thank you for being a source of emotional support, joy, and understanding. Your presence made this journey lighter and brighter.*

To my ***entire family****, near and far—your encouragement, patience, and love have surrounded me like a protective shield. This achievement is as much yours as it is mine.*

With all my heart, I dedicate this thesis to you. May Allah reward you and bless you always

Contents

Chapter I: Photovoltaic system Generalities.

Chapter II: Mathematical Modeling of Photovoltaic Systems

Chapter III: Photovoltaic System: Simulation and Results

Figures list

Tables list

List of Abbreviations

PV: Photovoltaic.

Ipv: Current supplied by the photovoltaic cell (A).

Iph: Current produced by the solar cell (A).

Id: Diode current (A).

Isc: Cell short-circuit current (A).

Is: Diode saturation current (A).

Ish: Shunt current (A).

Impp: Maximum power point current (A).

ΔIpv: Current variation (A).

Vmpp: Maximum power point voltage (V).

Voc: Open-circuit voltage (V).

Vth: Thermal voltage (V).

Vpv: Voltage across the photovoltaic cell (V).

ΔVpv: Voltage variation (V).

α: Current increment coefficient Isc.

βoc: Voltage increment coefficient.

A: Ideality coefficient of the diode.

K: Boltzmann constant 1.38. 10-23 (J/K).

q: Electron charge. q = 1.6.10-19 (C).

Pi: Constant parameters.

Ci: Constant parameters.

ns: Number of cells connected in series.

Rs: Series resistance (Ω).

Rsh: Shunt resistance (Ω).

DC: Direct current.

AC: Alternating current.

E: Direct voltage.

Ki: Power transistor.

Vs: Single-phase AC inverter output voltage.

Di: Freewheel diode.

Vfp: Voltage drop across the impedance Zd of the main phase.

Vbp: Voltage drop across the impedance Zi of the main phase.

Vfa: Voltage drop across

Vba: Voltage drop across the auxiliary phase impedance Zia.

P: Laplace transform.

Générale Introduction

GENERAL INTRODUCTION:

In recent years, the growing demand for clean and sustainable energy has led to an increased focus on photovoltaic (PV) systems, especially in remote and rural areas where access to electricity is limited. One of the most practical applications of PV technology is in water pumping systems, which offer a reliable and environmentally friendly solution for irrigation and water supply without relying on fossil fuels.

This thesis focuses on the **modeling, simulation, and control** of a solar-powered water pumping system using a **DC motor**. The main goal is to improve the system's efficiency and ensure stable operation under different sunlight and temperature conditions. To achieve this, **mathematical models** are developed for all major parts of the system: the PV generator, the power converter, and the DC motor.

The study also includes the use of **Maximum Power Point Tracking (MPPT)** techniques, specifically **Perturb and Observe (P&O)** and **Incremental Conductance (INC)**, which help to extract the maximum possible energy from the PV panels at all times.

Simulations are carried out using MATLAB/Simulink to test how the system performs under real-world conditions. Results show how each part of the system behaves and how control strategies affect performance.

Overall, this work aims to contribute to the design of efficient and intelligent solar pumping systems, which can play an important role in supporting sustainable development and clean energy access, especially in rural and off-grid communities

Chapter I

Photovoltaic System Généralités

I.1. Introduction:

One of the most significant sources of electrical energy generation worldwide is the usage of solar energy through photovoltaic (PV) technology, one of the many renewable energy sources. Globally, solar installations have grown significantly in recent years. When 2020 comes to an end, the cumulative installed capacity exceeded 760.4GW. [1] With reference to IRENA, [2] photovoltaic (PV) is the leading energy technology in terms of annual growth rate (over 35% in 2010–19).[3]

Globally, the use of photovoltaic has increased exponentially in recent years. Due to a number of circumstances, this causes numerous issues with the systems' quality. The photovoltaic module, the most important part of PV systems, can occasionally be challenging to diagnose. The primary issue is that, despite having very varying quality, all of the modules have a very similar appearance. Module flaws are typically invisible to the unaided eye, and certain techniques are needed to identify their causes. Because of this, many installations need to be monitored on a regular basis. According to current statistics, crystalline silicon photovoltaic modules' power ratings are degrading at a rate of 0.8% every year.1 Work can be done to increase the PV modules' dependability and service life by observing the difficulties associated with their operation.

I.2. Describe photovoltaic:

Using semiconducting materials that display the photovoltaic effect, photovoltaic (PV) is a technology that uses light to generate electricity. When exposed to sunlight, these materials—typically silicon—produce an electric current, which makes them an essential part of solar panels that provide sustainable energy. The process of turning light into electricity is known as the photovoltaic effect. PV systems use solar modules, which are made up of several solar cells that produce electricity. PV installations can be floating, wall-mounted, rooftop-mounted, or ground-mounted. Large utility-scale power plants with capacities ranging from hundreds of megawatts to tiny, roof-top mounted or building-integrated systems with capacities ranging from a few to many tens of kilowatts.

Photovoltaic systems, which comprise a wide range of electrical equipment, use PV cells. In addition to providing electricity to an electric power grid, PV systems can provide electricity in areas without electrical distribution networks. [3] PV arrays come in a variety of sizes and can be swiftly installed. Building-mounted PV systems have very little impact on the environment. The bulk of solar modules are now utilized for grid-connected power production systems, however the first practical use of photovoltaic was to power orbiting satellites and other spacecraft.

I.2.1. The impact of photovoltaic:

. The impact of photovoltaic, first discovered by A. Becquerel in 1839,[5]includes the photovoltaic effect, which is the process of turning light into electricity. This procedure creates a direct electric current by releasing electrons using photons from light. In the 1930s, solar electricity first appeared, with silicon photovoltaic cells being developed in 1954,[6]allowing solar energy to be used. By the 1970s, solar power had spread to electrify rural locations after being used for space shuttles in the 1960s. Megawatt-scale power plants and solar-powered consumer goods emerged in the 1990s as a result of advancements in the 1980s. Improved production methods and higher manufacturing volumes caused prices to fall dramatically in the 1990s. From 5 MW in 1982 to over 18 GW in 2013, the manufacture of solar modules increased dramatically worldwide.. Algeria's Condor Electronics began producing photovoltaic panels in varying power outputs from 70 W to 285 W at competitive prices in July 2013. [7]

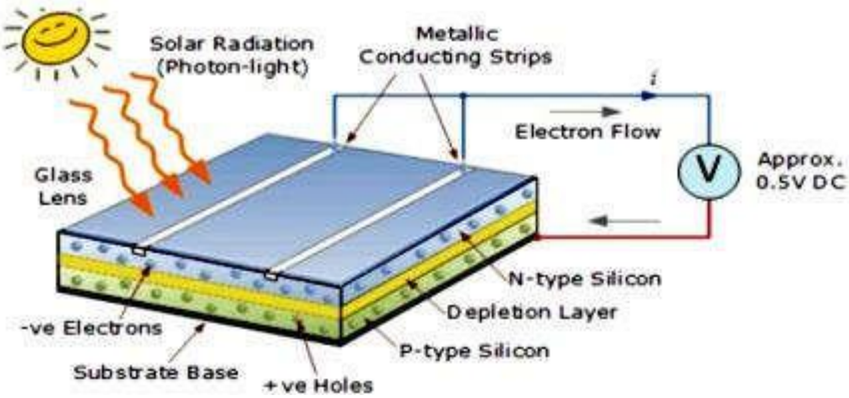


Figure I.1: Photovoltaic effect.

I.2.2. Technologies related to photovoltaic:

Photovoltaic (PV) technology converts sunlight into electricity using semiconductor materials exhibiting the photovoltaic effect. [8]

The basic building blocks of PV systems are PV cells, also known as solar cells. Usually generating 1 to 2 watts of power each, they are composed of materials such as silicon, gallium arsenide, or cadmium telluride. These cells are arranged in panels or modules, which can be used individually or linked to form arrays for applications ranging from small-scale devices like calculators to large-scale utility electricity generation. [8] PV systems can be mounted on various surfaces and can either be fixed or use solar trackers to follow the sun's path. Primary PV technologies include first-generation crystalline silicon cells, second-generation thin films, and third-generation cells with emerging materials. [9]

I.2.2.1. Crystalline silicon:

One kind of photovoltaic technology found in solar cells is crystalline silicon. With over 85% of global PV cell sales in 2011, it is the most widely used form of solar cell in commercially available solar panels. Crystalline silicon solar cells are made from mono crystalline (single-crystal) silicon or polycrystalline silicon. [10][11]

Wafer-based cells made of crystalline silicon (Si), including mono crystalline and polycrystalline Si, are used in the first generate. Notably, [12] the highest efficiency for Si-based wafer cells reached 26.7%.[12]With an efficiency of 24.4%, PV modules have also seen significant breakthroughs. The year 2019, Si-wafer-based PV technologies constituted approximately 95% of total production.[13]

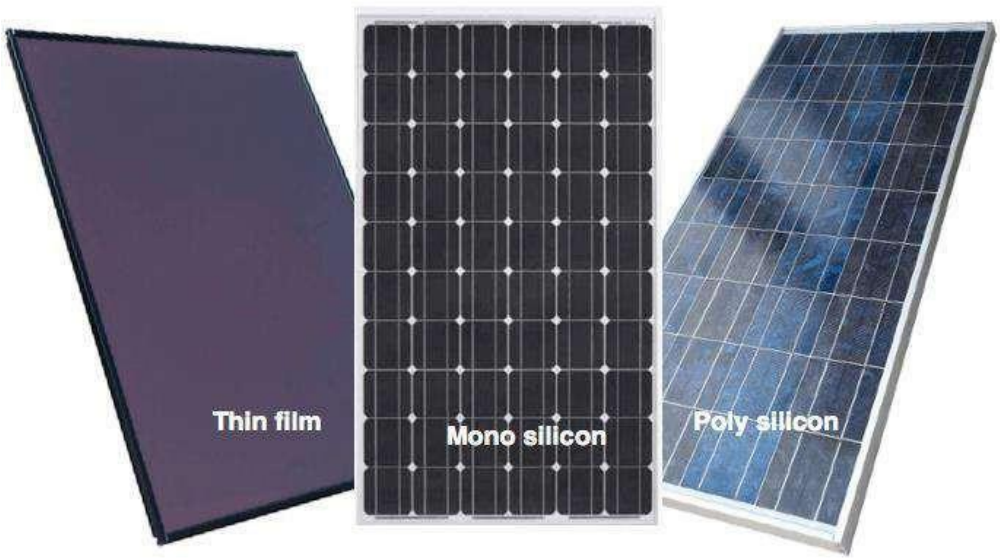


Figure I.2: Type of Photovoltaic cells.

I.2.2.2. Thin films:

The second generation of solar cells, known as thin-film solar cells, are made of cadmium telluride (CdTe), copper indium gallium selenide (CIGS),amorphous silicon (a-Si), and amorphous silicon: hydrogenated (a-Si:H) cells. [12]Compared to silicon (Si) solar cells built on wafers, this technique is easier to adopt because of its simpler manufacture method. They are still less efficient than first-generation cells, though. With regard to CIGS cells in particular, the most efficient thin-film solar cells have set a new record of 23.35% efficiency. With roughly 7% of the photovoltaic (PV) market, thin-film solar cell technology is the second most popular technology worldwide, after wafer-based Si. Compared to CIGS, CdTe and a-Si:H solar cells are simpler to manufacture., while the stability of CIGS- and CdTe-based cells is higher than that of a-Si:H cells.[11]

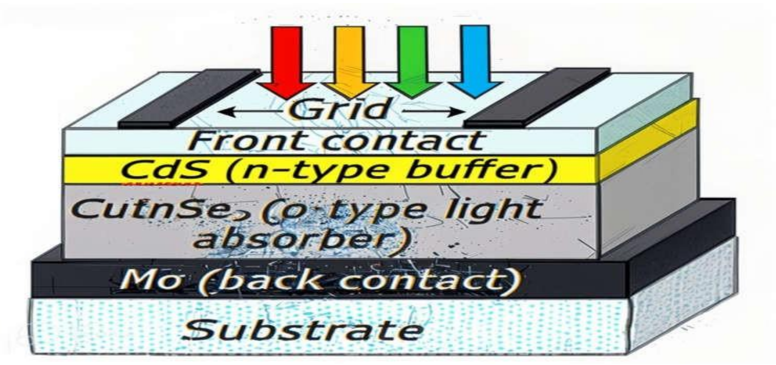


Figure I.3: A common GIGS solar cell construction.

I.2.2.3. New technologies:

Emerging technologies including organic, dye-sensitized solar cells (DSSC), quantum dots (QD), perovskite, and multi-junction cells are all part of the third generation of photovoltaic technology. The affordability of these new technologies is well-known. Of the several varieties of third-generation photovoltaic technology, perovskites in the form of thin films have the highest efficiency rate of 25.2%.[13]

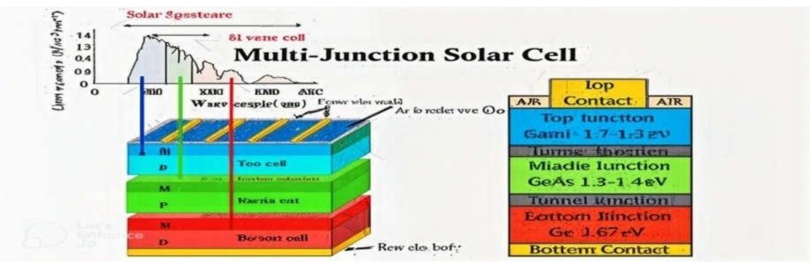


Figure I.4: A typical multi-junction solar cell structure.

I.3. Solar power:

An hour's worth of solar energy collected by the Earth's surface is equivalent to a year's worth of energy requirements. Knowing the sun's spectral factor is essential because it emits energy at 1367 W/m2. for creating solar energy (PV) systems. The visible spectrum, which has the maximum energy density, is where solar cells should collect energy. Direct, diffuse, and albedo radiation make up sunlight, collectively termed global radiation. [6]

The ozone layer, CO2, and other elements can cause the atmosphere to either absorb, scatter, or leave light undisturbed, water vapor, and atmospheric particulate matter. [1]

Ground-level energy absorption is influenced by air mass; atmospheric circumstances cause the AM0 irradiance level to drop to 1000 W/m2. AM1.5 serves as the standard test condition in solar cell design. [14]

I.3.1. Radiation from the sun:

The term "solar radiation" describes the energy that the Sun emits as electromagnetic waves., encompassing visible and ultraviolet light as well as infrared radiation.[5]

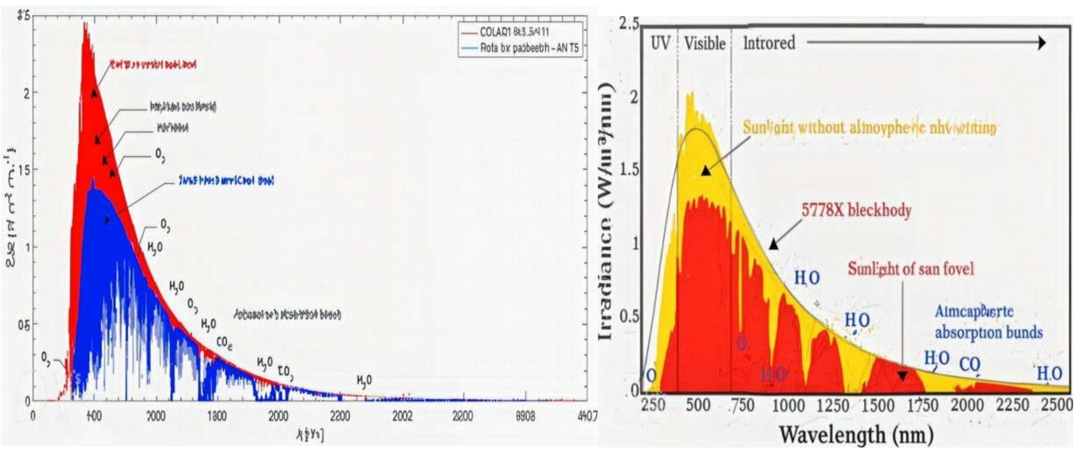


Figure I.5: the average spacing between wavelengths in the extraterrestrial solar spectrum.

I.3.1.a. The spectrum of the sun:

The simulated spectrum irradiance for different air mass (AM) and zenith values is depicted in the graph (figure I.3.2): Spectral irradiance plot for various AM and zenith values (latitude ¼36°, longitude ¼5°, and tilt angle ¼36°):

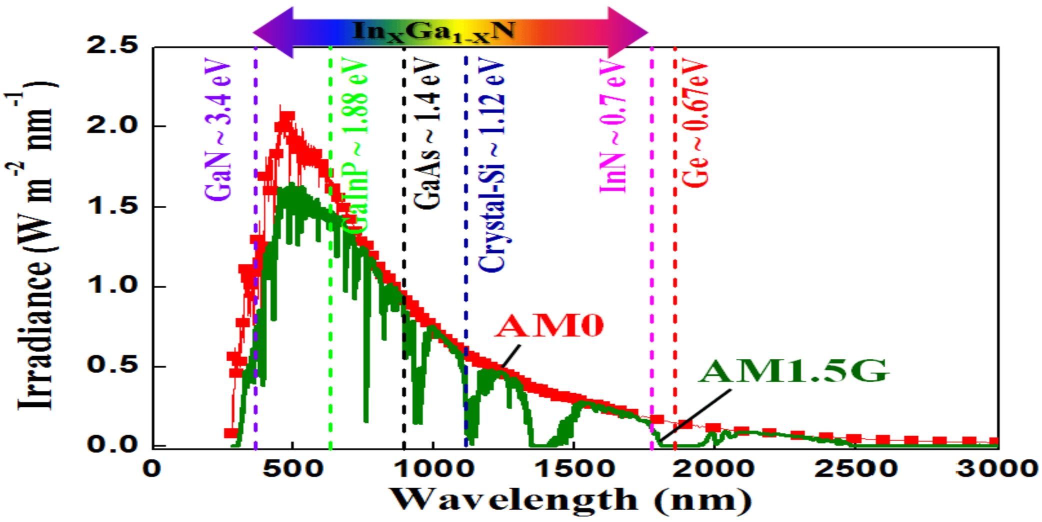


Figure I.6: Plot of spectral irradiance for different values of AM and zenith.

Photons are the primary energy source used in renewable energy solutions that capture solar radiation for terrestrial use. also known as "optical radiation," which fall within the spectral range of approximately 300-4000nm. [5]The intensity of solar radiation that strikes a hypothetical unit surface is known as solar irradiance, and it is expressed in W/m2. It does not take time-accumulated energy into consideration; rather, it represents an energy value that is instantaneous. Pyranometers are usually the main tool used by meteorologists to measure sun irradiation. Reference solar cells are also used for measuring global solar irradiance denoted by G.[8]

The following figure I.3.3provides a sample of the isolation recorded over the duration of 2020.[9] The following is the expression for the daily extraterrestrial radiation on a horizontal surface (Go):

$$G_o = \frac{24}{\pi}\left[1 + 0.033\cos\left(\frac{2\pi d}{365}\right)\right](\cos(\varphi)\cos(\delta)\sin(\omega_s) + \omega_s\sin(\varphi)\sin(\delta)) \quad (1.1)$$

The day of the year, latitude, and declination are represented by the letters d, φ, and δ, respectively. For the horizontal surface ωs, the sunset hour angle ωs is provided by

$$\omega_s = \cos^{-1}(-\,tak(\varphi)\,tak(ð))$$

The length of daylight is equal to the interval between sunrise and dusk, and it is one of the extraterrestrial variables in the classical Angstrom (1924) equation, which can be estimated from various sources. [15][16]

$$\cos(S_o) = -\tan(\varphi)\tan(\eth) \quad (1.3)$$

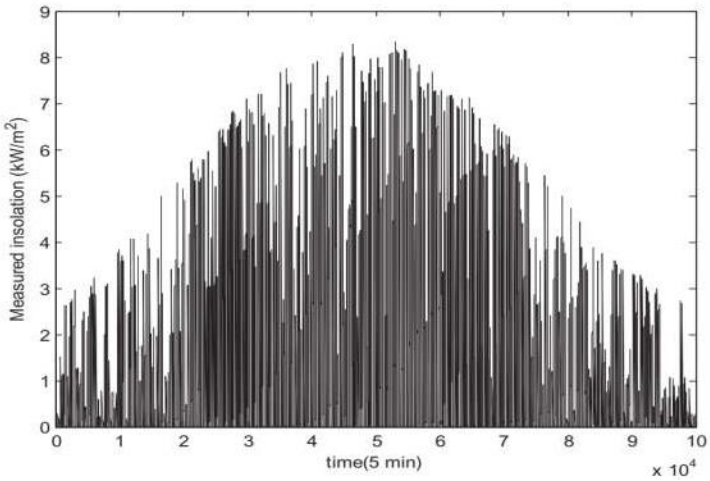


Figure I.7: The measures of insolation for 2020.

I.3.1.b.Radiation from space and the duration of the day:

The ratio of daily global radiation to daily extraterrestrial radiation on a horizontal surface is known as the daily clearness index, or Kt: $K_t = \frac{G}{G_o}$ (1.4)

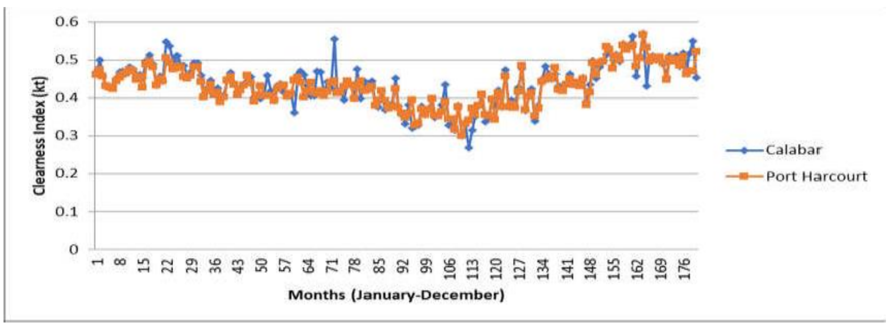


Figure I.8: presents a graphical representation of extraterrestrial radiation *(G**o**)* and the calculated clearness index *(K**t**)*.

I.3.2. Principles of Cell Operation:

I.3.2.1. Components of semiconductors:

In solar photovoltaic, semiconductors are used, materials with resistivity values between conductors and insulators (typically ranging from 10−4 to 0.5 ohmmeter). [18]

Silicon, germanium, and selenium are a few examples. Semiconductors, in contrast to conductors, have a negative temperature coefficient, which means that their resistance decreases as the temperature rises. In semiconductors, the conduction band is almost empty, with a tiny energy gap (about 1 eV) between it and the valence band, which is primarily populated with electrons. termed the forbidden energy gap. This small gap allows for the movement of valence electrons into the conduction band with minimal energy input. [7]

I.3.2.2. Semiconductor classification:

There are two main categories of semiconductor materials: pure intrinsic semiconductors and impure extrinsic semiconductors:

a) An inherent semiconductor:

A semiconductor material that has no discernible dopant species is called an intrinsic semiconductor, sometimes referred to as a pure semiconductor. An inherent semiconductor generates electron-hole pairs at normal temperature. Conduction through free electrons and holes created by the thermal energy-induced breakdown of covalent bonds begins when a potential is put across it. As a result, the intrinsic semiconductor's current flow consists of both electron and hole. In an intrinsic semiconductor, the number of holes in the valence band equals the number of free electrons in the conduction band. The magnitude of the current produced by electrons and holes is equal and the total current in an intrinsic semiconductor is the sum of hole and electron current.[18]

b) An external semiconductor:

Intrinsic semiconductors have low conductivity at ambient temperature because there aren't many free charge carriers (holes and electrons). A tiny quantity of an impurity, called a dopant, is purposefully added to intrinsic semiconductors in order to increase their conductivity.An extrinsic semiconductor is the next classification for this doped semiconductor. The dopants, which raise the quantity of free charge carriers in the semiconductor, can be either electron donors (n-type dopants) or electron acceptors (p-type dopants), thereby improving its conductivity. [19]

Doping is the process of adding impurities to an inherent semiconductor. Depending on the kind of impurity supplied, either the number of electrons or the number of holes rises throughout this process. There are two kinds of contaminants added:(1) pentavalent and (2) trivalent. Addition of pentavalent impurity produces free electrons, while in case of trivalent impurity, additional holes are generated. [18]

I.3.3. Extrinsic Semiconductor Types:

a) A semiconductor of the P type.

-Gallium and boron are common dopants for p-type semiconductors.

-The majority carriers in p-type semiconductors are holes, while the minority carriers are electrons.

-In p-type semiconductors, electrons make up the minority of the carriers, whereas holes make up the majority.

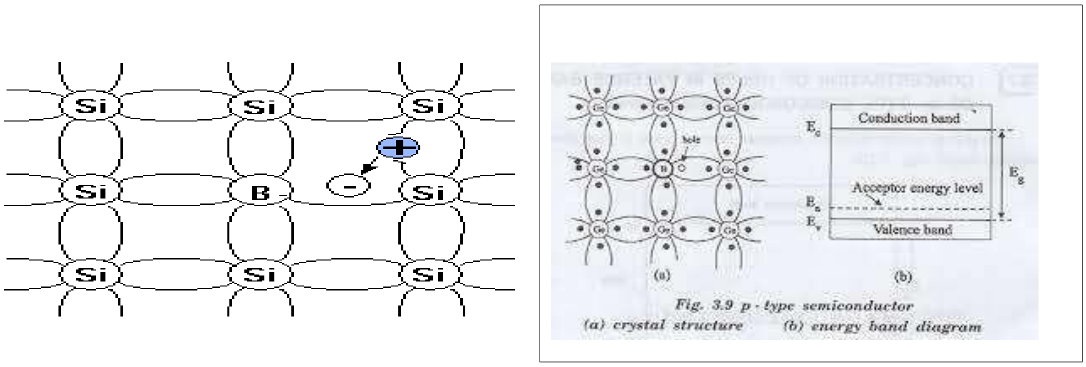


Figure I.9: The p-type semiconductor

b) N-type semiconductor:

-The majority carriers in n-type semiconductors are electrons, while the minority carriers are holes.

- Phosphorus and arsenic are common dopants for n-type semiconductors.

- An extrinsic semiconductor transforms into an n-type semiconductor when doped with electron donor atoms.

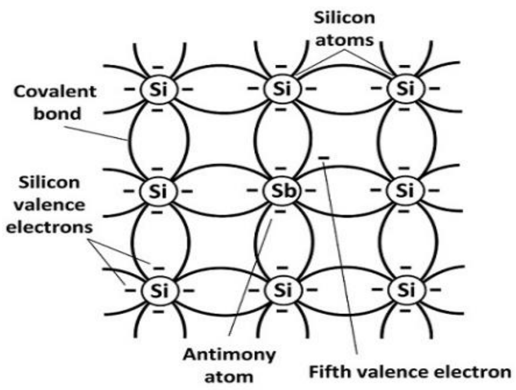


Figure I.10: n-type semiconductor.

I.4. The development of photovoltaic:

Semiconducting materials that exhibit the photovoltaic effect—producing voltage or electric current when exposed to light—are used in photovoltaic to convert light into electricity. P-type and n-type semiconductors combine to form a junction in a solar cell. Electrons in the cell receive energy from light, which enables them to move as an electric current. In order to produce a p-type semiconductor, polysilicon must be processed and boron added. PV cells include crystalline silicon, thin-film, and organic types, each with distinct pros and cons. [8][9][14]

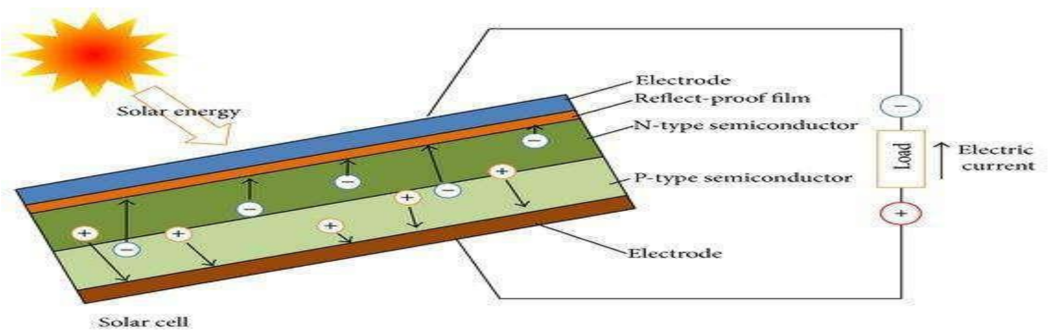


Figure I.11: The photovoltaic structure.

I.5. Photovoltaic systems:

I.5.1. Off-grid, standalone photovoltaic systems:

Electrical systems made up of an array of one or more PV modules are referred to as stand-alone photovoltaic (PV) systems or off-grid systems, conductors, electrical components, and loads, and are not connected to the power grid. [15]These systems are employed when customers want to be independent of the power supplier and in remote locations where running a power line to the grid is not feasible or cost-effective. Solar panels, charge controllers, batteries, inverters, and other balance-of-system elements are commonly found in standalone PV systems. These systems are made to deliver dependable electricity for a range of usage, including commercial, industrial, and residential ones.As it shown in the figure below

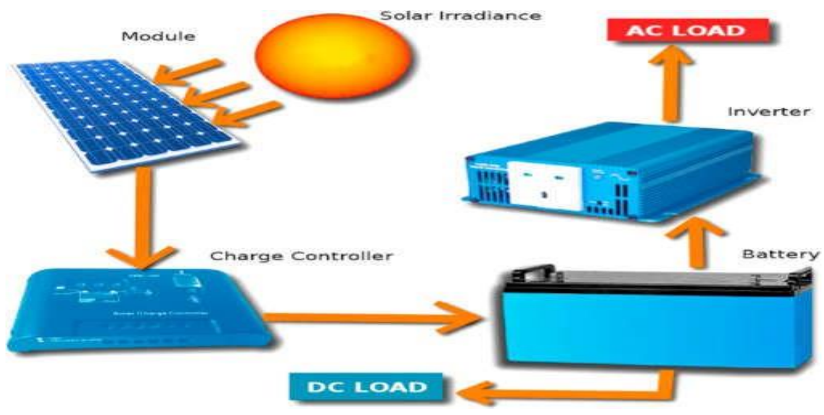


Figure I.12: Off-grid, standalone photovoltaic systems.

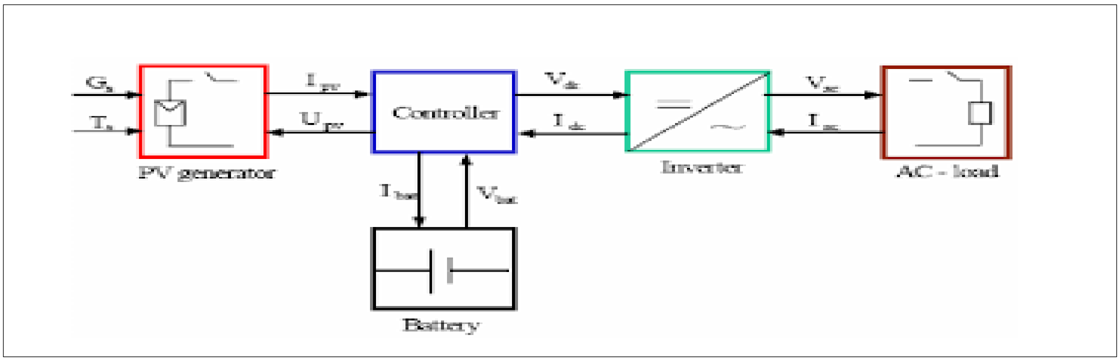


Figure I.13: Stand-alone photovoltaic system schematic.

I.5.1.1. Grid-connected photovoltaic systems:

Grid-connected PV systems are photovoltaic (PV) systems that produce electricity and are connected to the utility grid. These systems consist of solar panels, one or more inverters, a power conditioning device, and grid-connection hardware. They come in many sizes, from small rooftop systems for residences and commercial buildings to enormous utility-scale solar power plants. When conditions are right, the grid-connected solar system provides excess power to the utility grid for consumption by other users. Because grid-connected PV systems don't need a battery system, they are more user-friendly and less expensive than standalone systems.However, It does necessitate a utility grid connection, which means that the system will not function during power outages unless it has a battery backup system.[15]

Figure I.14: Diagrammatic illustration of a PV system connected to the grid.

I.5.1.2. Photovoltaic hybrid systems:

Hybrid photovoltaic (PV) systems are flexible renewable energy sources that can function independently during blackouts or link to the grid like conventional solar arrays. These systems can automatically switch between using grid power, solar power, and battery storage because they usually include solar panels, a hybrid inverter, and a battery bank. Homeowners may control their energy use, steer clear of periods of high electricity costs, and even supply backup power in the event of a grid failure thanks to this flexibility. Hybrid PV systems, which combine the advantages of off-grid and grid-tied systems, can be an affordable and environmentally friendly choice. They are a sensible option for a range of applications since they are made to adhere to pertinent standards and can be customized to satisfy certain energy requirements, including residential, commercial, and industrial use.[19]

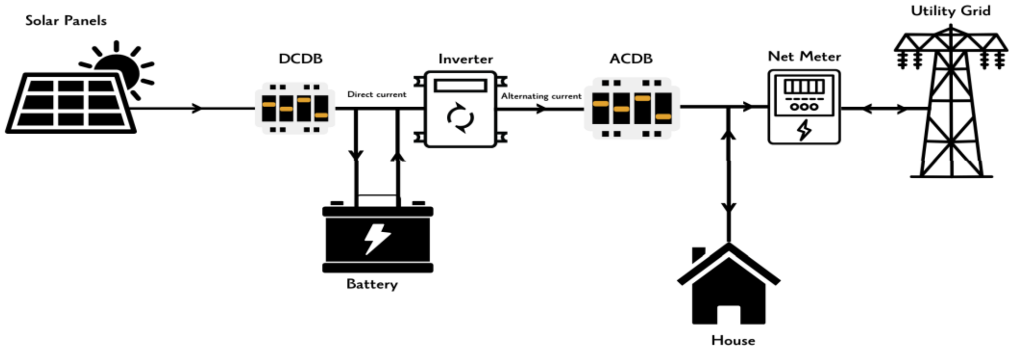


Figure I.15: photovoltaic systems that are hybrid.

I.5.3. Regulator:

A solar system's charge regulators are essential parts that control battery charging and discharging for maximum lifespan. As the battery gets closer to full charge, their main job is to reduce current, preventing the formation of small bubbles on the positive electrodes. [17] There are two main functions of the charge regulator:

• **Battery Protection**: The charge regulator guards against overcharging, which can harm the battery and reduce its lifespan, by managing the charging process.
• **Optimization**: By ensuring that the battery is charged effectively, the charge regulator maximizes the battery's capacity and performance.

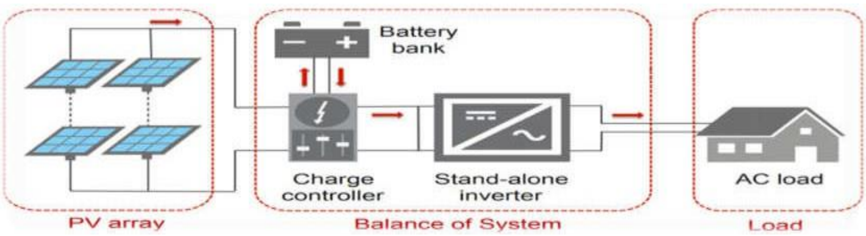


Figure I.16: The fundamental design of an autonomous solar energy system

I.6. Solar-powered module:

I.6.1.A photovoltaic module's composition:

Usually, a photovoltaic (PV) solar module is made up of six main parts., as depicted in figure I.6.1:

- Class: Provides PV cells and the module with protection.

- Sealant: To secure the module and guarantee its water proofnes

- The aluminum frame gives the module strength and structural stability.

- The PV cells are encased in an ethylene-vinyl acetate (EVA) coating that is resistant to moisture and weather.

- The semiconductor devices that turn sunlight into electricity are called photovoltaic cells.

- White Tedlar sheet: Increases big modules' mechanical strength, particularly in terms of durability and resistance to environmental factors. [19]

Figure I.17: Composition of a photovoltaic solar module.

I.6.2. PV Module Connection in Series and Parallel:

I.6.2.1. connection in series:

When identical cells or modules are connected in series, the voltage rises in proportion to the number of cells or modules connected, but the branch's current stays constant. This results in a larger overall voltage output since the voltage of the entire series branch is equal to the sum of the voltages of all the individual cells or modules.

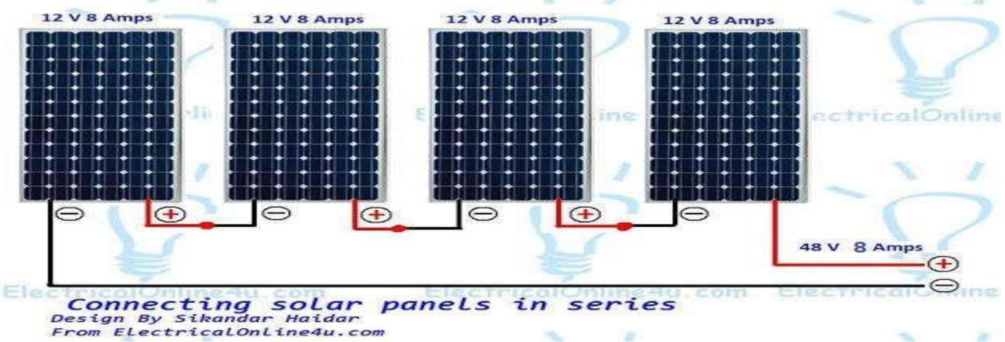


Figure I.18: Charge-Solar-Solar Panels Series Wired.

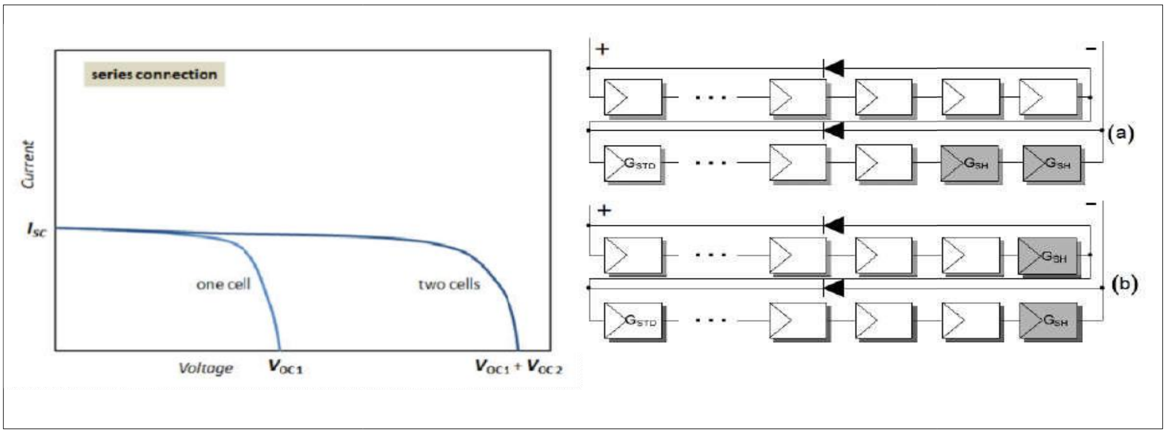


Figure I.19: Resulting characteristic of a grouping of ns cells in series.

I.6.2.2. Parallel linkage:

When photovoltaic (PV) modules are joined in parallel, the voltage stays constant while the current rises in direct proportion to the number of modules connected.

This configuration is used to increase the current output of the system. [40]

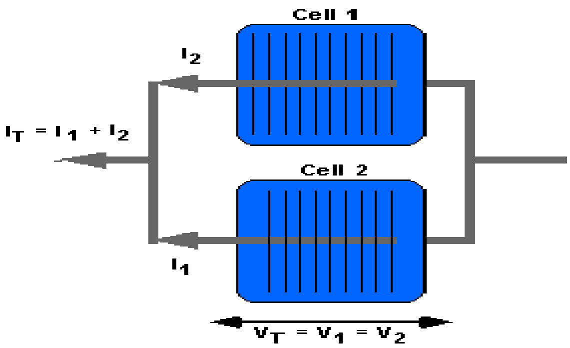


Figure I.20: Parallel Connection of PV Cells.

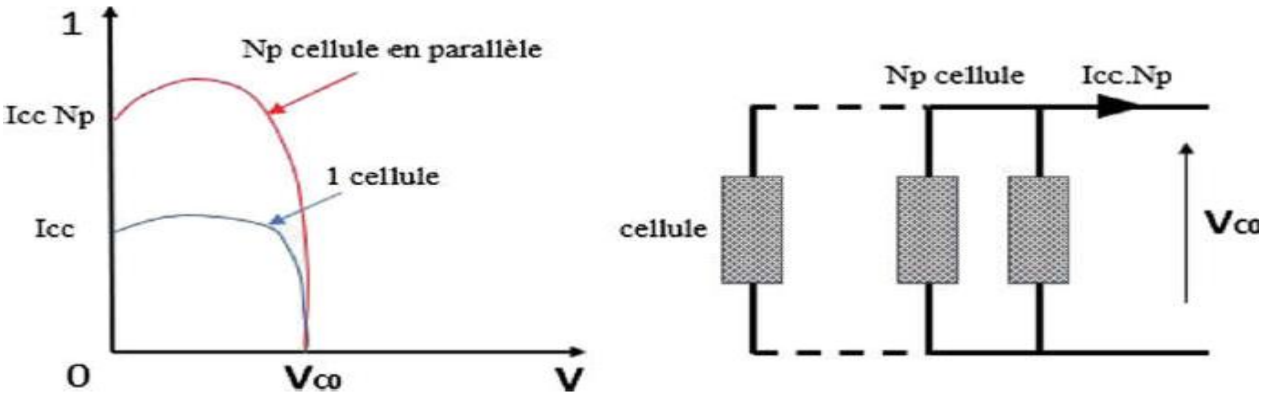


Figure I.21: Resulting characteristic of a grouping of n p cells in parallel.

I.6.2.3. Safeguarding of PV module :

A photovoltaic (PV) module must be protected using a number of steps to provide security and guard against harm to the system and its parts. The following are some crucial elements of PV module protection:

- Current protection: To guard against over current, which can result in heat effects and harm to cables and other parts, fuses or circuit breakers are employed. These devices ought to have the proper voltage and interrupt ratings and be specified for DC use.

- Insulation monitoring: For photovoltaic systems that do not need the ear thing of either conductor, insulation monitoring devices are utilized to identify any loss of insulation resistance.

-Array protection: To guard against overloads and short-circuit currents, DC cable systems are protected at the array level using fuse-links or other over current protection devices.

- Fire protection is essential because PV modules can be mounted on rooftops and are placed outdoors. Using double or reinforced insulation is one way to stop potentially harmful voltage from showing up on parts that are easily accessible.

- Environmental protection: Since PV systems are subject to the weather, protection system design should take the surrounding temperature and other outside factors into account.

This is an illustration of a photovoltaic module with safety features: Protection of PV Modules The PV module in this picture is protected from reverse current, over current, and environmental influences by a junction box, a fuse, and a bypass diode. The architecture of the system and local electrical codes will determine the particular protection devices and their ratings. codes. [19]

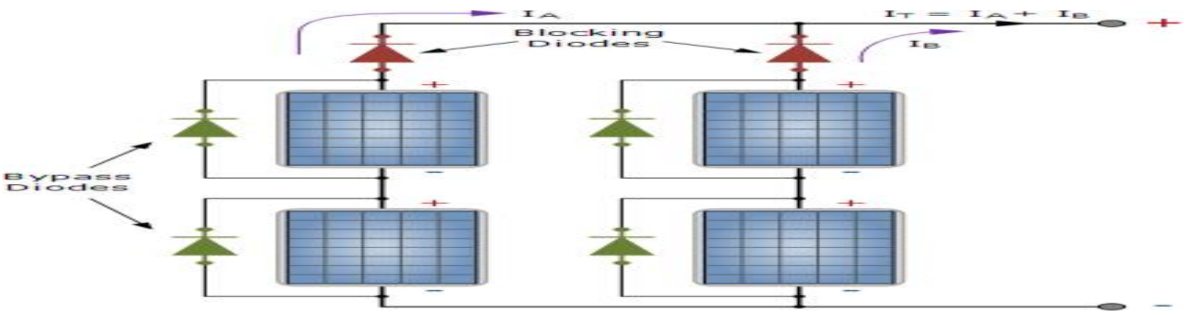


Figure I.22: Series/parallel wiring of photovoltaic modules with their protection diodes.

I.7. Features of a solar power plant:

I.7.1. Features of Current-Voltage:

The relationship between the output current and voltage of a photovoltaic (PV) cell, module, or array is described by the current-voltage (I-V) characteristics of a PV generator. A number of variables, including temperature, solar irradiation, and the design of the PV device, affect these properties. Key elements of PV I-V characteristics include the following:

- The greatest current produced when the PV device's terminals are shorted out is known as the short-circuit current (Isc), with zero voltage. [2]

-The greatest voltage produced while the PV device's terminals are open-circuited, meaning there is no current flowing through them, is known as the open-circuit voltage (Voc).

- The maximum power point, or MPP, is the operational point on the I-V curve where the maximum power production is achieved by multiplying the voltage by the current.

- Shape of the I-V curve: The I-V curve is nonlinear and has a distinctive "knee" shape. The MPP is usually found close to the curve's bend.

- Effect of solar irradiance: The amount of solar radiation hitting the PV device controls the output current (I). [2]

- Temperature effect: As the temperature rises, the PV device's voltage (V) falls.

- I-V curve scaling: The voltage rises when PV devices are coupled in series, and when connected in parallel, the current increases. [2]

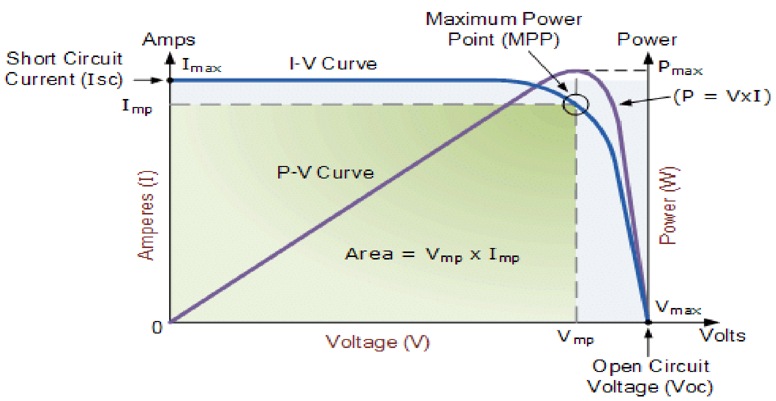


Figure I.23: Influence of illumination on I(V) and P(V).

I.8. Effects of Temperature and Irradiance

I.8.1. Effects of Illumination:

Irradiance has a major impact on photovoltaic (PV) performance since it directly influences the power and output current produced by solar cells. Higher irradiance results in higher output current, which raises the PV module's power output when all other factors remain constant. This relationship can be mathematically represented as follows: higher current and power output are the outcomes of increased irradiance.
The following are some ways that irradiance impacts PV performance:

- Current and Power Output: The I-V and P-V graphs show that the PV module produces more current and power as irradiance rises.

Temperature Effects: Higher temperatures can lower a PV module's open-circuit voltage (Voc), which lowers power output, even though irradiance improves power output. When building a solar PV system, the temperature coefficient of the PV module must be taken into account**.**

-Landscape and Obstacles: Elevation and obstructions like hills or trees can have an impact on irradiance levels, which in turn can have an impact on PV performance.

- An essential part of a photovoltaic system, the inverter output is susceptible to changes in temperature and irradiance.

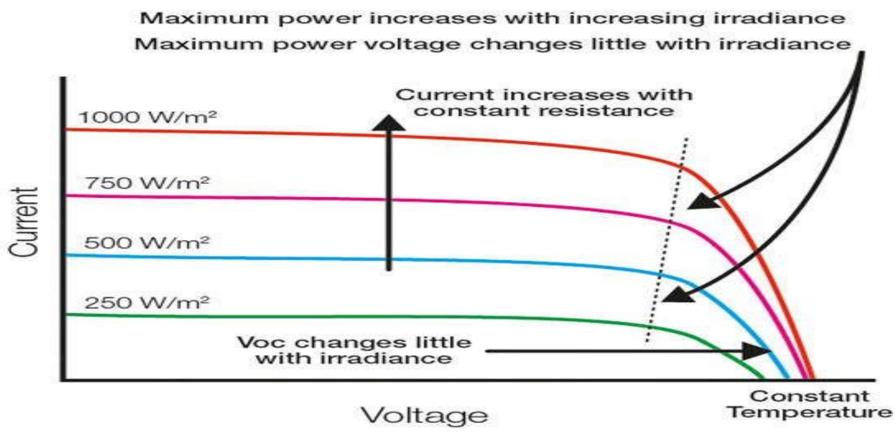


Figure I.24: The influence of temperature on the I (V) and P(V) characteristics.

I.8.2. The impact of temperature:

Experimental investigations have shown that temperature has a significant impact on solar cell performance. While the open-circuit voltage is significantly impacted by temperature, decreasing by about -0.4% per Kelvin (K), the short-circuit current is only slightly affected. As a result, temperature significantly affects solar cell efficiency. leading to power losses ranging from 9% to 15% for a temperature increase of 30°C. [3]

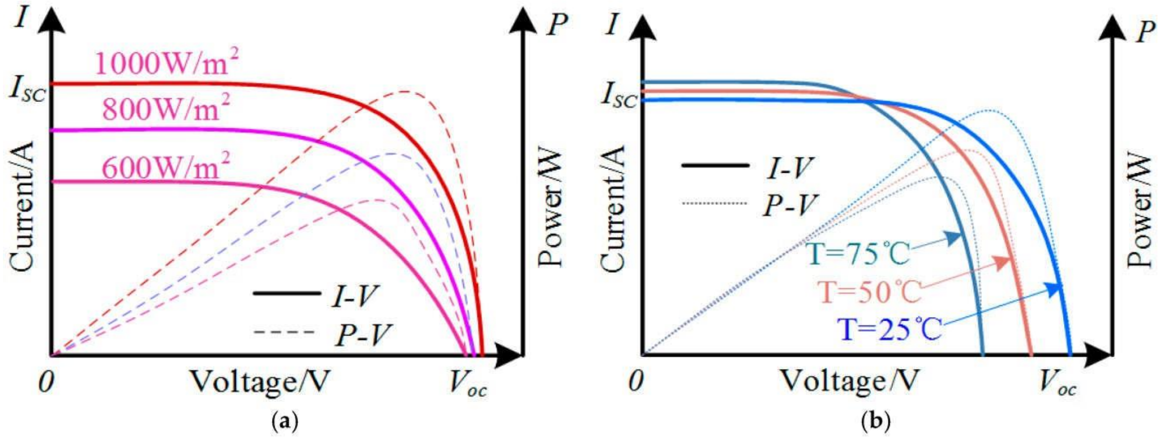


Figure I.25: The influence of temperature on the P(V) and I(V)characteristics

I.8.3. Solar panel orientation:

The following factors should be taken into account while deciding on solar panel orientation:

a- Angle: The panel tilt angle typically approximates the location's latitude to maximize annual energy production, with adjustments for seasonal variations. [2]

b- Direction: In the northern hemisphere, panels ideally face south, and in the southern hemisphere, they face north to capture the most sunlight throughout the day. [5]

c-Tracking Systems: For increased efficiency, consider advanced tracking systems that adjust

d- Shading: Avoid shading from nearby objects or structures, as it can significantly reduce energy production. [6]

panel orientation to follow the sun's path throughout the day. [6]

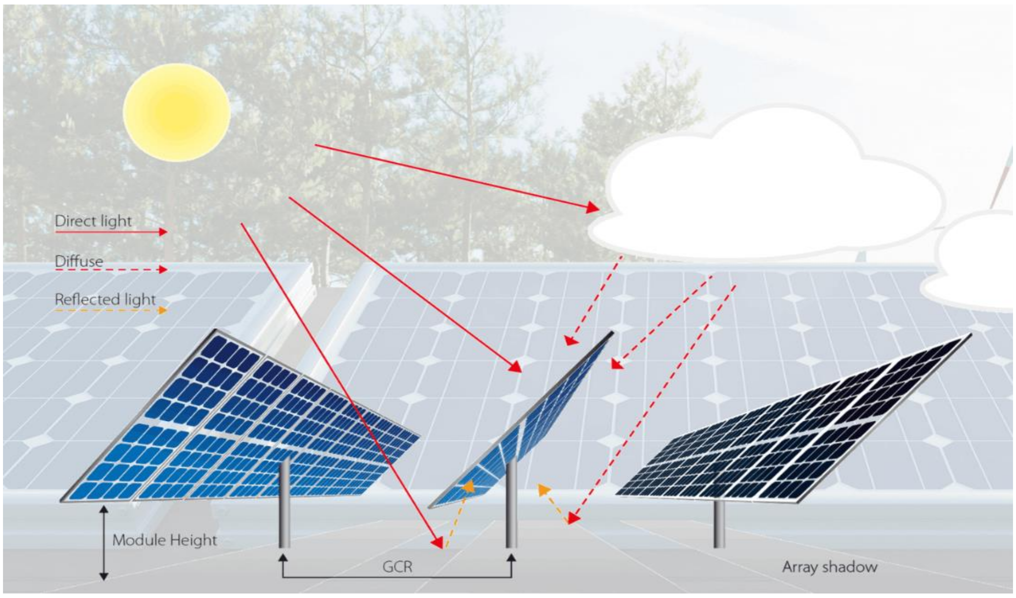


Figure I.26: Solar panel orientation.

I.8.4. Utilizing solar power:

Agricultural irrigation uses photovoltaic systems to power solar pumps and extract water from wells or other sources. In places without grid power or where installation is costly, this offers a dependable and affordable option. Solar pumps can replenish drinking water storage tanks in self-sufficient homes or fill livestock watering tanks, which is very helpful in isolated areas, meeting water needs beyond power line reach. [15][18]

Figure I.27: An application of photovoltaic systems.

I.9. Benefits and drawbacks of photovoltaic (PV) electricity:

I.9.1. PV (photovoltaic) energy benefits:

Table I.1: Benefits**.**

Reduced energy costs	Your energy costs might be considerably decreased by producing your own electricity.
Clean energy	PV systems don't waste natural resources, contaminate groundwater, or release greenhouse gasses.
Low upkeep	Because PV systems have durable materials and no moving parts, they require less maintenance.
Quiet operation	PV systems are silent and unobtrusive.
Renewable energy source	As long as the sun is present, solar energy will be available every day.

I.9.2. PV (photovoltaic) energy drawbacks:

Table I.2: Drawbacks**.**

Lack of knowledge and skills	Since photovoltaic technology is still in its infancy, its advancement may be constrained by a lack of pertinent data.
Dependency on the weather	Weather variations, such as cloudy days, can have an impact on solar energy output and momentarily lower the amount of electricity produced.
Requirements for energy storage	Batteries are used by certain PV systems to store energy, which raises the system's complexity, cost, and footprint.
Efficiency has to be increased.	For PV systems to be cost-effective, they must be combined alongside energy-efficient appliances.
High startup cost	Though cost is declining as the sector grows, the initial expenditure for PV systems can be somewhat substantial.

Conclusion:

Although photovoltaic (PV) energy has many advantages, such as renewable energy, environmental friendliness, low operating costs, and a long lifespan, it also has disadvantages, including high initial costs, reliance on weather, space requirements, energy storage requirements, and possible environmental effects. PV energy is still a viable and growing energy source, nevertheless, with the potential to reduce greenhouse gas emissions and combat climate change. PV energy is anticipated to become more widely available and common in the future as costs come down and technology improves.

Chapter II

Mathematical Modeling of Photovoltaic System

II.1. Introduction:

One essential instrument in the field of renewable energy engineering is the mathematical modeling of photovoltaic (PV) systems. The need for precise and trustworthy techniques to forecast PV system performance is growing as the demand for clean and sustainable energy solutions rises globally. Because of shifting environmental circumstances like temperature, shade, sunshine intensity, and load levels, photovoltaic systems exhibit nonlinear behavior. Because of this, relying only on physical measurements is not enough for effective system design and control [20][21].

To get around this problem, mathematical modeling provides a powerful way to simulate and predict how PV systems would function under various operating conditions. These models explain how the system's electrical output and the external environmental elements interact, helping researchers and engineers better understand and optimize system behavior [23].

These mathematical models are necessary for the creation of precise, economical system simulations by contemporary simulation tools like **MATLAB/Simulink** and PV system. This helps reduce the risks and expenses involved in real-life system testing [24][25].

Last but not least, mathematical modeling is crucial for both assessing and forecasting PV system performance and for increasing efficiency, reliability, and practical application of solar energy technologies worldwide [27][28].

II.2. Comparable Circuit Diagrams:

An equivalent electrical circuit that depicts the internal behavior of a PV cell is frequently the starting point for mathematical modeling of PV systems. Analytical equations describing the cell's current-voltage (I-V) and power-voltage (P-V) characteristics under varied operating situations can be developed thanks to these models.

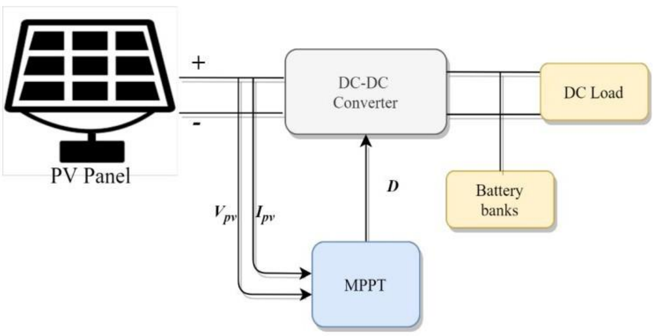
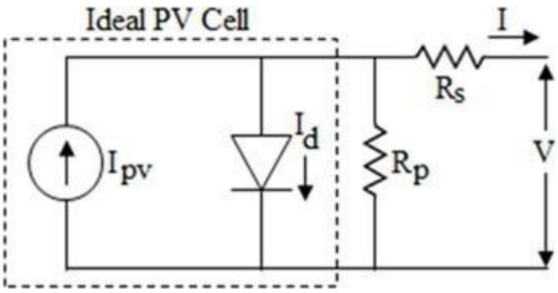


Fig.II.1 : solar energy system.

A photo-generated current source, one or two diodes to simulate the p-n junction's nonlinear behavior, and one or two resistive components to take internal losses and leakage currents into consideration are usually included in the analogous circuit. The model's accuracy and applicability for real-world applications are impacted by its complexity.



FigII.2: Equivalent solar cell circuit.

II.2.1. Model Electrical:

The most basic and basic model is this one. It includes:

A recent source The current generated by photolysis is represented by IphI_{ph}Iph.

A diode D to simulate the behavior of nonlinear junctions.

Equation:

I = I_ph - I_0 (exp (V / nV_T) - 1)

I: Output current

V: Output voltage

Iph: Photo-generated current

I0: Diode saturation current

n: Ideality factor (typically 1–2)

VT = kT/q: Thermal voltage

k: Boltzmann’s constant

T: Cell temperature in Kelvin

q: Electron charge

a).Model Electrical:

The I-V and P-V curves that describe the PV module's operation and its electrical properties are what define it. An analogous circuit model is typically used to study the output current/voltage (I-V curve), which represents the performance of PV systems (solar cells/panels). In order to account for energy losses in this model, this equivalent circuit consists of a current source with one or two diodes linked in parallel and up to two resistors, one connected in parallel and the other in series. Four fundamental layouts based on these electrical components.

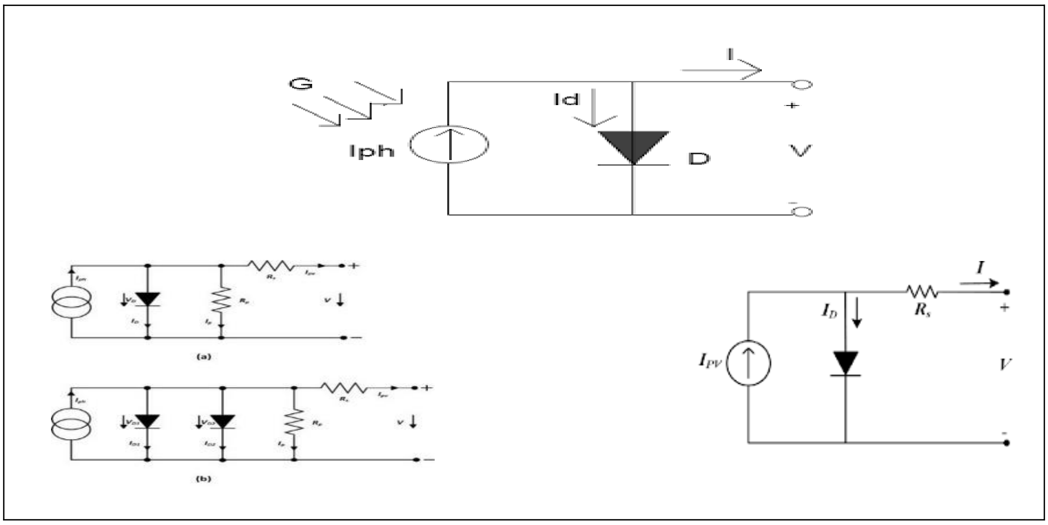


Figure II.3: différent équivalent circuit modèles.

Table.II.1: The primary formula for every equivalent circuit model configuration.

a) The Single-Diode-Model "SDM" (The ideal/ 1-diode Model):	$I = I_{ph} - I_d = I_{ph} - I_{01}[\exp(\frac{V}{a_1 V_t})_1]$
b)The SDM with4 parameters(The1-diode/1-resistor model):	$I = I_{ph} - I_d = I_{ph} - I_{01}[\exp(\frac{V+IR_s}{a_1 V_t})_1$ ¿
c)The SDM with5 parameters(The1-diode/2-resistors model):	$I = I_{ph} - I_d - I_{sh} = I_{ph} - I_{01}[\exp(\frac{V+IR_s}{a_1 V_t})_1$ ¿ $\frac{V+IR_s}{R_p}$
d)The2-diodes/2-resistors model:	$I = I_{ph} - I_d - I_{sh} = I_{ph} - I_0[\exp(\frac{V+IR_s}{a_1 V_t})_1$ ¿ $I_{02}[\exp(\frac{V+IR_s}{a_2 V_t})_1] \frac{V+IR_s}{R_p}$

Depending on the settings, the electrical model faithfully replicates power-voltage (P-V) and current-voltage (I-V) curves, as well as maximum power point values, short-circuit current, and open-circuit voltage, over a variety of module temperatures and irradiation levels.

II.3 The Impact of Irradiance and Temperature on the PV Model:

Environmental factors, especially solar irradiation and cell temperature, have a significant impact on photovoltaic (PV) cell performance. Any correct mathematical model of a PV system must take into account these two parameters, which have a direct impact on the electrical output characteristics of a PV cell, including current, voltage, and power

II.3. 1. Effect of Solar Irradiance:

Solar irradiance (G) is the power per unit area received from the sun in the form of electromagnetic radiation. As irradiance increases, the number of photons striking the PV surface also increases, resulting in a proportional rise in photo-generated current.

The relationship is given by:

$$I_{ph} = \left(\frac{G}{Gref}\right) \cdot I_{ph,ref}$$

Where:

I_{ph}:Photo current at current irradiance G

G: Current irradiance (W/mZ)

Gref : Reference irradiance, usually 1000 W/mZ

$I_{ph,ref}$ Photocurrent under standard test conditions (STC)

Increases in irradiance shift the I–V and P–V curves upward, increasing both current and the maximum power point (MPP). Voltage changes only slightly with irradiance.

II.3.2. Effect of Temperature:

Temperature has a more complex effect. As temperature increases:

- The open-circuit voltage **(***Voc***)** decreases.
- The short-circuit current **(***Isc* **)** increase**s s**lightly.
- The overall power output **decreases**.

This is primarily due to enhanced carrier recombination within the cell and increased thermal voltage.

The open-circuit voltage is affected as follows:

$$Voc(T) = Voc(Tref) - \beta(T - Tref)$$

Where:

- β: Temperature coefficient for voltage (V/°C)
- T: Current cell temperature (°C)
- Tref: Reference temperature (usually 25°C)

In addition, the thermal voltage VT used in the Shockley diode equation, is given by:

$$V_t = \frac{kT}{q}$$

Where:

- k: Boltzmann constant (1.38×10−231.38 \times 10^{-23}1.38×10−23 J/K)
- T: Absolute cell temperature (K)
- q: Electron charge (1.6×10−191.6 \times 10^{-19}1.6×10−19 C)

II.3.3. Comprehensive PV Cell Model Equation:

When both temperature and irradiance effects are considered, the full single-diode model for a PV cell becomes:

Where: $$I = Iph - I_0\left(\exp\left(\frac{V + I R_s}{nV_t}\right) - 1\right) - \frac{V + I R_s}{Rsh}$$

- I: Output current (A)

- V: Terminal voltage (V)
- I_0: Diode reverse saturation current (A)
- Rs : Series resistance (fi)
- NRsh: Shunt resistance (fi)
- n: Diode ideality factor
- V_t: Thermal voltage (V)

This nonlinear equation is the foundation for performance simulation and control of PV systems under variable environmental conditions

II.4. Simulation Tools and Mathematical Modeling of the DC Motor in PV Pumping Systems:

In photovoltaic (PV) pumping systems, simulation tools and mathematical modeling play a critical role in evaluating and optimizing system performance. A typical PV pumping system integrates a solar array, a DC motor, and a water pump. To analyze the entire system accurately, it is essential to model both the PV generator and the DC motor using simulation platforms such as MATLAB/Simulink, PV system, and LTspice.

II.4.1. Simulation Tools for PV and DC Motor Systems:

MATLAB/Simulink provides a graphical environment for modeling dynamic systems. The "Simscape Electrical" toolbox is particularly suited for PV system modeling and control design [27].**PV system** is widely used for performance analysis and sizing of PV installations, particularly in real-weather environments [28].**LTspice** allows electrical circuit-level simulation and is ideal for analyzing the switching behavior of converters and power electronics used between the PV array and motor.

Simulation tools facilitate:

- Time-domain analysis of current, voltage, and torque.
- Implementation of control algorithms (e.g., PI/PID for speed control).
- Efficiency evaluation under variable irradiance and temperature conditions.

II.4.2. Mathematical Modeling of the DC Motor:

A DC motor converts electrical energy into mechanical energy. It can be mathematically modeled using both **electrical** and **mechanical** equations.

Electrical Equation (based on Kirchhoff's law):

$$V_a = Eb + R_a I_a + L_a \frac{dI_a}{dt}$$

Where:

- V_a : Armature voltage (V)
- Eb : Back electromotive force (V)
- R_a:Armature resistance (fi)
- L_a:Armature inductance (H)
- I_a:Armature current (A)

The back EMF is proportional to motor speed:

$$Eb = ke \cdot \omega$$

- ke: Back EMF constant (V·s/rad)
- ω: Angular velocity (rad/s)

Mechanical Equation (based on Newton's second law):

$$T_m = J \frac{d\omega}{dt} + B\omega + TL$$

Where:

- T_m :Developed torque (Nm)
- J: Moment of inertia (kg·mZ)
- B: Viscous friction coefficient (N·m·s/rad)
- TL : Load torque (Nm)

Torque is also related to the current:

$$T_m = k_t \cdot I_a$$

- k_t : Torque constant (Nm/A)

II.4.3. Integration of PV and DC Motor in Simulation:

In simulation tools like MATLAB/Simulink, these equations are used to build block diagrams that link the PV output to the motor's input. This is vital for designing Maximum Power Point Tracking (MPPT) algorithms and speed controllers to stabilize pump performance under fluctuating solar conditions

II.5. Power Electronics Interface Modeling (Converter Modeling):

In photovoltaic (PV) water pumping system, a power electronics interface is essential to ensure proper energy conversion and efficient operation. The most commonly used interface is the **DC-DC converter**, which acts as a bridge between the PV generator and the DC motor load. This converter not only regulates the voltage levels but also enables **Maximum Power Point Tracking (MPPT)**, ensuring the PV system always operates at its highest efficiency point.

II.5.1. Role of DC-DC Converters in PV System:

The power electronics interface plays three major roles:

- **Voltage adaptation**: Matches the variable output of the PV array to the required voltage level of the motor.
- **Impedance matching**: Optimizes energy transfer by adjusting the duty cycle.
- **Enables MPPT algorithms**: Adjusts operating point to extract the maximum possible power under changing irradiance and temperature.

The most widely used converter in PV system is the **Boost Converter**, due to its ability to step up low voltages (especially under low irradiance) to required levels.

II.5.2. Boost Converter Modeling:

Boost converter also called as high efficiency step-up converter or parallel chopper, which has an output DC voltage greater than its input DC voltage. It consists of two semiconductor switches and one storage element. Figure (II.5) shows the circuit diagram of a boost converter. It consists of an inductor, an MOSFET switch, a fast switching diode and a capacitor

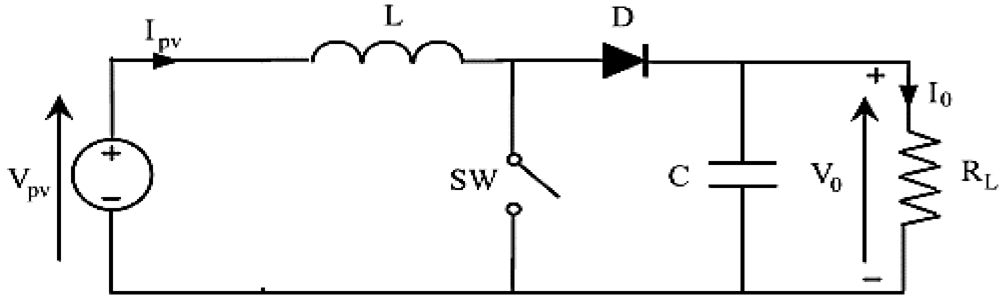


Figure II.4: Circuit diagram of a Boost converter.

The configurations of the boost converter circuit during switching ON and OFF intervals are shown in Figures (II.6) and (II.7) respectively.

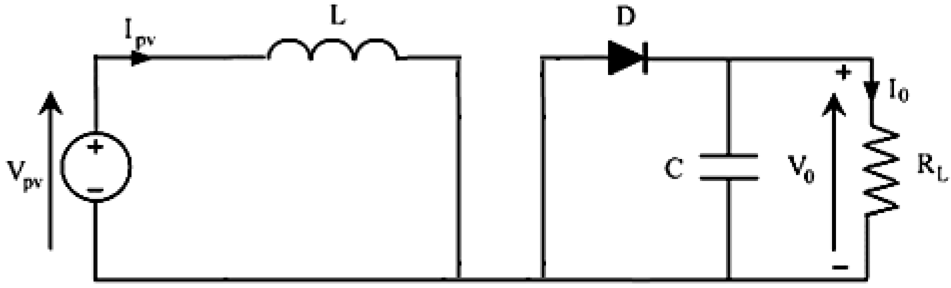


Figure II.5: ON state of the MOSFET switch.

When the IGBT is switched ON, the inductor is directly connected to the input voltage source. In this case, the inductor current rises charging it and the inductor is storing energy while the diode is reverse biased disconnecting the load (RL) and output capacitor (C) from the source voltage. During this interval, the pre-charged capacitor assures constant voltage across the load terminals [10].

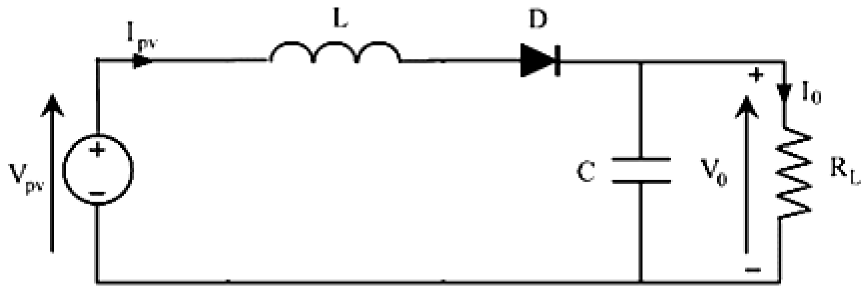


Figure II.6 OFF state of the IGBT switch.

When the IGBT is switched OFF, the diode is forward biased and both the source and the charged inductor are connected to the load. The inductor releases the energy stored in it. This energy is transferred to the load in the form of voltage that adds to the source voltage. Hence, the converter has boosts the input voltage

Steady-State Voltage Gain:

Where: $$Vout = \frac{Vin}{D-1}$$

- Vout: Output voltage
- Vin: Input voltage from PV panel
- D: Duty cycle (0 < D < 1)

This equation shows that as the duty cycle increases, the output voltage increases.

Inductor Current Ripple:

$$\frac{V_{in} \cdot D}{{}_{s}L \cdot f} = {}_{L}\Delta I$$

Where:

- ΔIL: Inductor current ripple
- L: Inductance (H)
- fs: Switching frequency (Hz)

Output Voltage Ripple:

$$\frac{I_{out} \cdot D}{f_s \cdot C} = {}_{out}\Delta V$$

Where:

- ΔVout:Output voltage ripple
- Iout : Output current
- C: Output capacitance (F)

II.5.3. Integration with MPPT and PV Dynamics:

The duty cycle D is dynamically adjusted by the **MPPT controller** (e.g., Perturb and Observe or Incremental Conductance algorithms) based on real-time measurements of PV voltage and current.

By integrating the boost converter model with the PV cell model and DC motor model in a simulation tool (e.g., MATLAB/Simulink), the complete system behavior can be evaluated under variable weather and load conditions.

II.5.4. Efficiency Considerations:

Efficiency considerations are critical in the design and evaluation of photovoltaic (PV)-based system, particularly when integrated with DC motors for water pumping applications. The overall efficiency determines how effectively solar energy is converted into mechanical output, and it directly influences the sizing, cost, and long-term sustainability of the system. Assessing efficiency across each stage of energy conversion—from the PV module, through the power electronics, to the DC motor—is essential for optimizing system performance.

II.6. Photovoltaic Conversion Efficiency:

Photovoltaic efficiency η pv is the ratio of the electrical power output to the solar power incident on the panel's surface:

Where:

- V·I: Electrical output power (W)
- G: Solar irradiance (W/mZ)
- A: Surface area of the panel (mZ)

PV efficiency is sensitive to environmental conditions:

- **Temperature rise** leads to a decrease in output voltage, reducing overall efficiency.
- **Dust, aging, and shading** reduce the incident radiation, lowering output current.

Efficiency values typically range from 15% to 22% under standard test conditions (STC), but drop significantly under real-world conditions [28].

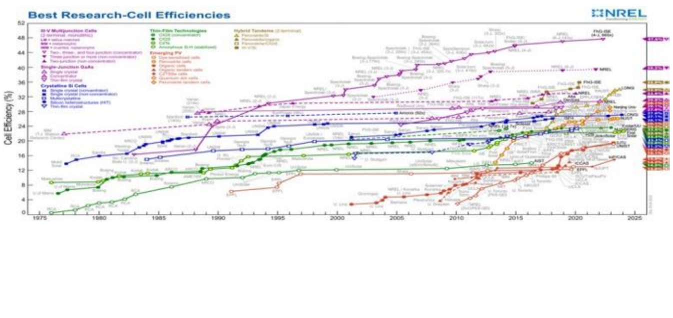


Fig.II.7: Conversion Efficiency of Photovoltaic.

II.6.1. Power Electronics Efficiency:

DC-DC converters, particularly boost converters, are essential in PV systems to regulate the voltage for maximum power transfer. Their efficiency η is given by:

Several factors reduce converter efficiency:

- **Conduction losses** in semiconductors
- **Switching losses** at high frequencies
- **Parasitic resistances** in passive components

Well-designed converters typically achieve 85%–95% efficiency, but thermal management and component selection play a crucial role in maintaining high performance [29].

II.6.2. DC Motor Efficiency:

DC motor efficiency η motor reflects the conversion of electrical input power into mechanical power output:

Where:

- T: Motor torque (Nm)
- ω: Angular velocity (rad/s)

Motor efficiency depends on:

- **Load conditions**
- **Armature losses** (IZR losses)
- **Friction and windage losses**
- **Magnetic core losses**

Under optimal conditions, DC motors operate at 75%–90% efficiency [30].

II.6.3. Total System Efficiency:

The overall system efficiency is a multiplicative product of the individual efficiencies:

$$motor\eta \cdot conv\eta \cdot pv\eta = total\eta$$

This composite efficiency reflects the percentage of solar energy that is ultimately converted into useful mechanical work. Accurate modeling of these efficiencies is necessary for performance prediction, component sizing, and control system design

II.7.3. Example: PV–Converter–Motor Chain:

PV module equation:

Using this, one can predict I at given V, G, and T.If measured I is significantly lower → possible shading, degradation, or mismatch.

Boost converter equation:

$$Vout = \frac{Vin}{D-1}$$

If measured ≫Vout ¿ $\frac{Vin}{1-DV}$, the converter may have switching loss, faulty control signal, or damaged components.

DC motor equations:

$$\frac{T_m \cdot \omega}{{}_aV_a \cdot I} = {}_{motor}k_t I_a, \quad \eta = {}_mL_a \frac{{}_adI}{dt}, \quad T + {}_aR_aI + {}_bE = {}_aV$$

Changes in ω despite stable Va and Ia → mechanical friction, wear, or bearing issues.

II.7.4. Implementation Strategy:

A diagnostic system compares model predictions with live sensor readings in real time:

Thres hold-based logic or observers (e.g., Luenberger, Kalman filters) raise alarms when the residual ε(t) exceeds expected limits.

This approach is scalable, allowing detection of partial faults, intermittent degradation, or drift in system parameters.

Advantages of This Approach

- Non-invasive: No need to dismantle or interrupt the system.
- Predictive: Identifies early trends before they become failures.
- Adaptive: Works with various loads and environmental changes.
- Efficient: Reduces downtime and enhances energy yield

Conclusion:

This chapter presented a structured mathematical modeling approach for photovoltaic water pumping systems driven by DC motors. Each subsystem—PV module, DC-DC converter, and DC motor—was modeled to reflect its electrical and dynamic behavior under varying environmental and operational conditions. Key components were analyzed using standard circuit-based models, including the single-diode representation of PV cells and the boost converter model. The impact of irradiance, temperature, and load variations on system performance was quantified through derived equations. Moreover, MPPT techniques (P&O and INC) were mathematically formulated to illustrate power optimization mechanisms .The chapter concluded with the integration of performance diagnosis concepts, emphasizing how mathematical models support early fault detection and system efficiency analysis. Overall, the modeling framework established in this chapter forms the analytical basis for simulation, control design, and performance evaluation of solar-powered pumping systems.

Chapter III

Photovoltaic System Simulation and Results

III. Introduction:

The simulation environment and outcomes of the suggested photovoltaic (PV) water pumping system powered by a separately stimulated DC motor are shown in this chapter. The system is simulated to assess its performance under dynamic solar and load conditions following the development of the mathematical model and control algorithms in the preceding chapters.

The simulations aim to assess the effectiveness of the **Maximum Power Point Tracking (MPPT)** algorithm, the DC-DC boost converter, and the motor controller in ensuring efficient operation and energy utilization. Accurate modeling of these components is crucial for maximizing solar energy extraction and maintaining the stability of the pumping process [29].

The simulation is implemented using MATLAB/Simulink, a powerful and widely used platform for modeling nonlinear dynamic systems. In this work, key components such as the PV array, MPPT controller (based on the Perturb and Observe or Incremental Conductance method), DC-DC converter, and separately excited DC motor are modeled in detail [30]. Performance indicators including power output**,** current-voltage behavior**,** motor speed response, and **s**ystem efficiency are analyzed and discussed.

Additionally, the system's behavior under changing environmental conditions such as irradiance and temperature is examined to highlight the robustness of the control method. Such analysis is vital for real-world implementation of standalone PV water pumping systems, especially in remote or rural areas where grid access is unavailable [31], [32]

III.1. Simulation Model Description:

In order to evaluate the performance of the proposed photovoltaic (PV) water pumping system, a comprehensive simulation model was developed using **MATLAB/Simulink**. This model integrates all major components of the system, including the **PV array**, the DC-DC **boost converter**, the MPPT controller, the separately excited DC motor, and the water pump (represented as a mechanical load).

The simulation aims to reproduce realistic operating conditions by modeling both the electrical **behavior** and **dynamic** response of each subsystem. The system operates in standalone mode, which makes it suitable for **remote locations** where grid access is unavailable.

a). The main components of the system are as follows:

- **PV Array:**

  A group of solar panels or modules connected together electrically in series and parallel structure to form solar array and this solar array is responsible to produce higher amount of power.[33]

- **Boost Converter:**
  Used to regulate the output voltage of the PV array and to ensure proper energy transfer to the motor. The duty cycle of the converter is controlled dynamically by the MPPT algorithm.

- **MPPT Controller:**
  Implements either the **Perturb & Observe (P&O)** or the Incremental **Conductance (INC)** algorithm to continuously track the Maximum Power Point (MPP) of the PV system [34].

- **DC Motor (Separately Excited):**
  Receives the electrical power from the boost converter and drives the pump. Its behavior is described using a set of differential equations representing both the electrical and mechanical parts.

- **Water Pump (Load):**
  Modeled as a mechanical load with torque characteristics dependent on the motor speed, simulating the real operation of water delivery systems.

The simulation model provides a reliable platform to analyze the impact of changing environmental conditions (irradiance and temperature) on the overall performance and stability of the system.

III.1.1. Photovoltaic Array:

The system's primary power source is the photovoltaic array, which uses photovoltaic cells to transform solar radiation into electrical energy. The Single Diode Equivalent represent is used to represent it, and it accurately depicts the nonlinear I-V characteristics of an actual PV module under various environmental factors including ambient temperature and solar irradiation. Manufacturer datasheets and experimental values were used to create the array parameters in this simulation. In order to replicate realistic daily sun profiles, temperature and irradiance inputs were changed over time.

Figure III.1: Photovoltaic Array.

III.1.2. DC-DC Boost Converter:

A boost converter, also known as a step-up converter, is a DC-DC converter that raises the input DC voltage to a preset output voltage. It works by transforming a steady voltage into one of higher magnitude. The boost converter is made up of a solid-state switch (which functions similarly to a transistor), an inductor, a diode, and a capacitor. The switch is controlled using pulse width modulation (PWM), which modifies the output voltage. The boost converter can operate in two main modes: when the switch is off and the diode is on, and when the switch is on and conducting. In a useful boost Maintaining the duty cycle within a certain range is essential for converters to prevent instability.

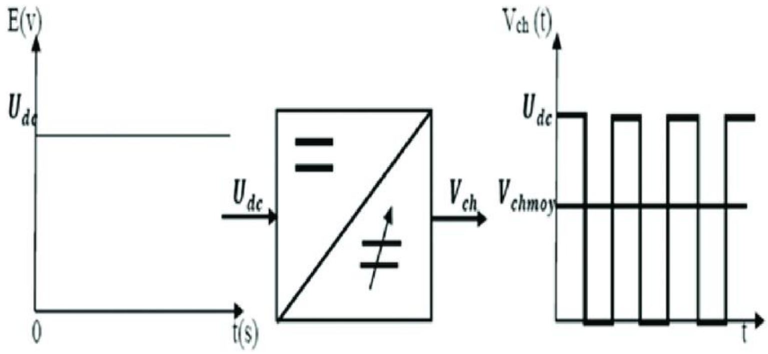


Figure III.2: The basic schematic of a converter.

III.1.3. Modeling of boost converter:

An investigation of the digital control elements of a hybrid electric system through the modeling and operation of a boost converter connected to a DC drive system.

A state-space model for decision-making and an effective switching strategy are presented in this study that describes the modeling and controller design for a non-inverting boost converter.

III.1.4. MPPT Controller:

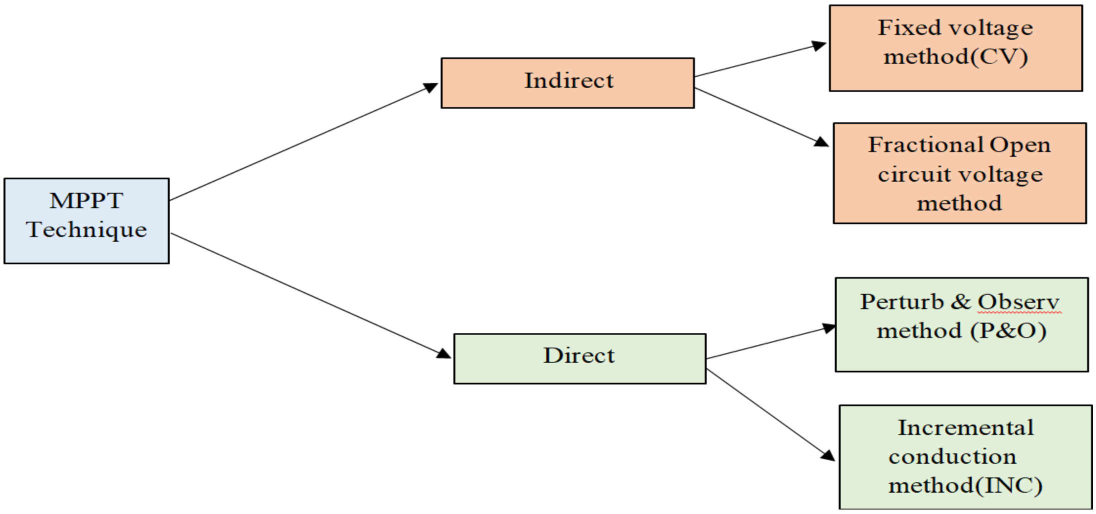


Figure III.2: Type of MPPT control.

III.1.5. P&O (Perturb and observ) method:

Due to its ease of use and simplicity, the P&O approach is frequently chosen. The duty cycle value α is the output of this algorithm, which takes the voltage Vpv and current Ipv as inputs. As implied by its name and illustrated in Figure II.19, the fundamental idea behind this method is to alter the duty cycle α while disturbing the Vpv voltage. The algorithm then determines the power produced by the panel P(n) and contrasts it with the power P(n-1) that was previously generated. The duty cycle fluctuation will remain in the same direction if the power rises, indicating that the power is getting closer to the Maximum Power Point (MPP). On the other hand, a drop in power signifies a departure from the MPP, which causes the duty cycle variation direction to reverse, as demonstrated

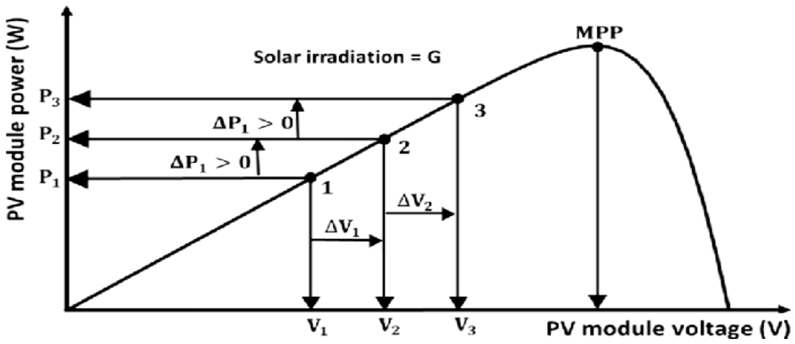


Figure III.4: curves of PV characteristics for the P&O MPPT technique curve V-P

III.1.6. Pertutber and Observer (P&O) Algorithms with Variable Step Size:

The P&O algorithm's convergence time to the maximum power point and the oscillation that takes place around it are both impacted by the choice of step size ($d\alpha$). There are P&O algorithms with adjustable step sizes between two or more variables to achieve a suitable balance between speed and accuracy. One such algorithm is the one proposed by. This algorithm modifies the step size between two values, C1 and C2, after comparing the absolute amount of power variation with a threshold. [35]

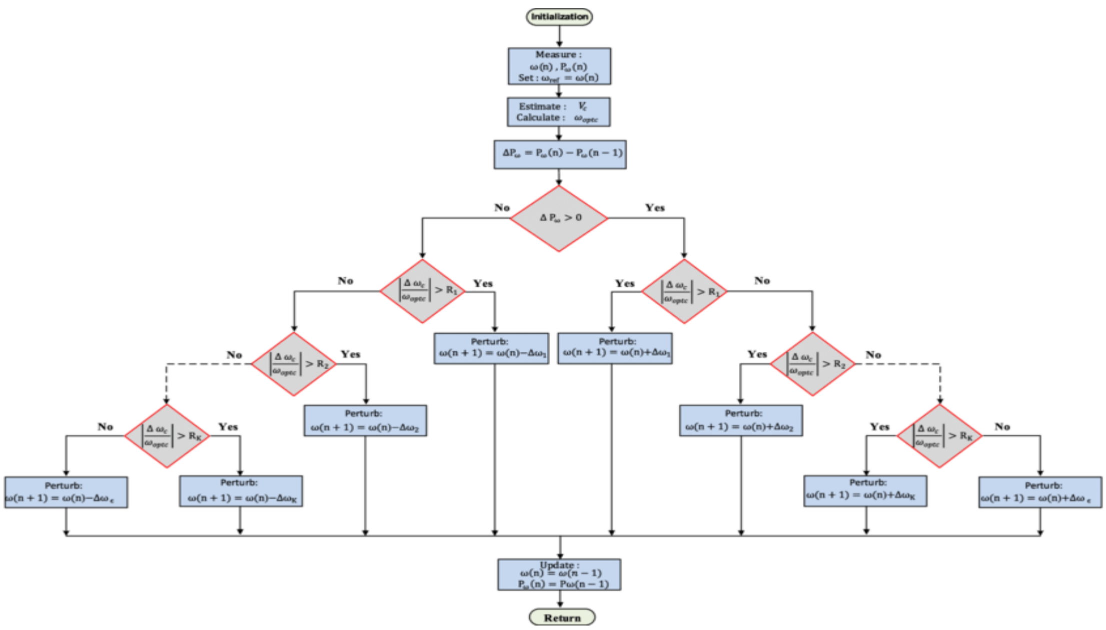


Figure III.5: P&O Algorithm Flowchart.

III.1.7. Modeling Command MPPT:

In order to model Maximum Power Point Tracking (MPPT) methodologies, solar systems' performance under various conditions must be simulated and optimized. A number of research concentrate on using modeling to increase the effectiveness of MPPT algorithms:

• A study highlights the algorithm's function in determining the highest power production by providing a step-by-step simulation of a solar system using several MPPT algorithms.
• The effects of modified MPPT approaches on enhancing PV systems' dynamic and steady-state performance in the face of shifting weather patterns. [36]
• The significance of effective control strategies is highlighted by research on modeling and control for solar systems under changeable climatic circumstances using MPPT algorithms. [36] [37]

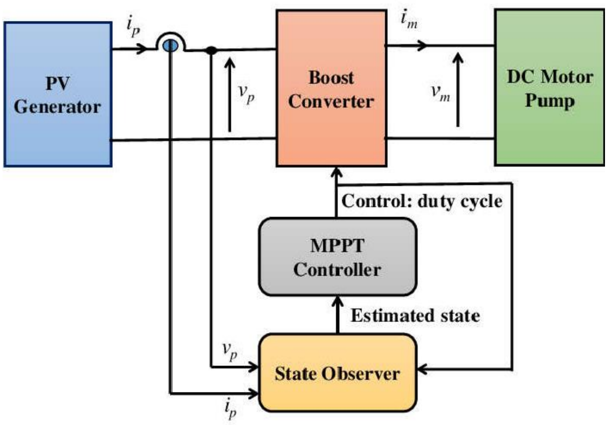


Figure III.6: Schematic of MPPT control.

III.1.8. Incremental Conductance (INC) with Variable Step Size – Academic Overview

General Conceptl

The **Incremental Conductance (INC)** algorithm is an advanced MPPT (Maximum Power Point Tracking) technique used in photovoltaic systems. It is based on the mathematical condition at the Maximum Power Point (MPP), which satisfies:

$$\frac{I}{V} - = \frac{dI}{dV} \Rightarrow 0 = \frac{dP}{dV}$$

This equation means that the MPP is reached when the incremental conductance ($\frac{dI}{dV}$) is equal in magnitude and opposite in sign to the instantaneous conductance ($\frac{-I}{V}$).

a). How it works:

- If<$\frac{-I}{V}\frac{dI}{dV}$, the system is **to the left** of the MPP → increase voltage.
- If>$\frac{-I}{V}\frac{dI}{dV}$ the system is **to the right** of the MPP → decrease voltage.
- If =$\frac{-I}{V}\frac{dI}{dV}$, the MPP is found.

INC outperforms traditional P&O in dynamic conditions because it **avoids oscillation** around the MPP once it is reached.

b). Drawback of Fixed Step Size in INC:

Using a **constant step size** for voltage or duty cycle change can lead to similar trade-offs:

- **Large step size** → faster convergence but higher oscillation.
- **Small step size** → reduced oscillation but slower response.

This is inefficient, particularly under rapidly changing solar irradiance conditions.

c). Variable Step Size in INC:

To solve this, **variable step size** methods are introduced in INC. The idea is to **adapt the step size** based on the proximity to the MPP, determined by the error:

$$\left|\frac{I}{V}+\frac{dI}{dV}\right|=\epsilon$$

- When ϵ\epsilonϵ is **large**, the system is far from MPP → **increase step size**.
- When ϵ\epsilonϵ is **small**, the system is close to MPP → **reduce step size**.

d). Step Size Formula Example:

Where:

$$\left|\frac{I}{V} + \frac{dI}{dV}\right| \cdot K = \Delta D$$

- ΔD: is the change in duty cycle.
- K: is a gain factor (positive constant).
- The term inside the absolute value gives the deviation from the ideal MPP condition.

This dynamic adjustment ensures **smooth convergence** and **minimal energy loss** due to unnecessary oscillations.

e). Benefits of Variable Step INC:

- **Faster tracking** of MPP under rapidly changing conditions.
- **Minimal steady-state oscillation** around the MPP.
- **Higher energy harvesting efficiency** compared to fixed step methods

The system incorporates an MPPT controller to guarantee that the PV array runs at its Maximum Power Point (MPP). The controller calculates the instantaneous power, keeps an eye on the PV voltage and current, and modifies the duty cycle as necessary. Two well-known algorithms were taken into consideration: Incremental Conductance (INCC) and Perturb and Observe (P&O). Because of its quicker convergence and superior performance in situations with rapidly fluctuating irradiance, INCC was chosen for this simulation.

III.2. Flaws in Photovoltaic Panels:

There are four different types of loss in the ltaic system. [37]

- Long-term, ineffective flaws: These occur when a physical issue occurs and the system is disconnected for a long time. [38]

-Short faults with zero efficiency: These occur when the system is momentarily shut off due to an inverter disconnect. [38]

- Shading flaws: These occur when a shadow passes over objects like wires, structures, trees, clouds, etc.

- Errors and defects in maximum power point tracking (MPPT) are the causes of flaws that reduce efficiency when there is no shading. [39]

III.2.1. Schottky Diode in PV Systems:

A Schottky diode is a semiconductor device known for its low forward voltage drop and fast switching speed. Unlike conventional PN-junction diodes, it is formed by a junction between a metal and an N-type semiconductor, which results in superior performance in power electronic applications.

III.3. Characterization of the PV module:

In this study, we simulated the KC200GT photovoltaic module, which consists of 54 monocrystalline silicon solar cells measuring 125.125mm connected in series.

The module can produce a maximum power of 200 watts at 32 volts. This allowed us to determine the power as a function of voltage and the current as a function of the voltage of the module studied for an irradiance of 1000 W/m2.

The electrical characteristics of the KC200GT Photovoltaic module under standard test conditions are shown in Table III.1

Table III.1: Characteristics of the KC200GT PV module.

Total number of cells in series (N_s)	54
Rated power(W)	200.143 W
Short-circuit current(I_{sc})	8.21 A
Open circuit voltage(V_{oc})	32.9 V
Current at Maximum power (I_{mp})	7.61 A
Voltage at Maximum power (V_{mp})	26.3 V

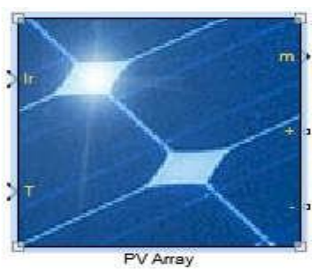


Figure III.7: Block diagram of the solar module in MATLAB.

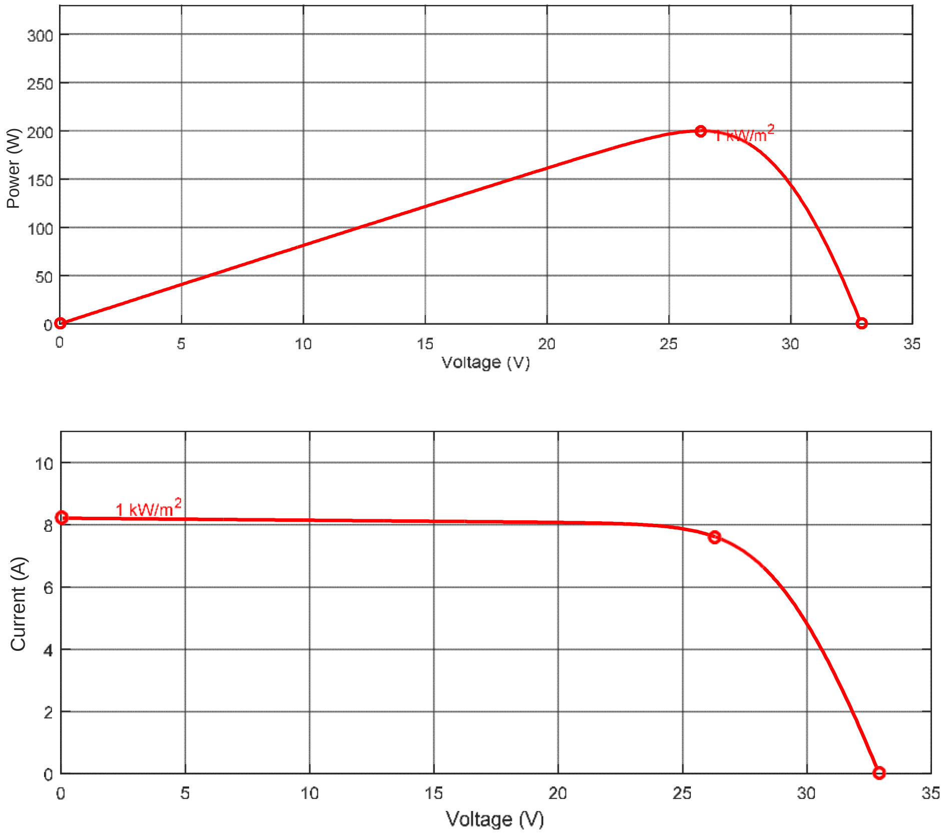


Figure III.8: P-V Characteristic of a PV module under STC (25 W/m2).

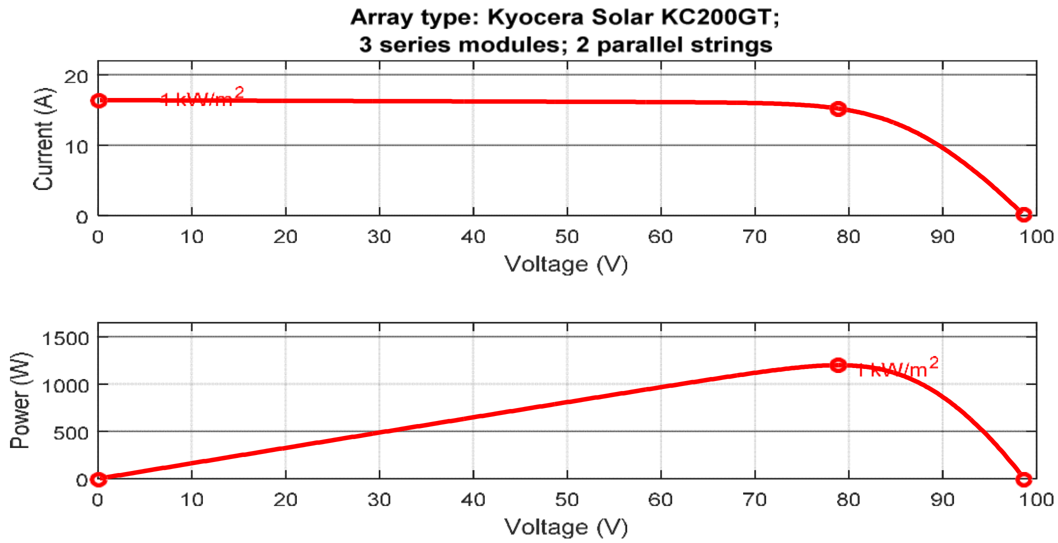


Figure III.9: V, P-V Characteristic of a PV Array under STC (25 W/m2).

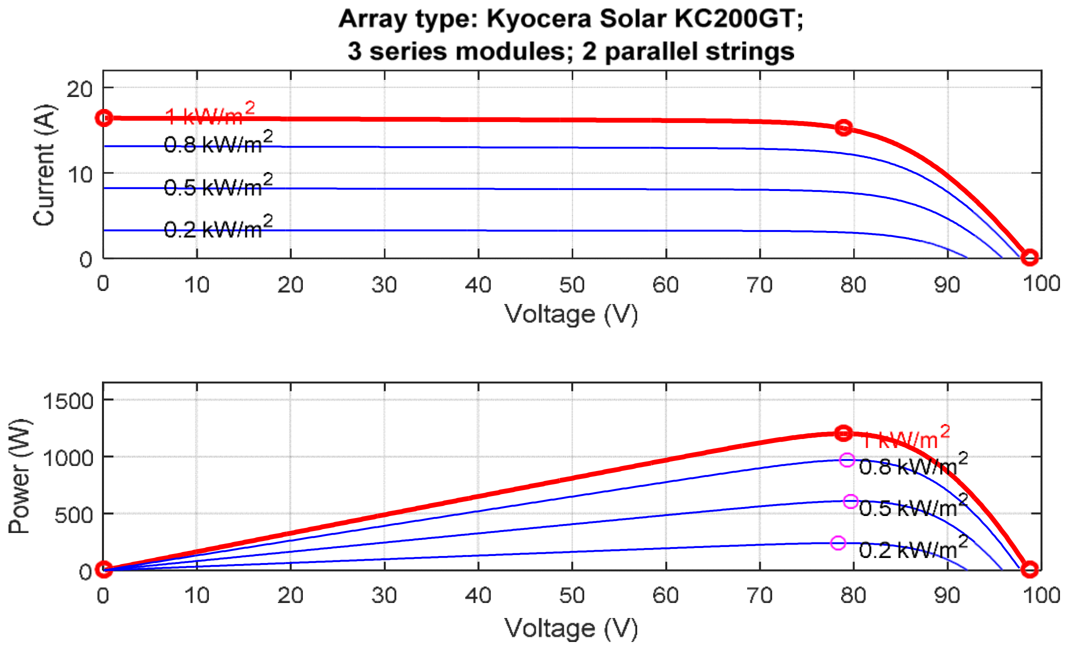


Figure III.10: Simulation results of the I_V characteristics for various irradiance.

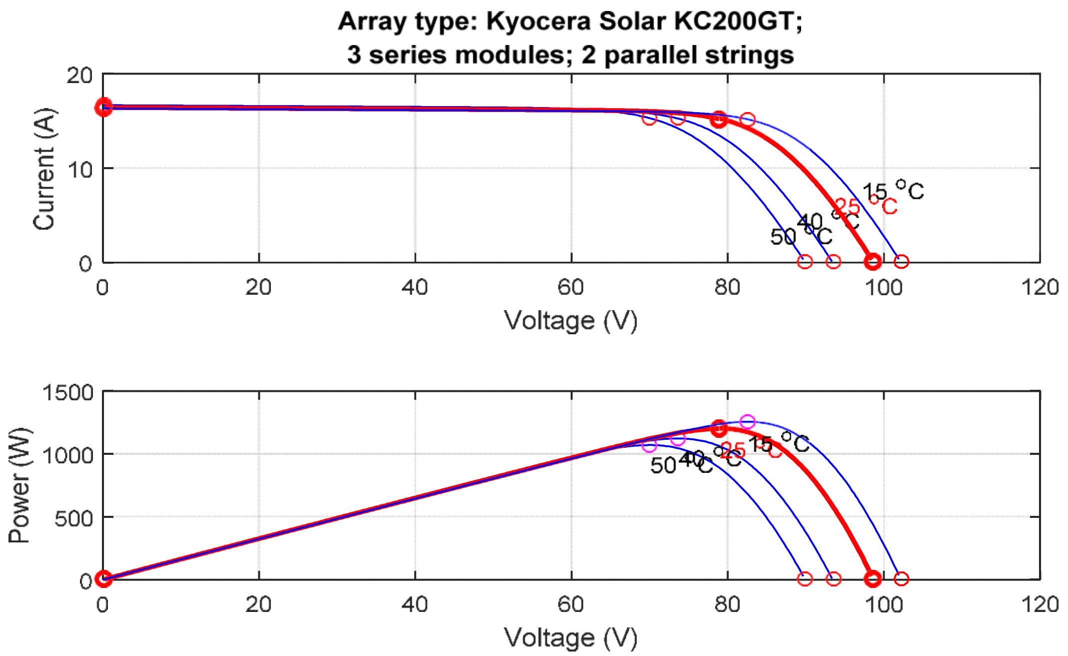


Figure III.11: Simulation results of the I_V characteristics for various temperatures

III.4: Simulation of DC-DC boost:

To maximize power output under various climatic circumstances, ensure effective energy conversion, and optimize the performance of solar PV systems, DC-DC boost converter simulation with solar panels is crucial.

To demonstrate the role of boost converters, we used Matlab software for the simulation and we take (E=100V, L= 4e-4H, C1=4700e-6F , C2 = 1200e-6F, R=200, D = 0.5).

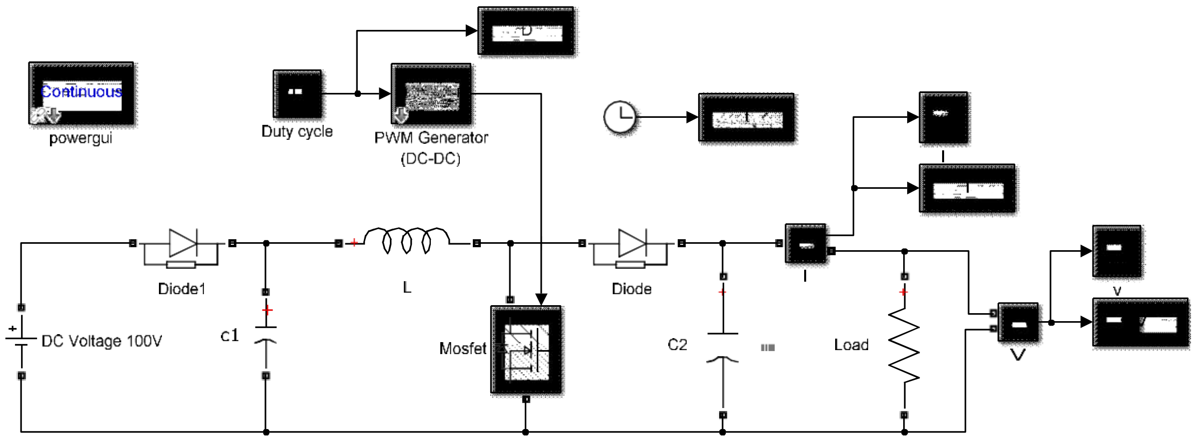


Figure III.12: Simulation of DC-DC boost in Matlab/Simulink.

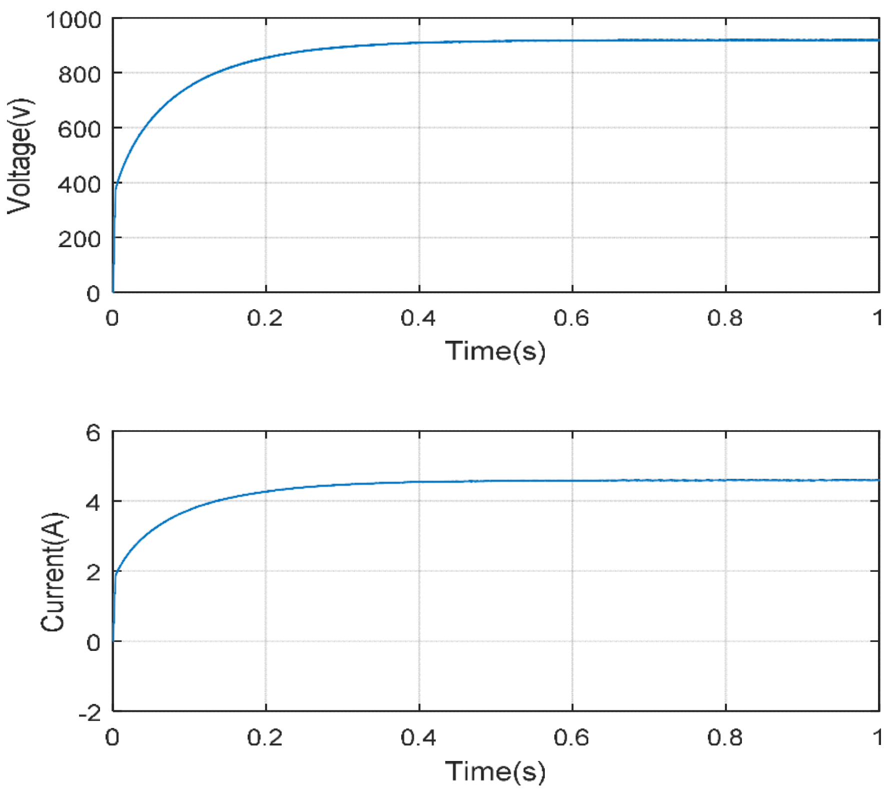


Figure III.13: Outputs voltage and current of the boost converter.

III.5.Simulation of "P&O" MPPT Control:

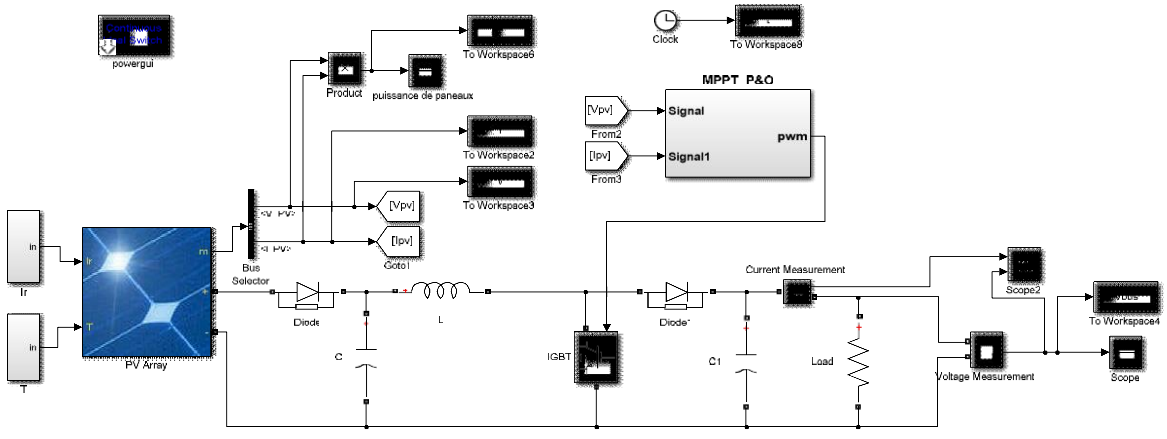


Figure III.14: Scheme SIMULINK of the PV system with MPPT control

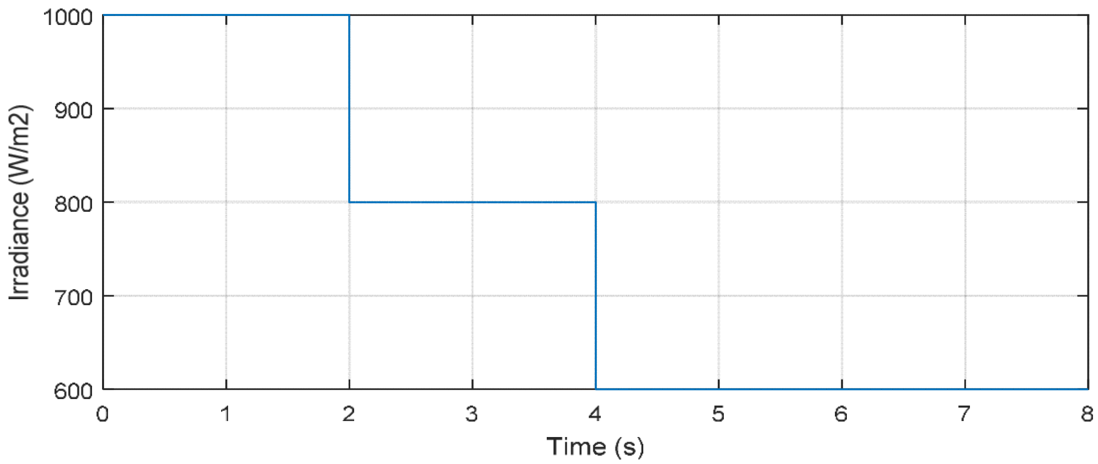


Figure III.15: irradiance profile over time.

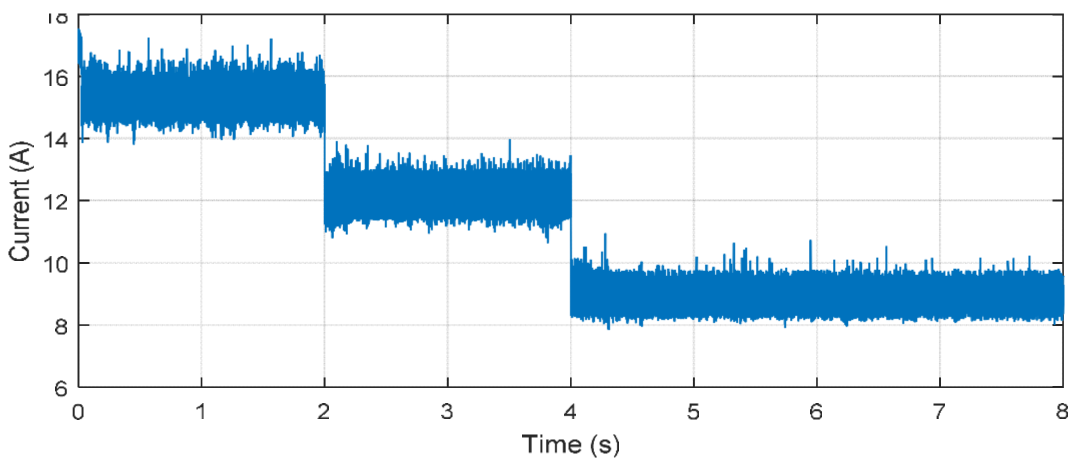


Figure III.16: Output current profile over time.

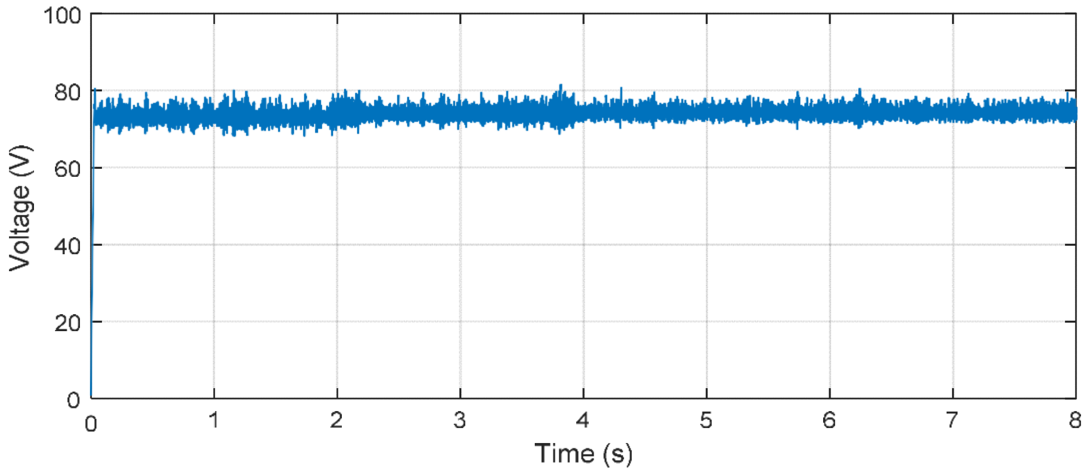


Figure III.17: Output voltage profile over time.

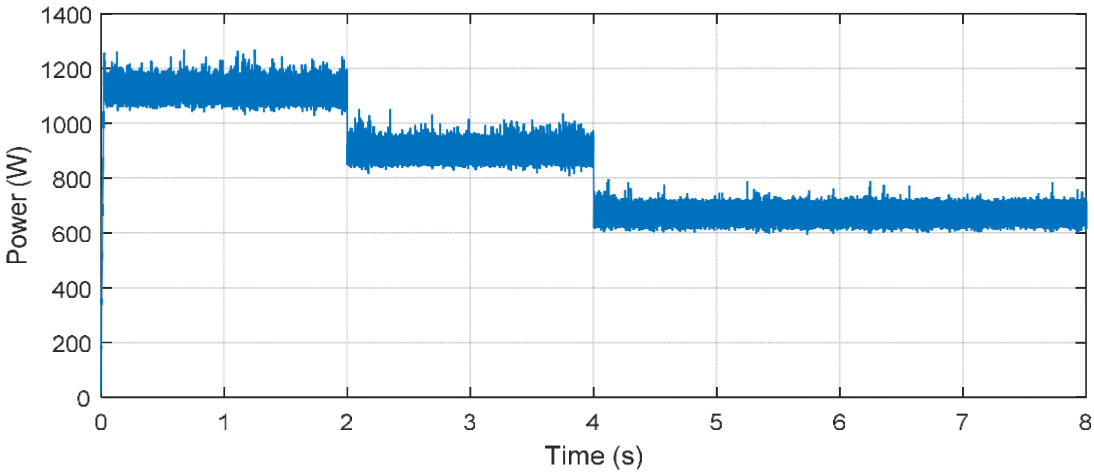


Figure III.18: Power profile over time.

Conclusion:

This chapter presented the simulation-based evaluation of the photovoltaic water pumping system controlled by a DC motor. A comprehensive system model was implemented using MATLAB/Simulink to assess its performance under varying operating conditions, particularly fluctuations in solar irradiance and ambient temperature. Two MPPT algorithms—**Perturb and Observe (P&O)** and **Incremental Conductance (INC)**—were integrated into the simulation to compare their effectiveness in tracking the maximum power point. The results showed that while both methods successfully followed the MPP, the INC algorithm demonstrated superior accuracy and responsiveness under rapidly changing conditions, whereas the P&O algorithm exhibited occasional oscillations near the MPP. System variables including voltage, current, output power, and motor speed were monitored to evaluate both steady-state and transient responses. The simulation confirmed the system's stability and adaptability, though minor dynamic deviations highlighted the need for further control optimization. In summary, the use of mathematical modeling combined with advanced MPPT control techniques provided valuable insights into the real-time behavior and reliability of the proposed PV-driven pumping system.

GENERAL CONCLUTION

GENERAL CONCLUTION:

This thesis has addressed the modeling, simulation, and control of a photovoltaic (PV)-driven water pumping system utilizing a DC motor. Through a multidisciplinary approach combining electrical engineering, power electronics, and control theory, the study developed a complete mathematical and simulation framework to analyze and optimize system performance under dynamic environmental conditions.

The initial chapters provided a comprehensive theoretical background on PV technology, followed by detailed mathematical modeling of key components—including the PV generator, boost DC-DC converter, and DC motor. Additionally, the integration of **Maximum Power Point Tracking (MPPT)** techniques, specifically **Perturb and Observe (P&O)** and **Incremental Conductance (INC)**, was analyzed both mathematically and through simulation.

Simulation results, conducted in MATLAB/Simulink, revealed the system's ability to operate reliably across varying solar irradiance and temperature levels. The comparison between P&O and INC highlighted the superior responsiveness of INC under fast-changing conditions, while P&O remained effective in stable scenarios. Key system metrics such as output power, motor speed, and voltage regulation were assessed to validate control efficiency.

The study emphasizes the role of mathematical modeling in enabling performance prediction, fault detection, and real-time optimization. It concludes that integrating accurate models with intelligent MPPT control can significantly enhance the efficiency and reliability of solar pumping systems, particularly in rural and off-grid applications.

Looking ahead, future work may focus on implementing hardware-in-the-loop testing and exploring AI-based control algorithms to further improve system adaptability and energy utilization.

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