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THEME

Enhanced Control of a Photovoltaic Pumping System Associated with a Synchronous Reluctance Motor

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بسم الله الرحمن الرحيم
Sidi

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Dedication

In the name of God, the Merciful
Praise be to Allah Almighty
We dedicate this humble work as respect, appreciation and thanks:
To our dear fathers, mothers and brothers who helped us from near and far.
To everyone who contributed to the development of this humble work and all these are dear to us.

Abstract

الملخص

Abstract

The most common problem in remote places and the most isolated communities that are far from waterways and electricity grid. To ensure the water supply anywhere, we have to use a standalone power supply, and photovoltaic solar energy is one of the most common of these energies. This combination is called "Photovoltaic Water Pumping System" . This system is the perfect way to fix the water supply's problems, by extracting and pumping the water from a well even in rural areas and places, and that is the system’s goal. The photovoltaic water pumping system can be used in many domains, including residential, farming (irrigation, breeding, and agriculture), water purification, or firefighting. It combines two principle parts that are the photovoltaic system and the pumping system.

Keywords: Photovoltaic energy , Centrifugal Pumps , SynRM .

الملخص

المشكلة الأكثر شيوعا في الأماكن النائية والمجتمعات الأكثر عزلة البعيدة عن الممرات المائية وشبكة الكهرباء .لضمان إمدادات المياه في أي مكان، يتعين علينا استخدام مصدر طاقة مستقل، والطاقة الشمسية الكهروضوئية هي واحدة من أكثر هذه الطاقات شيوعا .يسمى هذا المزيج" نظام ضخ المياه الكهروضوئية." هذا النظام هو الطريقة المثلى لإصلاح مشاكل إمدادات المياه، من خلال استخراج وضخ المياه من بئر حتى في المناطق والأماكن الريفية، وهذا هو هدف النظام .يمكن استخدام نظام ضخ المياه الكهروضوئية في العديد من المجالات، بما في ذلك السكنية أو الزراعية(الري والتربية والزراعة)أو تنقية المياه أو مكافحة الحرائق. فهو يجمع بين جزأين رئيسيين هما النظام الكهروضوئي ونظام الضخ..

الكلمات المفتاحية :الطاقة الكهروضوئية، مضخات الطرد المركزي، محركات الممانعة المتزامنة. **SynRM**

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General Introduction

General Introduction

Currently, great efforts are being made to find sources for producing electrical energy without emitting carbon dioxide into the environment. Solar photovoltaic (PV) energy is among the most popular renewable energy sources, and is considered one of the best solutions available for producing clean and sustainable electricity

Among the popular practical applications of photovoltaic solar energy systems, we find photovoltaic water pumping systems, which are an ideal option, especially in isolated and remote areas, as they constitute a promising alternative to traditional pumping systems that rely on diesel engines, as they are environmentally friendly, do not emit carbon or noise emissions, and require low maintenance

Photovoltaic pumping systems (SPVWPS) are a promising and effective solution, providing good performance, high reliability, and are widely accepted in irrigation applications, livestock watering, and even domestic use in isolated areas. These systems are also able to operate in harsh climatic conditions, and their operation can be adapted according to water demand and the availability of solar energy.

Although pumps associated with direct current (DC) motors are widely used, brushless motors are a more attractive alternative due to lower maintenance costs and longer life. Many studies have begun to explore alternatives such as induction motors (IM), permanent magnet synchronous motors (PMSM), as well as reluctance synchronous motors (SynRM).

This note aims to model and simulate a solar PV pumping system directly coupled to a synchronous reluctance motor (SynRM), in an efficient and cost-effective manner.

In this system, the motor is directly connected to the solar panels through an inverter without the need to use a DC/DC converter, which simplifies the structure and reduces the cost.

The Maximum Power Point Tracking (MPPT) algorithm has also been adopted to increase the efficiency of solar energy extraction, and the motor is controlled using Field Oriented Control (FOC) technology.

This work includes the following chapters:

Chapter One: A general theoretical presentation about photovoltaic energy systems and pumping systems, explaining some of the methods and algorithms used to extract the maximum possible power, taking into account the effects of changing temperatures and the intensity of solar radiation on the efficiency of the system.

The second chapter: deals with modeling the basic parts of the studied system, starting with the synchronous reluctance motor (SynRM), and the role of the inverter in converting energy from direct current to alternating current with frequency and capacity control. We also discuss equations and mathematical modeling of the engine and pumping system.

Chapter Three: Presenting the MPPT algorithm to make the most of solar energy, in addition to explaining the FOC motor control technology, as this technology allows independent control of the torque and magnetic field components. Despite the difficulties of implementing it previously, However, the development of microcontrollers and signal processors has made this technology a popular choice in modern control applications. The chapter concludes with the presentation and discussion of the results using Matlab/Simulink.

The final chapter: a general conclusion of the work and a review of future research prospects.

Chapter I

State of the art photovoltaic

I.1 Introduction

Given the abundance and sustainability of solar energy, its diverse advantages render its adoption in the industrial sector essential. However, the primary challenge lies in developing methods to utilize solar energy as a substitute for conventional energy sources. One such approach is the photovoltaic (PV) process, which converts solar radiation into electrical energy. In a society increasingly threatened by pollution and the greenhouse effect, the generation of clean energy has become a fundamental necessity [1].

Photovoltaics represent a clean, inexhaustible energy source and constitute a vital component of the broader category of renewable energy technologies. It holds significant potential to meet the growing global energy demand while mitigating greenhouse gas emissions and reducing environmental pollution. Despite its intermittent nature, photovoltaics offers numerous advantages, making it an appealing alternative or complement to traditional electricity generation methods [2]:

- It is a reliable technology that requires minimal maintenance.
- It generates electricity using a free and renewable source—solar energy.
- It operates without the need for any fuel.
- It functions silently and is environmentally friendly, producing no pollution.
- It has an operational lifespan of approximately 25 years

This chapter provides a general overview of photovoltaic (PV) systems. It includes a concise description of the most commonly used solar cells and their configurations. Subsequently, various models of PV systems will be presented and analyzed. The most appropriate model will then be selected, followed by a detailed explanation of the corresponding governing equations. Finally, the selected model will be simulated under two conditions: varying solar irradiance with constant temperature, and constant solar irradiance with varying temperature.

I.2 What is photovoltaics?

Photovoltaic solar energy is derived from the conversion of sunlight into electricity through the use of semiconductor materials, such as silicon, which serves as the primary raw material in photovoltaic solar panels. The term *photovoltaic* originates from the Greek language and consists of two components:

- *Photos*, meaning "light."
- Volt, the unit of electrical voltage, named after Alessandro Volta.

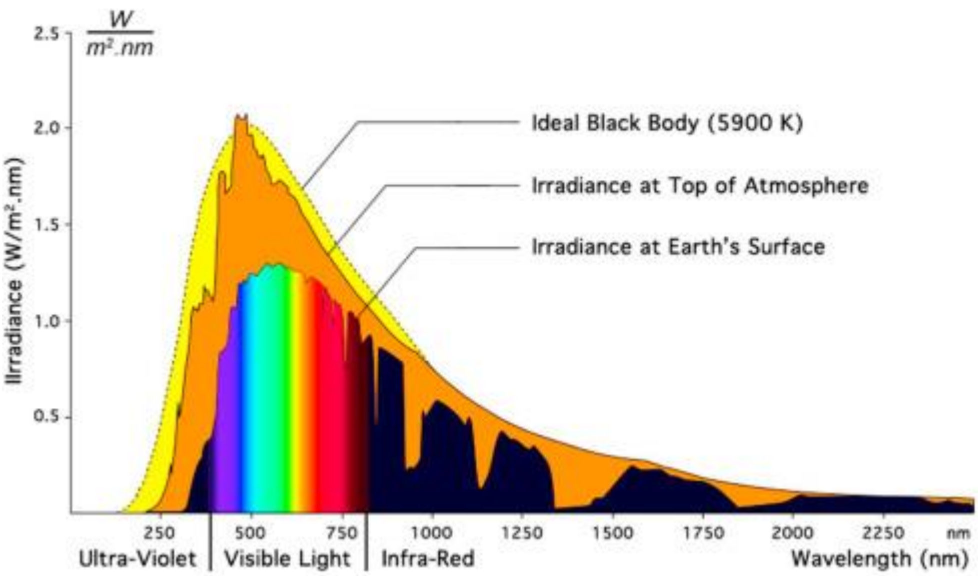
I.3 History of photovoltaics

Some important data in photovoltaics [3].

- **1839**: French physicist Edmond Becquerel discovers the photovoltaic effect.
- **1875**: Werner von Siemens publishes an article on the photovoltaic effect in semiconductors.
- **1954**: American researchers Chapin, Pearson, and Prince develop the first photovoltaic cell.
- **1958**: A solar cell with 9% efficiency is used to power the first satellite utilizing solar energy.
- **1973**: The University of Delaware constructs the first residential building powered entirely by photovoltaic energy.
- **1983**: The first photovoltaic-powered vehicle completes a long-distance journey of 4,000 kilometers in Australia.

I.4 Photovoltaic phenomenon and physicsof PV cell

Temperature significantly influences the performance of a solar cell. The maximum achievable voltage across a solar cell corresponds to the bandgap voltage, which occurs when the cell's temperature approaches absolute zero (0 Kelvin) [4]. As the temperature increases, both the bandgap energy and the voltage across the cell decrease. Due to the reduced bandgap, less photon energy is required to excite electrons, resulting in a slight increase in output current. However, this is offset by a more substantial reduction in output voltage, leading to an overall decline in the solar cell's output power. The power output of a solar cell increases with rising irradiance and decreasing temperature. Consequently, optimal locations for photovoltaic (PV) panel installation are in cold climates that receive abundant sunlight [3].



FigureI.1:SolarRadiationSpectrum[5]

I.5 Solar energy

The solar constant refers to the density of solar energy incident on the outer boundary of the Earth's atmosphere, on a surface oriented perpendicular to the Sun's rays. This value is commonly approximated as 1360 W/m². At the Earth's surface, however, the solar energy density is reduced to approximately 1000 W/m² due to atmospheric absorption and scattering.

While investigating the photoelectric effect, Albert Einstein discovered that light exhibits not only wave-like properties but also particle-like behavior. He demonstrated that the energy of light is carried by discrete particles known as photons. The energy of a photon is given by the relation[5]:

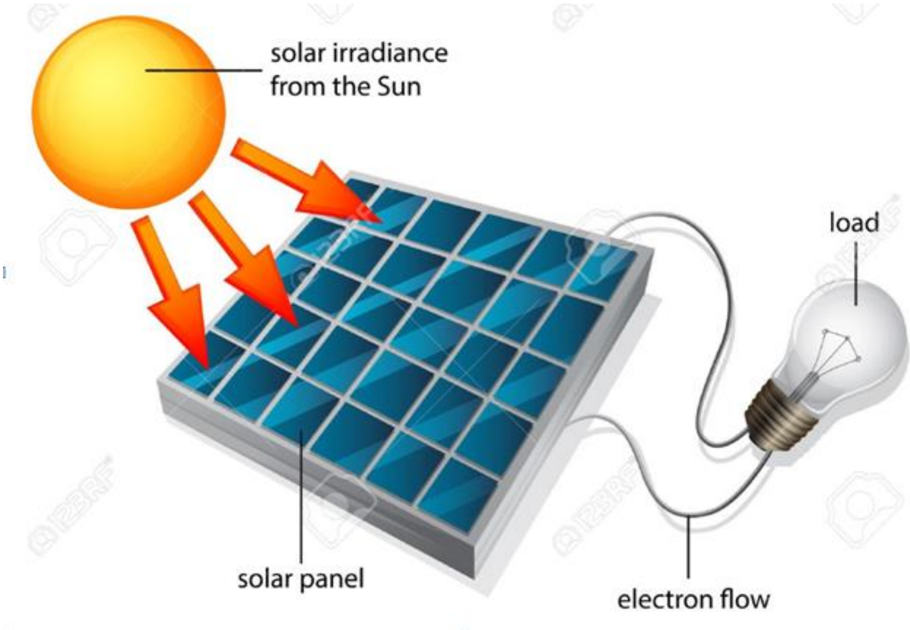
$$E=(h.c)/\lambda \qquad (I.1)$$

h: Planck's constant [j. s^(-1)].

C:thespeedoflight[m.s^(-1)]. λ: the

wavelength [m].

Thus ,the shorter the wavelength, the greater the energy of the photon



FigureI.2:Solar energy[1].

I.5.1 Solar radiation

- **Direct radiation**

Solar flux in the form of parallel rays coming from the sun disk without having been dispersed by the atmosphere. [6]

- **Diffuse radiation**

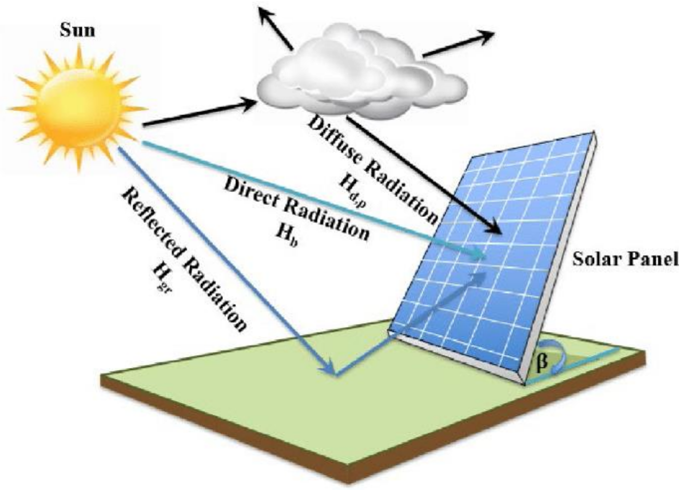
It is the part of the radiation coming from the sun, having undergone multiple reflections (dispersions), in the atmosphere. [6]

- **Reflected radiation**

It is the part of the so/lar illumination reflected by the ground, this radiation depends directly on the nature of the ground (cloud, sand, etc.). It is characterized by a coefficient specific to the nature of the bond called Albedo (ε) $0 \leq \varepsilon \leq 1$. [6]

- **Global radiation**

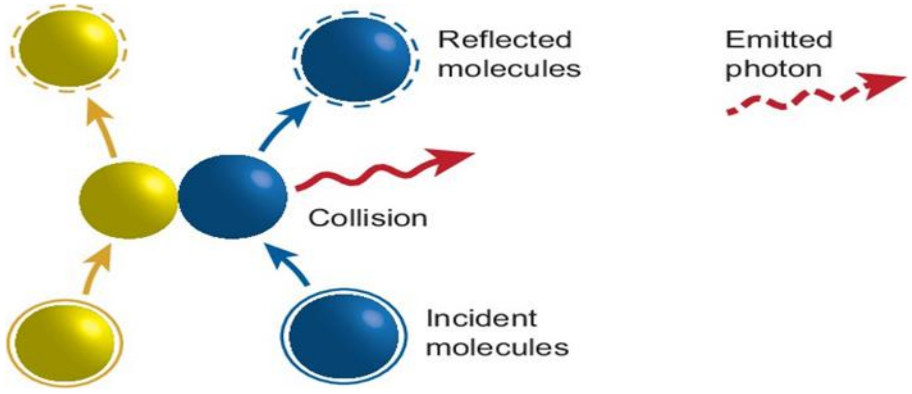
A plane receives from the ground a global radiation which is the result of the superposition of the three compositions direct, diffuse and reflected. [6]



FigureI.3:Types of solar radiation (Direct, Diffuse and Reflected). [6]

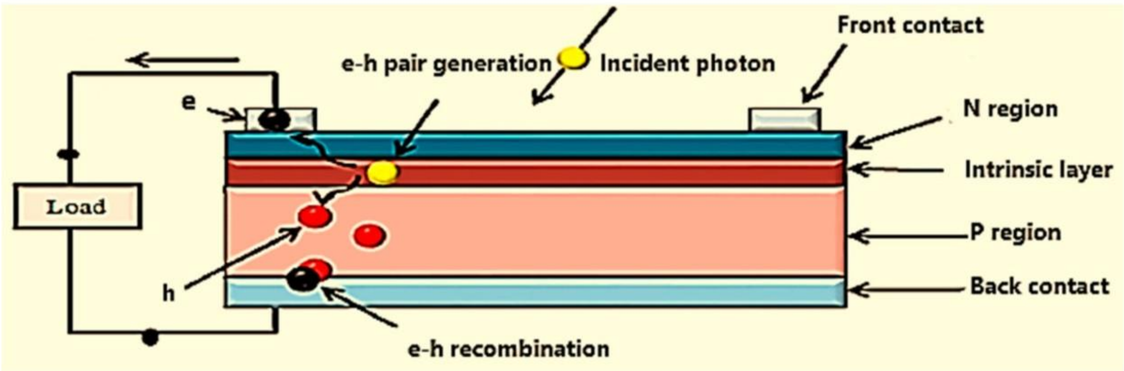
I.6 Operating Principles of a cell

A photovoltaic (PV) cell, commonly referred to as a solar cell, consists of a junction formed by two semiconductor materials—one doped with acceptor atoms (P-type) and the other with donor atoms (N-type). At the interface of these two layers, an internal electric field is established, which remains present even in the absence of light. When the cell is exposed to varying levels of sunlight, photons—light particles carrying sufficient energy—interact with the atoms within the crystal structure (Figure I.4). These photons can excite electrons from the valence band to the conduction band of the semiconductor material, thereby generating electron-hole pairs. In the presence of the built-in potential barrier, these charge carriers are separated and collected at the external surfaces of the P-type and N-type regions[2].



FigureI.4: Collision between a photos Nan diatom. [2]

As a result, a potential difference is established between the two surfaces of the photovoltaic cell. Metallic contacts on the front and back of the cell collect the electrons and holes, enabling the generated electric current to flow through an external circuit (Figure I.5) [5]. Even when a photon possesses excess energy, it can only liberate a single electron; the surplus energy is dissipated as heat. The N-type region is overlaid with a metallic grid that functions as the cathode, while the opposite face of the crystal is covered with a metallic back contact, serving as the anode. The total thickness of the crystalline structure is typically on the order of a few millimeters.

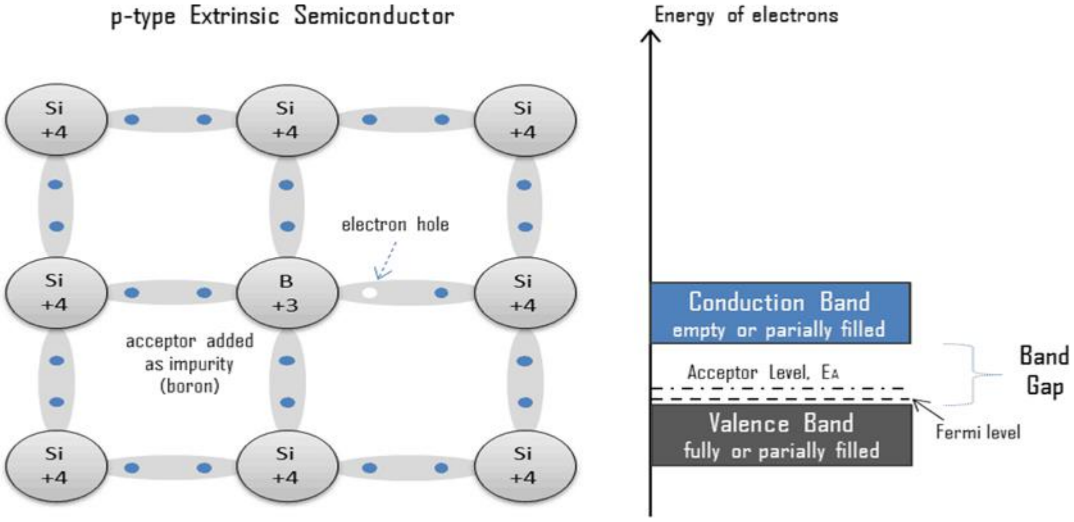


FigureI.5: Photovoltaiccell.[5]

I.6.1 Types of Extrinsic Semiconductors

I.6.1.1 P-type semiconductor

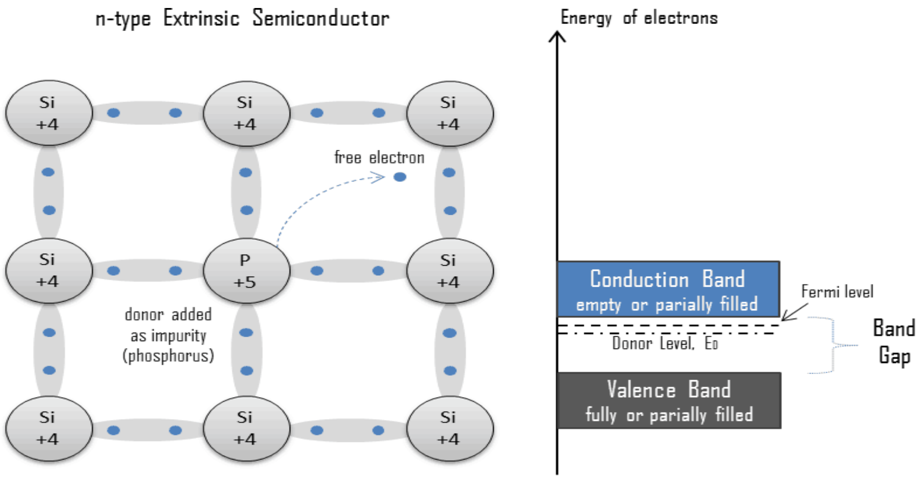
A P-type semiconductor is a category of extrinsic semiconductor formed by introducing a trivalent impurity into an intrinsic (pure) semiconductor. Common examples of trivalent impurities include aluminum, gallium, and indium. When such impurities are added to an intrinsic semiconductor, they introduce additional holes, and are therefore referred to as acceptor impurities. As a result, holes constitute the majority charge carriers in a P-type semiconductor.[7]



FigureI.6:Structureofp-type semiconductor[7]

I.6.1.2 N-type semiconductor

An N-type semiconductor is another form of extrinsic semiconductor, produced by introducing a pentavalent impurity into an intrinsic (pure) semiconductor. Common examples of pentavalent impurities include antimony, arsenic, and bismuth. When such an impurity is added to a pure semiconductor, it contributes additional electrons, and is therefore referred to as a donor impurity. In an N-type semiconductor, electrons serve as the majority charge carriers.[7]

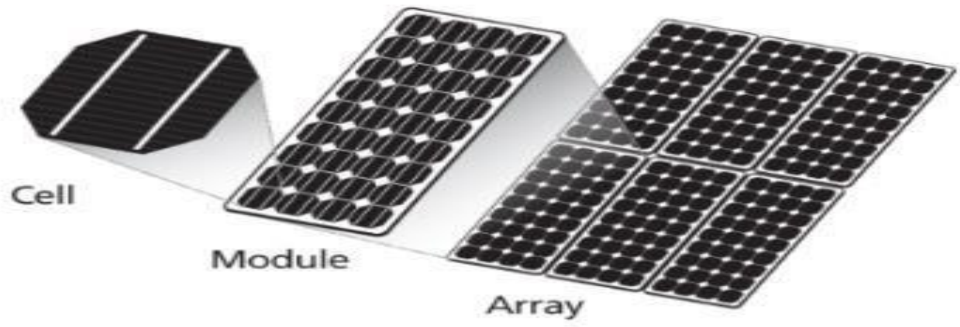


FigureI.7:Structureofn-type semiconductor[7]

I.7 Structure of photovoltaic

Photovoltaic (PV) systems are rated based on the maximum direct current (DC) power output of their PV modules (or cells) under Standard Test Conditions (STC). These conditions include a module (cell) operating temperature of 25°C, an incident solar irradiance of 1000 W/m², and a spectral distribution corresponding to Air Mass 1.5. However, as such conditions are not typically representative of actual operating environments, the real-world performance of PV modules and arrays is generally approximately 85% of the STC-rated output.

To achieve higher voltage, current, and power levels, photovoltaic cells are electrically interconnected in series and/or parallel configurations. PV modules, which serve as the fundamental building blocks of PV systems, consist of circuits of solar cells encapsulated within environmentally protective laminates. One or more PV modules are assembled into photovoltaic panels, which are pre-wired and designed for field installation. [5]



FigureI.8:photovoltaiccell,moduleand array[5]

I.8. Generations of Photovoltaic

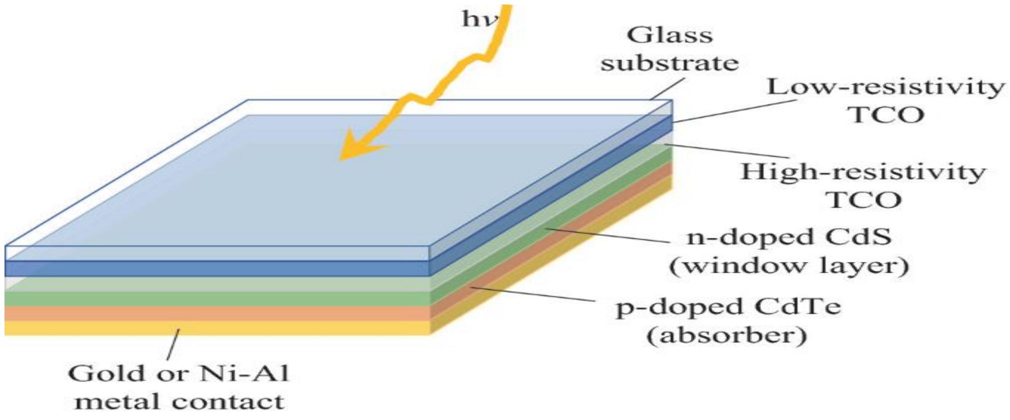
Photovoltaic(PV)cellscanbecategorizedbyfourmaingenerations:first,second,third, and fourth generation. Each generation has its own characteristics, advantages, and disadvantages.

I.8.1. First Generation

Crystalline silicon (c-Si) solar cells, the most widely used type of solar cell today, fall under this category. These cells are fabricated by melting and crystallizing silicon to produce highly pure silicon wafers. First-generation solar cells are well-known for their long lifespan (exceeding 25 years) and high efficiency (ranging from 15% to 20%). However, due to the high cost of silicon and the energy-intensive manufacturing process, they remain the most expensive type of solar cell to produce.

I.8.2. Second Generation

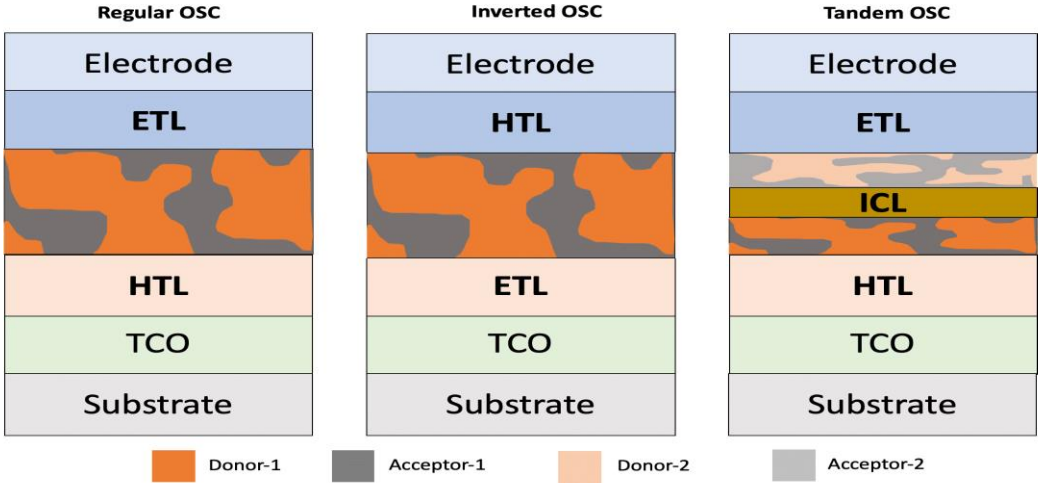
Second-generation solar cells, commonly referred to as thin-film solar cells, are designed as a more cost-effective alternative to crystalline silicon cells. These cells are constructed from a thin layer of photovoltaic material that is deposited onto a substrate, such as glass or plastic. Common types of thin-film solar cells include cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon. While second-generation solar cells typically exhibit lower efficiency than first-generation cells (ranging from 10% to 15%), they are also less costly to manufacture



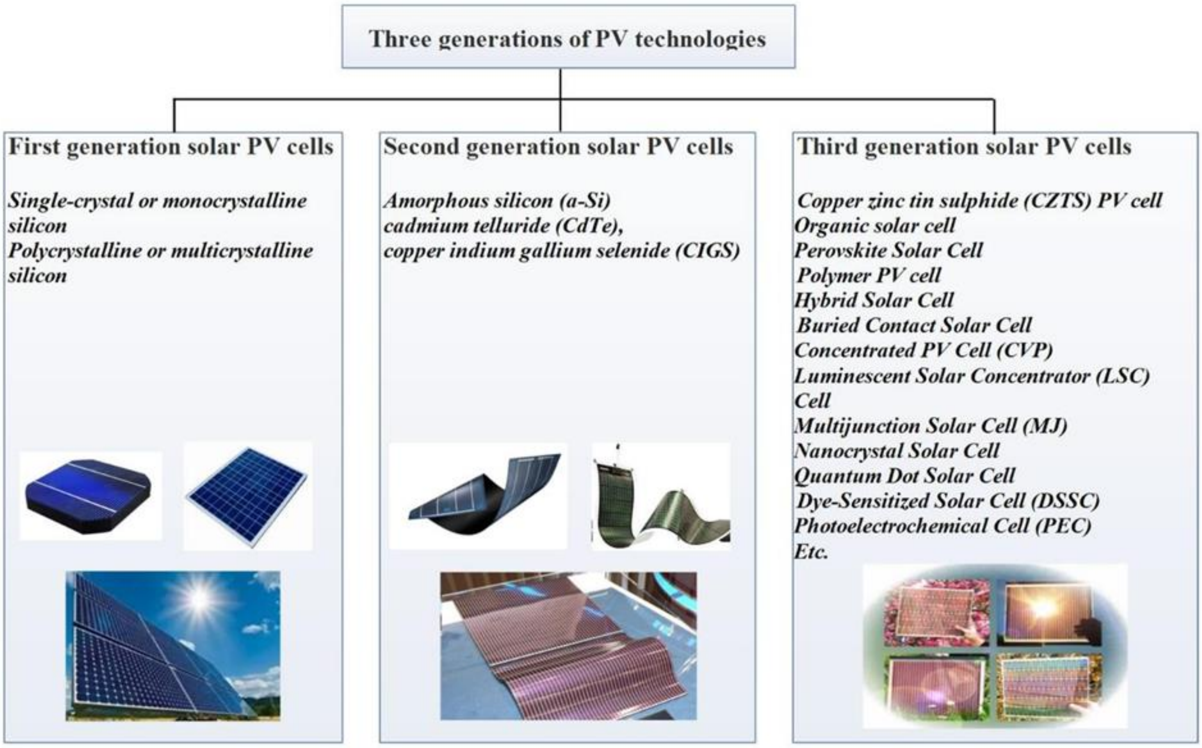
FigureI.9:SecondGenerationSolarCell[7]

I.8.3. Third Generation

Third-generation solar cells are currently under development and have the potential to surpass the efficiency and cost-effectiveness of both first and second-generation cells. These cells incorporate a range of novel materials and technologies, including organic solar cells, dye-sensitized solar cells, and perovskite solar cells. While third-generation solar cells are still in the early stages of development, they hold significant promise for potentially revolutionizing the solar energy industry. [6]



FigureI.10:SchematicdiagramoftypicalBHJ-OSC(RegularOSC,invertedOSCandtandemOSC)[6]

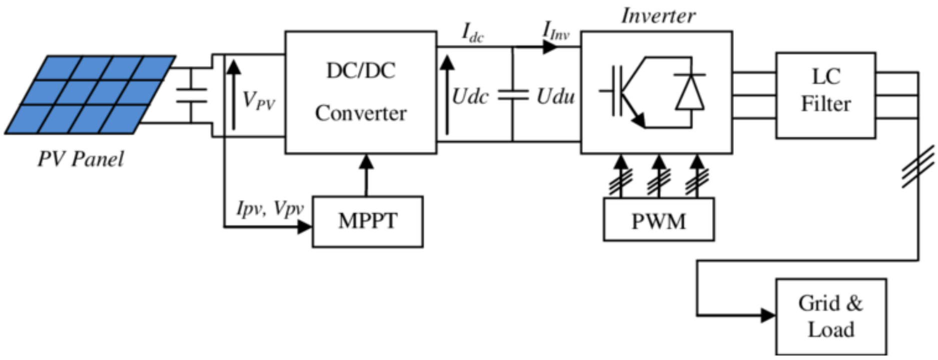


FigureI.11: The three generations of solar photovoltaic (PV)cells.[6]

I.9 Synoptic diagram of the photovoltaic conversion chain

The photovoltaic (PV) conversion process can be represented using a synoptic diagram, which serves as a simplified block diagram to emphasize the primary components and their interactions. Below is an overview of the key elements involved [8]:

- **PV Panel**: This constitutes the fundamental component of the system, consisting of interconnected solar cells that convert sunlight (photons) into direct current (DC) electricity via the photovoltaic effect.
- **Maximum Power Point Tracking (MPPT) Unit (Optional)**: This electronic device optimizes the output power of the PV panel by adjusting its operating voltage and current to achieve the maximum power point (MPP) under varying conditions such as fluctuations in sunlight intensity and temperature.
- **DC-DC Converter (Optional)**: In certain systems, a DC-DC converter is employed to modify the voltage level from the PV panel to match the voltage requirements of the inverter or the connected load.
- **DC-AC Inverter**: This device converts the DC electricity generated by the PV panel (or the DC-DC converter) into alternating current (AC) electricity, which can be used by household appliances or fed into the power grid.
- **Load**: This refers to the device or system that consumes the generated AC electricity, such as household appliances, lighting systems, or the electrical grid



FigureI.12:Synopticdiagramofthephotovoltaicconversionchain.[9]

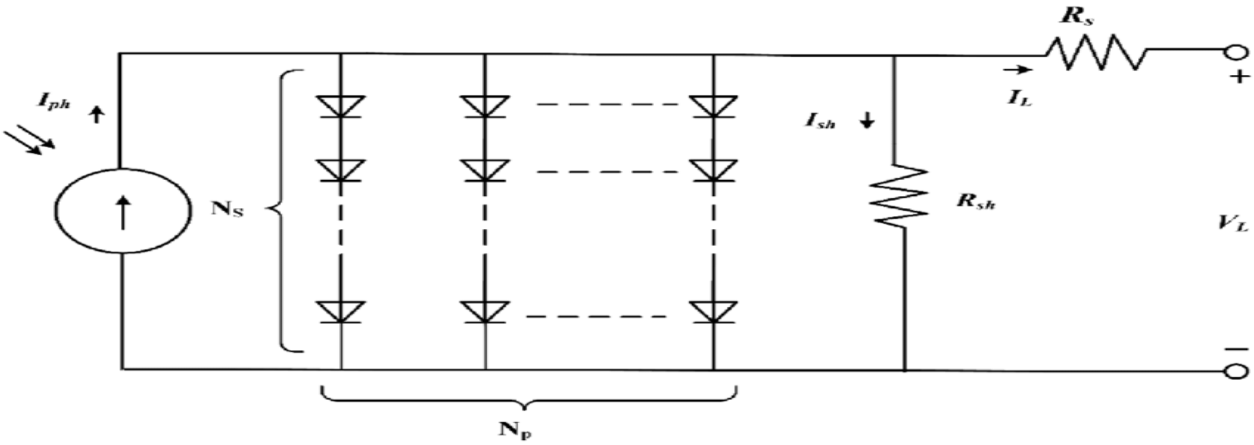
I.10 Photovoltaic cell

Photovoltaic cells, derived from the terms *photon* (a unit of light energy) and *volt* (a unit of electrical potential), are electronic components composed of semiconductor materials, with silicon being the most commonly used material in its various forms.

These cells directly convert light energy into electrical energy through the photovoltaic effect. Given that sunlight serves as the primary source of light energy, these devices are commonly referred to as solar cells.

I.11 Photovoltaic module

Due to the low power output of individual photovoltaic (PV) cells, these cells are connected in a series-parallel configuration to form a PV module capable of producing the required power. Typically, the PV module is rated according to its DC output power under standard test conditions (STC), which are conventionally defined as an irradiance of 1000 W/m² and a PV cell temperature of 25°C [5]. Figure I.38 illustrates the equivalent circuit of a PV module. The nonlinear current-voltage characteristic of the PV module is represented by the following equation, assuming all cells are identical [5]:



FigureI.13:The equivalent circuit of a PV module.

Where:

I_{PV}: is the module output current (A).

V_{PV}:is the module output voltage(V).

N_S: is the number of cells connected in series

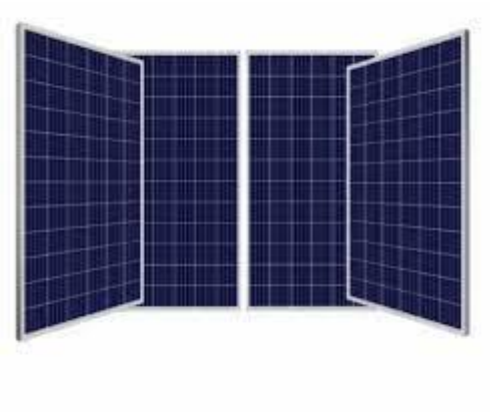
N_p:is the number of cells connected in parallel

The photovoltaic (PV) module considered in this thesis is the Trina Solar TSM-250PA05.08 model. The power versus voltage (P-V) and current versus voltage (I-V) characteristics of the Trina Solar TSM-250PA05.08 PV module under standard test conditions (STC) are depicted in Figure I.14. A PV module can operate at various points along the I-V curve, with the power output being determined by the specific operating point. Three key operating points on the I-V curve are critical for assessing the performance of a PV module: the maximum power point, the short-circuit current, and the open-circuit voltage.

- The maximum power point (MPP) refers to the specific point on the current-voltage (I-V) curve at which the photovoltaic (PV) module operates at its maximum power output.

- The short-circuit current point is defined by a zero voltage across the terminals of the PV module and the corresponding short-circuit current (Isc).

- The open-circuit voltage point is characterized by a zero current at the terminals of the PV panel and the corresponding open-circuit voltage (VOC).

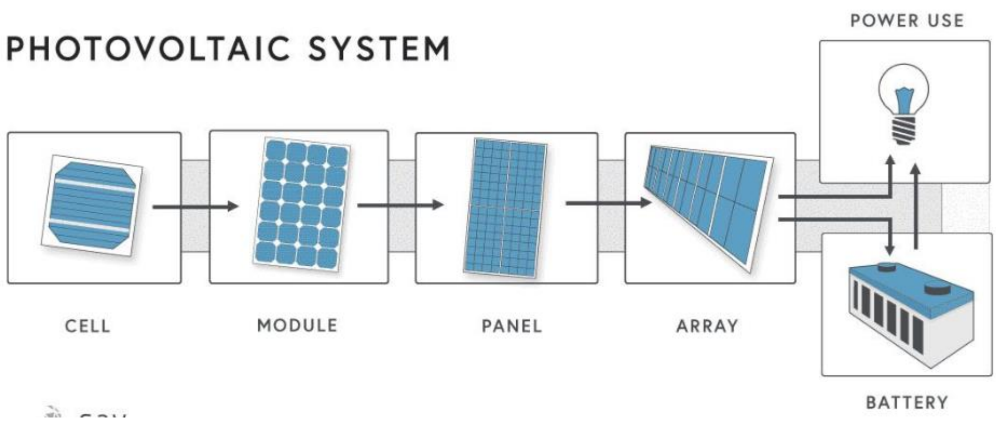


(a) ***(b)***

FigureI.14:(a)I-Vand(b)P-VcharacteristicsofthesolarTrinaSolarTSM-250PA05.08PVmodelunder STC.[10]

I.12 Composition of a photovoltaic module

Solar radiation is transformed into direct current electricity through a photovoltaic cell, which is a semiconductor device. Since sunlight is typically a radiation source, they are commonly referred to as solar cells. Individual PV cells act as the foundational components for modules, which further serve as the building blocks for arrays and complete PV systems (refer to Figure I.15) [10].



FigureI.15:The Composition of a Solar Cell.[10]

I.13 Connection of Photovoltaic Cells (The Photovoltaic Module)

An elementary photovoltaic cell constitutes a low-power electrical generator, insufficient on its own for most domestic or industrial applications. Photovoltaic generators are, therefore, made by connecting a large number of elementary cells in series and/or parallel.

A series connection of (Ns) cells increases the voltage of the photovoltaic generator. The cells are traversed by the same current, and the resulting characteristic of the series connection is obtained by adding the voltages of the individual cells, as represented in figure (1.17).

Equation (1.3) summarizes the electrical characteristics of a series connection of (Ns) cells:

$$V_{oc_{N_s}} = N_s \times V_{oc} \quad ; \quad I_{cc_{N_s}} = I_{cc}$$

- V_{ocNs}: The sum of the open-circuit voltages of the (Ns) cells in series.
- I_{ccNs}: The short-circuit current of the (Ns) cells in series.

This connection system is generally the most commonly used for commercial photovoltaic modules.

As the surface area of the cells increases, the current produced by a single cell steadily increases with technological advancements, while its voltage remains very low. The series connection thus allows for an increase in the overall voltage, thereby enhancing the total power output.

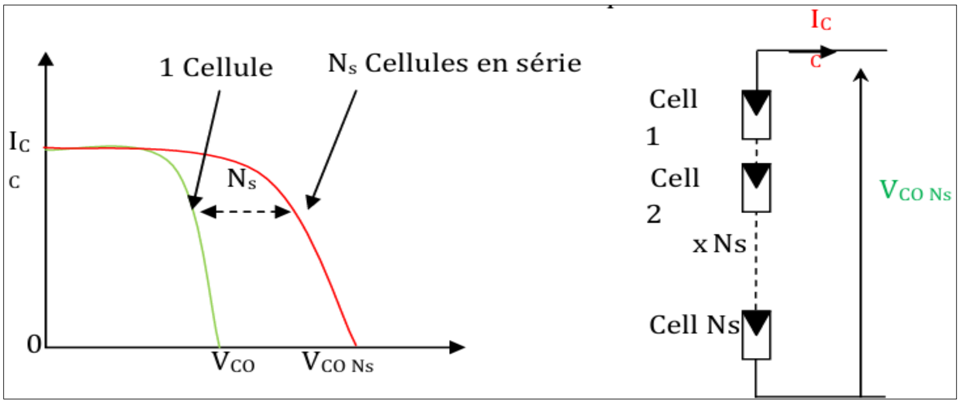


Figure I.16: Resulting characteristic of a series connection of (Ns) cells.

I.13.1 Parallel Connection of Cells

A parallel connection of (Np) cells is possible and allows for an increase in the output current of the generator thus created. In a grouping of identical cells connected in parallel, the cells are subjected to the same voltage, and the resulting characteristic of the grouping is obtained by adding the currents.

Equation (I.4) and figure (I.18) summarize the electrical characteristics of a parallel connection of (Np) cells.

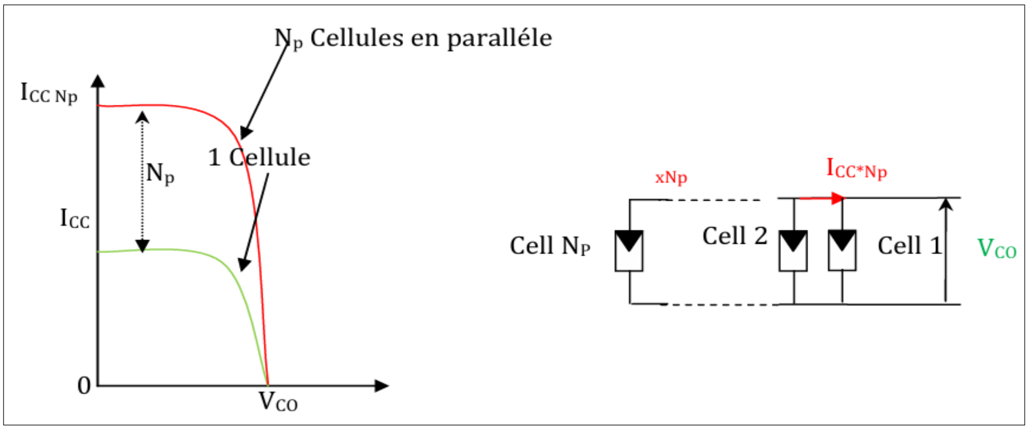


Figure I.17: Resulting characteristic of a parallel connection of (Np) cells [14,15].

Avec : $I_{ccN_p} = N_p \times I_{cc}$; $V_{ocN_p} = V_{oc}$

- I_{ccNp}: The sum of the short-circuit currents of (Np) cells connected in parallel.
- V_{ocNp}: The open-circuit voltage of (Np) cells connected in parallel.

I.13.2 Hybrid Connection of Cells (Series & Parallel)

Depending on the series and/or parallel connection of these cells, the values of the total short-circuit current and the total open-circuit voltages are given by the following relations:

$I_{cc}^t = N_p \times I_{cc}$; $V_{oc}^t = N_s \times V_{oc}$

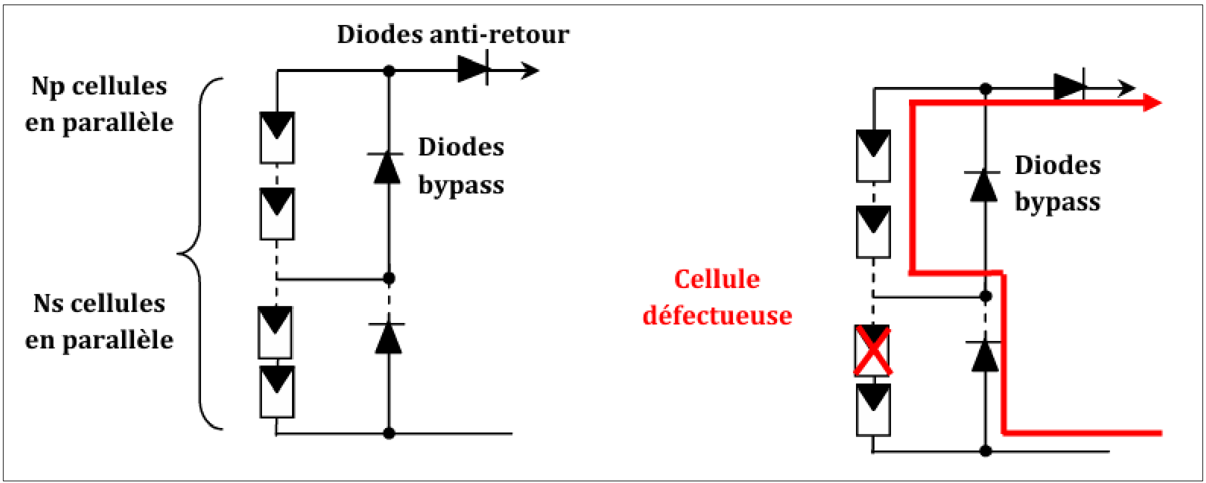


Figure I.18: Resulting characteristics of a hybrid connection of (Ns x Np) cells [14, 15].

Where:

- N_s: Number of cells connected in parallel.
- N_p: Number of cells connected in series.
- I_{cc}^t: Total short-circuit current.
- V_{oc}^t: Total open-circuit voltage.

Thus, the characteristic (Ipv Vpp of a photovoltaic generator can be considered the result of a network of (Nss Npp cells connected in series/parallel. The overall characteristic can also vary depending on illumination, temperature, cell aging, shading effects, or illumination inhomogeneity. Furthermore, even single shading or degradation of a cell in a series connection can cause a significant reduction in the current produced by the photovoltaic module

When the current drawn exceeds the current produced by the poorly illuminated cell, the voltage of that cell becomes negative, turning it into a receiving element. The cell then dissipates an excessive amount of electrical power, which could lead to its destruction if the fault persists for too long. This phenomenon is known as the "hot spot effect".

To address this issue, photovoltaic panels are equipped with bypass diodes, which serve to protect cells that become passive. When the bypass diode activates, it short-circuits a part of the module, thereby preventing reverse currents within defective cells. However, this effective solution reduces both the power output and the voltage across the module terminals. The degradation of a cell renders the group of cells associated with the defective cell, and protected by the bypass diode, incapable of producing power.

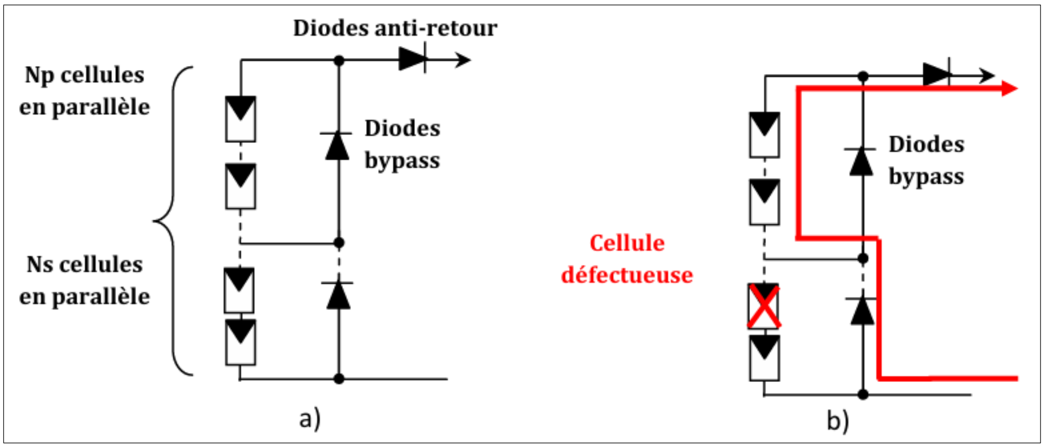


Figure I.19: a) Classical architecture of a photovoltaic module with protective diodes.

b) Failure of one of the PV module cells and activation of the bypass diode, highlighting the circulation current Ipv.

This phenomenon of partial power loss should be compared to the total loss of a module in the event of a problem with a single cell in a module operating without protections.

I.14 Installation and protection of a PV module

I.14.1 Site selection

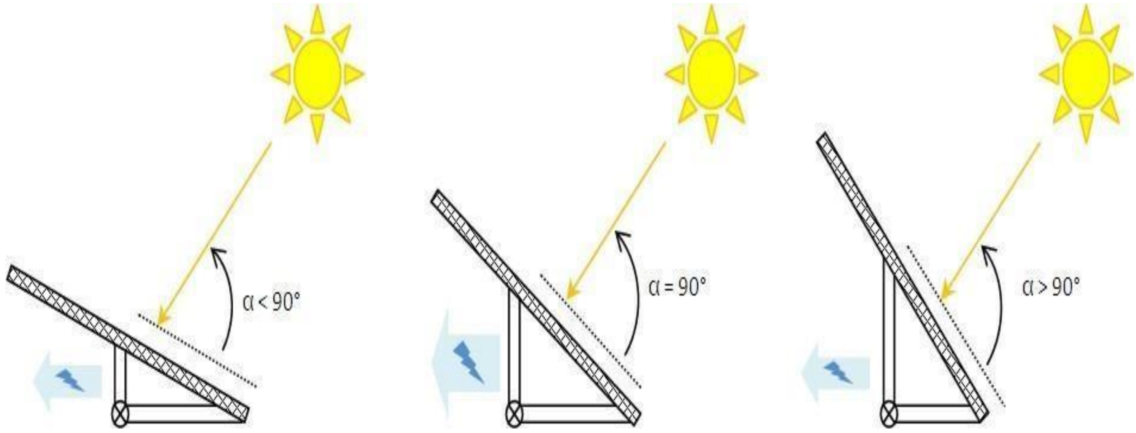
The panels must be placed in such a way that no shade (tree, buildings) can cover them during the day, whatever the inclination of the sun during the seasons. The modules will be spaced out from the surface that supports them in order to promote natural convection and limit their heating. [8]

I.14.2 Inclination

The module will be tilted on the basis of the value of the latitude, which constitutes a good summer/winter compromise for annual production.

The angle formed by the sun's rays and the solar panel is called the angle of incidence (denoted α). The production is maximum if the sun's rays reach the surface of the panel perpendicularly at noon (solar time).

Inclinationof90° in relation to the sun's rays(in the center)=optimal production. [8]



FigureI.20:Tilt of solar panel.[8]

I.14.3 Solar installations

- The photovoltaic panels produce a direct electric current;
- The regulator optimizes the charging and discharging of the battery according to its capacity and ensures its protection;
- Theinvertertransformsdirectcurrentintoalternatingcurrenttosupplyt heAC receivers;
- The batteries are charged by day to be able to supply power at nigh to ronbad weather days;
- Specific DC receivers can be used. These devices are particularly economical. [8]
-

I.14.3.1 Connection to the regulator

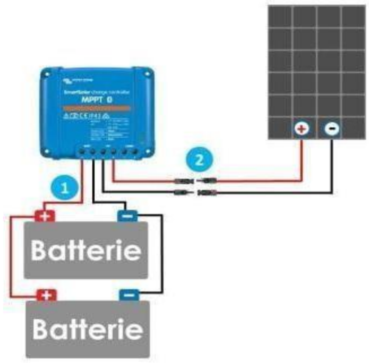
After marking the location of the battery, regulator and panel according to the cable lengths and advice above, the system components should be connected to the regulator in the following order after Grounding: [8]

a. Battery

First remove the fuse on the + cable

Connect the cables to the controller: red on the + terminal, black on the- terminal.

Connect the other end of the red cable to the + terminal, black to the - terminal of the battery, following the diagram below (red cable and black cable at each end of the system in parallel).



FigureI.21:Connectiontotheregulator.[8]

b. Panel

Coverthepanelwithprotectiontopreventanyproductionofelectricity.Connectthe cables back to the panel.

Red on red and black on…blue.

Connect the other end of these cables to the regulator :terminals + and-.

c. Consumers

Theenergyproducedsuppliesoneormoreconsumerappliances(lighting,refrigeration, pumping, etc.).

- Put all consumers in the off position;
- Connect the cables from the distribution box to the regulator;

- Then check all the polarities, the quality of the connections;
- Now install the fuse on the battery cable and on the regulator;
- Remove the protective cover on the solar panel;
- Turn on the consumers.

I.14.4 Lightning protection and grounding

I.14.4.1. Protection against lightning

A surge protector is necessary to protect installations from high voltage transients. Placed between the panel fuse and the regulator, it will be connected to the ground in order to evacuate the lightning potentially attracted by the metal structure of the modules (itself connected to the ground). When using a corrugated local network, an AC surge protector will also be used at the head of the installation.

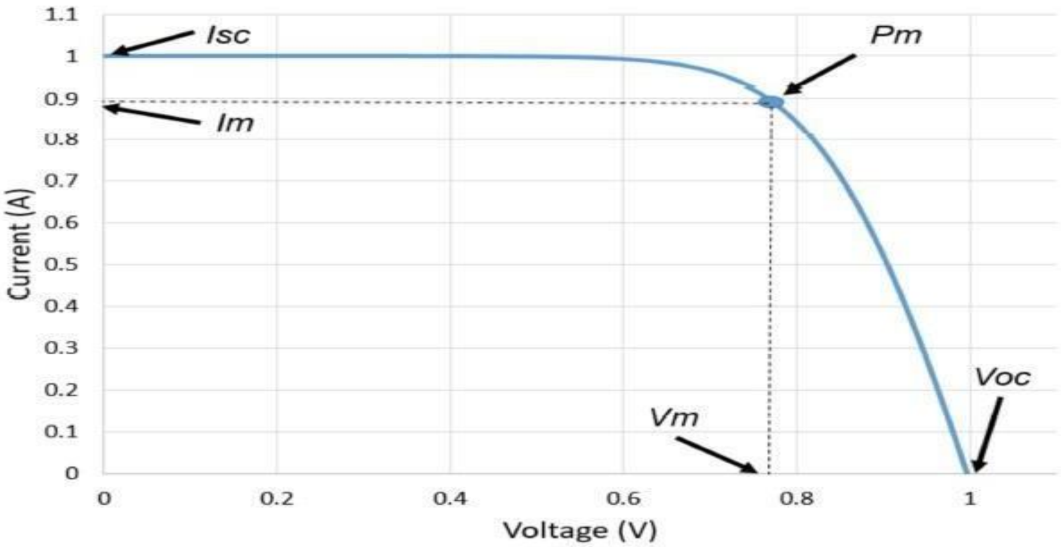
I.14.4.2. Grounding Grounding

Groundingwillensuretheprotectionofpeopleandequipment:thestructureofthe modules, the surge arresters, and the inverter will be connected to the ground. [8]

I.15. Electrical Characteristics of a Photovoltaic Generator

I.15.1. Current-Voltage Characteristics

The (I-V) curve of a solar cell is obtained from the voltage, current, and power characteristics of a particular PV cell, array, or module. These features provide data concerning the electrical behavior and its capability to produce power. Bearing in mind that manufacturers provide parameters of PV modules and the (I-V) characteristics in the standard test conditions. These conditions are represented by STC: 1000W/m² of irradiance, 25ºC cell temperature and air mass 1.5. [9]



FigureI.22:I-V characteristic curve.

I.15.2. A PV Cell Parameters

The main parameters that characterize a photovoltaic cell are [10] :

a. Open-Circuit Voltage Voc:

The open-circuit voltage is the voltage at which no current flows through the external circuit, it is the maximum voltage that a solar cell can deliver. V_{OC}corresponds to the forward bias voltage, at which the dark current density compensates the photocurrent density. V_{OC} depends on the photo-generated current density and can be calculated from Eq. (I.2)assuming that the net current is zero,

$$V_{OV}= \frac{K_B T}{q} ln(\frac{I_{ph}}{I_0}+1) \quad (I.2)$$

b. Short-Circuit Current:

The short circuit current of the solar cell is the maximum current; its value can be achieved when there is no load and voltage.

$$I_{sc}=\frac{I_{ph}}{1+\frac{R_s}{R_{sh}}} \qquad \text{(I.3)}$$

c. Maximum power point:

The maximum power point of the solar cell is the maximum power that the solar cell is able to produce in the operating conditions. It is the area of the product of the maximum current $I_{mp}$and Voltage V_{mp}as shown in the equation (I.4).

$$P_{mp}=I_{mp}.V_{mp} \qquad \text{(I.4)}$$

d. Fill Factor FF:

FF can be defined as the ratio of the maximum power (MP) generated by the solar cellto the product of the voltage open circuit $V_{oc}$and the short circuit current I_{sc}

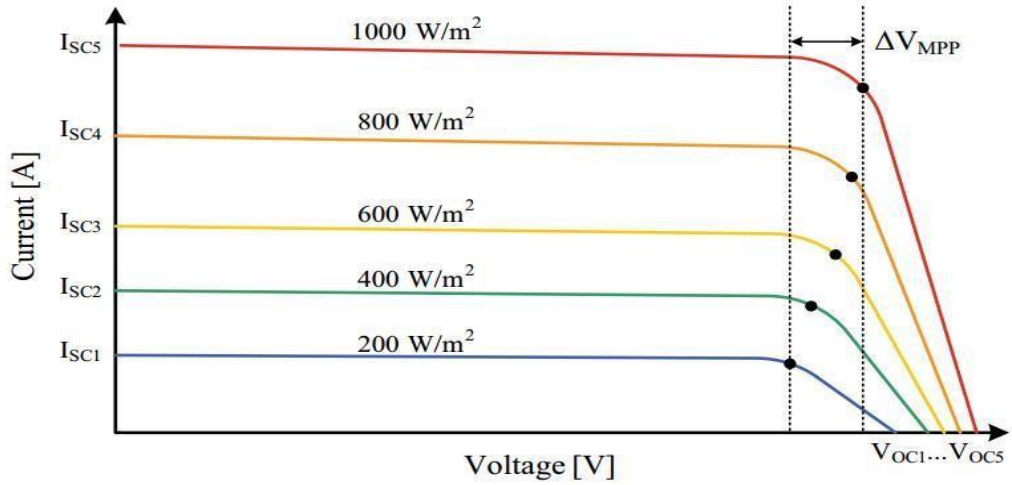
e. Conversion efficiency of the device (η):

The connection of solar cell to an electrical circuit leads to the conversion and the collection a percentage of power. This is referred to as Conversion efficiency of the device(η). Besides, the calculation of this term is executed through the use of a ratio of themaximum power point, Pmax, divided by the input light irradiance (G, in W/m^2) in the standard test conditions (STC) and the surface area of the solar cell (Ac in m^2)[11].

I.16. Influence of Irradiance and Temperature

I.16.1. Solar Irradiation effect

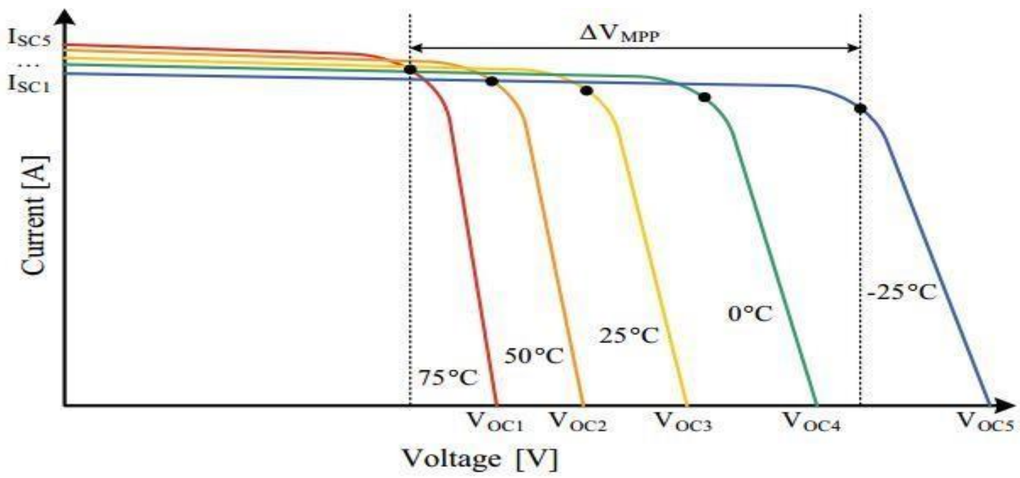
Throughout the day, solar irradiance has a higher variation more than the temperature, and it influences on the efficiency of the PV cells. As shown in Figure I.23, the electrical current generated depends directly on the absorbed solar radiation.



FigureI.23:I–V Characteristic curve of a PV module[12].

I.16.2 Temperature effect

As presented in Figure I.24, the voltage of the PV panel is influenced by the temperature variation. Using the same previous PV panel, the ($VMPP$) value is less roughly during hot summer days by 10 V, and in the winter days is roughly higher than the STC (Standard Test Conditions) value by 10 V. However, the PV system current just barely increases with the temperature.



FigureI.24:I–V Characteristic Curve of a PV Module at Constant Received Solar Radiation and Variable Temperature [12].

I.17. The photovoltaic generator

The photovoltaic generator system consists of several modules and a set of components that help in energy generation and conversion.

FigureI.25:Photovoltaic generator.[5]

I.17.1 Energy storage (Battery)

The capacity of a battery is expressed in ampere-hours (Ah). Most of batteries used in PV systems are lead-acid batteries. In some applications, for extreme climate conditions nickelcadmium batteries are used which is the relative high cost. [13]

I.17.2 Charge regulators

Charge regulators are the link between the PV modules, battery and load. They protect the battery from overcharge or excessive discharge by regulate the input and the output currents.

I.17.3 Inverters

The inverter's main functions are: transformation of DC electricity into AC, wave shaping of the output AC electricity, and regulation of the effective value of the output voltage.

I.17.4 Load

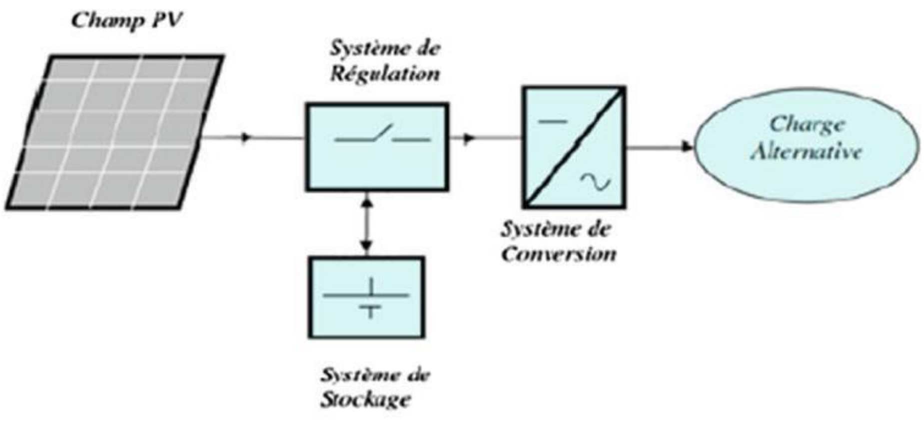
The appliances, lights and equipment being powered by a PV solar system constitute electric loads of the PV system. Energy-efficient loads contribute to overall system efficiency and economy.

I.18. Applications of photovoltaic systems

There are several structures of the main applications of photovoltaic systems.

I.18.1 Autonomous photovoltaic installations

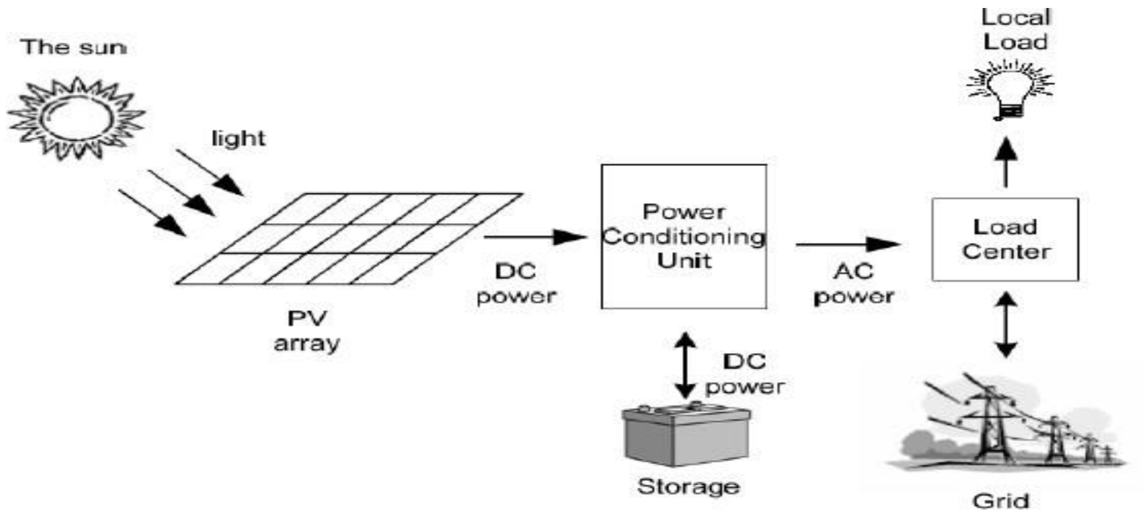
The role of autonomous systems is to feed one or more consumers located in an area isolated from the electricity grid. The photovoltaic field see figure (I.26) can provide directly the electrical energy required to operate receivers (lighting and household equipment). [10]



FigureI.26: Simplified diagram of anautonomous photovoltaic installation[5]

I.18.2.Grid-ConnectedPhotovoltaic Systems

Such a system is installed on a site connected to the network. Usually on homes or businesses that wish to use a form renewable energy and that benefit from good sunshine. A grid-connected photovoltaic generator does not need energy storage and thus eliminates the most problematic (and expensive) link.

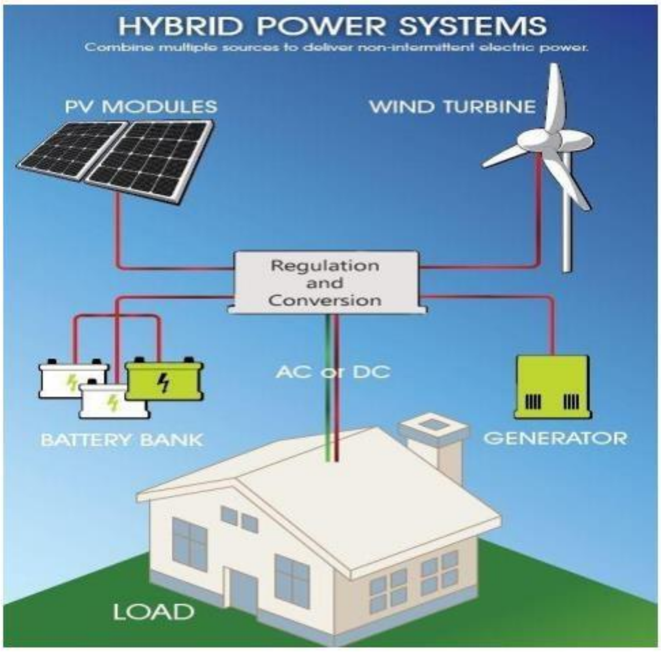


FigureI.27: Grid-Connected Photovoltaic Systems[13]

I.18.3.Hybrid photovoltaic systems

These are systems that bring together different sources of energy such as a wind plant, diesel generator or cogeneration plant in addition to photovoltaic generator.

This type of installation is used when the photovoltaic generator alone does not cover all the energy required. [13]



FigureI.28: Hybrid photovoltaic systems[13]

I.19. Advantages and disadvantages of PV (photovoltaic) energy

I.19.1. Advantages

High reliability; modules are guaranteed for 25 years by most manufacturers. It has no moving parts, which makes it particularly suitable to isolated regions. This is the reason for its use on spacecraft. The nature of modulator of the photovoltaic panels allows the simple and adaptable to various energy needs. Systems can be sized to power applications ranging from milliwatts to megawatts; Their operating costs are very weak given the discounted interviews, and they do not require fuel or transportation or highly specialized personnel.

Photovoltaic technology has ecological qualities because the final product is non-polluting, silent, little waste.

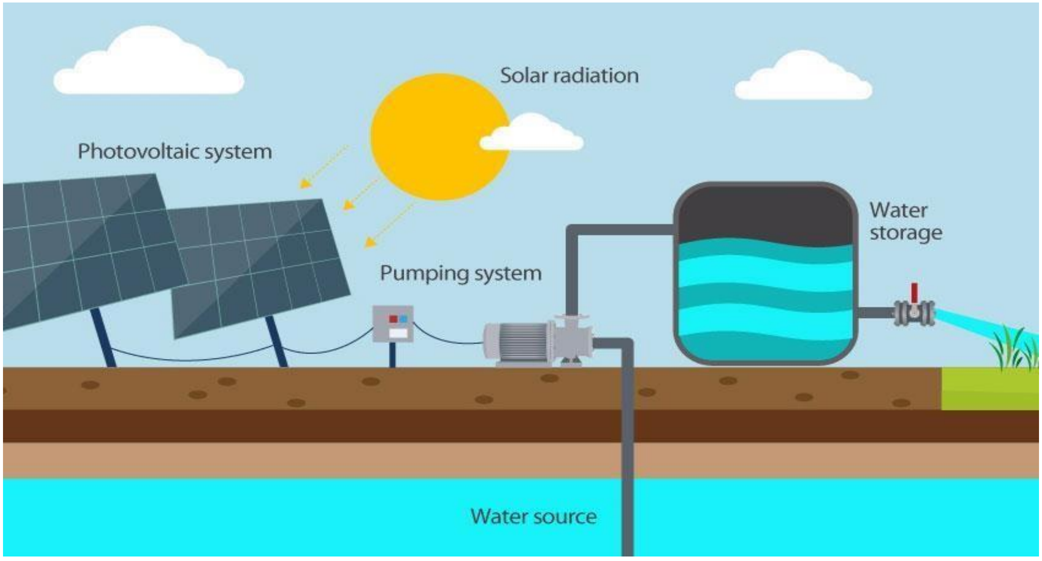
I.19.2.Disadvantages

The manufactures of the photovoltaic module is high technology and requires high-cost investments; occupation of space for large installations; the actual conversion efficiency of a module is low (the theoretical limit for a crystalline silicon cell is 28%); photovoltaic generators are not competitive with diesel generators only for low energy demands in isolated areas.

Finally, when the storage of electrical energy in chemical form (battery) is necessary, the cost of the photovoltaic generator is increased, reliability and performance of the system remain equivalent. However, provided that the battery and the components of associated regulations are wisely chosen.

I.20. Water Pumping Over The Sun

The most common problem in remote places and the most isolated communities that are far from waterways and electricity grid. To ensure the water supply anywhere, we have to use a standalone power supply, and photovoltaic solar energy is one of the most common of these energies. This combination is called "Photovoltaic Water Pumping System" as presented in Figure I.29. This system is the perfect way to fix the water supply's problems, by extracting and pumping the water from a well even in rural areas and places, and that is the system’s goal. The photovoltaic water pumping system can be used in many domains, including residential, farming (irrigation, breeding, and agriculture), water purification, or firefighting. It combines two principle parts that are the photovoltaic system and the pumping system.



FigureI.29: Photovoltaic Water Pumping System[7].

I.20.1. Selection for solar pumping system

Solar pumps are very popular in the field of mini-systems drinking water supply. Historically diesel generators have been widely used to address rural pumping station electrical supply problem. However, the operation of diesel engines requires many hours of maintenance (replacement of filters, filling of fuel tanks, drains). Conversely, solar pumps require only a minimum of attention and some types of pumps can even WO <<< RK for upto 5 years without any intervention. Their daily functioning as the sun goes by in automatic and unattended. This type of solution is perfectly suitable for applications located far and monitoring of a diesel solution is difficult [8]. Pumping covers a large majority of needs:

- Domestic.
- The provision of drinking water.
- Livestock.
- Irrigation.

I.20.2. Types of solar pumping:

I.20.2.1. Pumping over the sun: (direct pumping system):

Pumping <<with the sun>> allows having a simple, reliable and less expensive photovoltaic system. Here the water is pumped and stored in a tank, over the day. Then we talk about hydraulic storage. Stored water will be distributed as required.

I.20.2.2. Indirect pumping: (Pumping with energy storage):

Here it is the electric energy that will be stored in batteries. Pumping will be possible even in the absence of the sun. Such a system is more expensive than the previous one, given the need to change the batteries, as they have a short lifespan [9].

I.20.3. The Components of a PV Pumping System

A solar pumping system usually consists of [10]:

- The photovoltaic generator (PVG).
- The electric pump group.
- Command and control electronics.
- The storage unit.

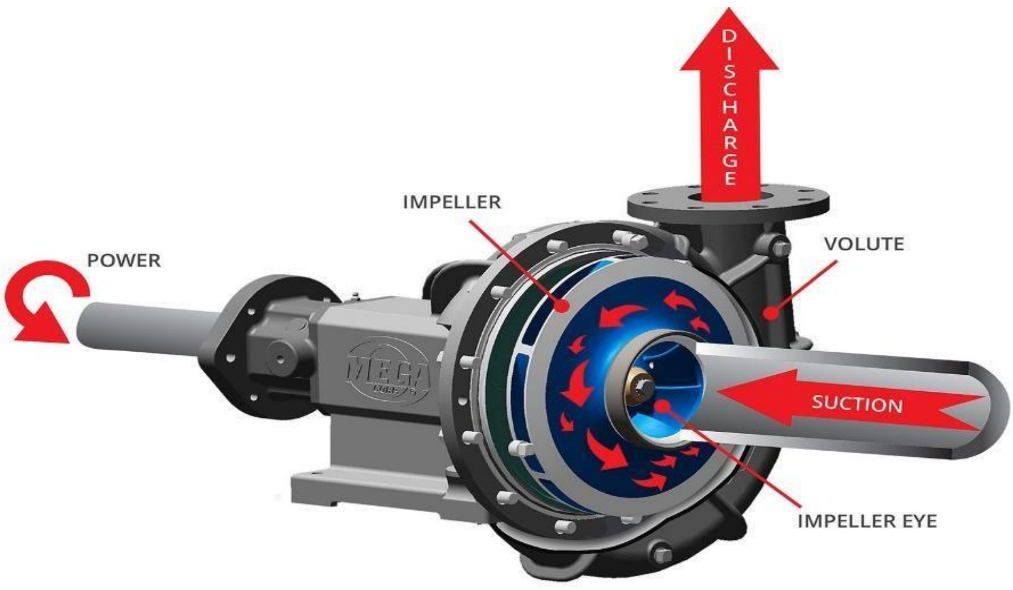
I.20.4. The Electric Pump Set

I.20.4.1. The Pumps

A pump is a device that moves fluids (liquids or gases), or sometimes slurries, by mechanical action. It is a device for aspirating and repressing. There are two large types of pumps: centrifugal pumps and positive displacement pumps. These last are suitable for raising low flow rates at high pressures.

I.20.4.2. Centrifugal Pumps

Centrifugal water pumps use centrifugal force to pressurize and move water from the inlet to the outlet. A rotating set of vanes (called an 'impeller') is spun by the pump shaft. As water is forced through the impeller, rotational energy is transferred from the impeller to the water, which gains velocity and pressure through the centrifugal force applied and is flung from the impeller. The volute (a spiral-shaped case) funnels the now-pressurized water to the outlet. Image below shows clockwise rotation as viewed from the motor mound. [9]



FigureI.30:Centrifugal Pump.[9]

In our SWPS, a dynamic pump (centrifugal) has been selected as it requires less maintenance and offers better ability to match with output of PV generators.

The torque of the pump is proportional to the square of the rotor speed:

$$T_L = K_p \Omega_r^2 \qquad \text{(I.7)}$$

where K_P is the proportionality constant and it is given by:

$$K_p = P_{np} / \Omega_{rn}^3 \qquad \text{(I.8)}$$

The water rate and pressure of the pump depend on the available mechanical power at the rotating impeller and the total head. The determination of the pump's output parameters can be simplified using affinity laws which require only pump ratings and actual input parameters; rotor speed and torque [13].

a. The Affinity Laws

Processes require the satisfaction of the hydraulic parameters of head and flow rate. The Affinity Laws are mathematical relationships that allow for the estimation of the changes in the pump performance curves as a result of a change in the shaft speed (N) or in the impeller diameter.

Fixing the impeller diameter, the Affinity Laws state that for a given pump, the flow rate (Q) will be directly proportional to the speed, the head (H) will be directly proportional to the square of the speed, and the required power (P) will be directly proportional to the cube of the speed [14]:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \qquad \text{(I.9)}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

I.20.4.3. The Advantages of Centrifugal Pump

- They do not require any valves, or many moving parts. This makes them easy to produce with many different materials. It also allows them to move at high speeds with minimal maintenance.
- Their output is very steady and consistent. Most of all, they are very small compared to other types of pumps that create the same output.
- They can deal with large volumes of water.

I.21 Conclusion

In this chapter, we have covered the fundamentals of photovoltaic systems, as well as their components and main types. The operating concept of solar cells, as well as their modeling, assessment parameters and characteristic curves form which, the impact of ambient temperatures and solar irradiance levels were visualized and extracted.

Chapter II

Photovoltaic Generator Modeling

II.1 Introduction

Photovoltaic (PV) systems are at the forefront of renewable energy technologies, converting solar radiation into electricity through the photovoltaic effect. This chapter provides an exhaustive exploration of PV generator modelling, a critical process for designing efficient and reliable solar energy systems. The modelling encompasses the physics of PV cells, electrical configurations of modules and arrays, and advanced techniques for parameter identification and performance optimization. As global energy demands rise, accurate PV models are essential for maximizing energy yield, reducing costs, and integrating solar power into smart grids. This expanded discussion includes theoretical foundations, practical challenges, and real-world applications, offering a comprehensive resource for engineers and researchers.

The importance of PV modelling lies in its ability to predict system behavior under varying environmental conditions, such as irradiance and temperature fluctuations. By understanding these models, designers can optimize system configurations, enhance energy conversion efficiency, and ensure compatibil- ity with energy storage and grid systems. This chapter is structured to cover the following: PV cell fundamentals, generator configurations, equivalent cir- cuit models, parameter identification methods, and the design of PV modules and arrays. [16]

II.2 PV Cells

Photovoltaic cells are the fundamental units of PV systems, leveraging semicon- ductor materials to generate electricity from sunlight. This section provides a detailed analysis of PV cell operation, material properties, and performance fac- tors, supplemented by practical examples and theoretical insights. [17]

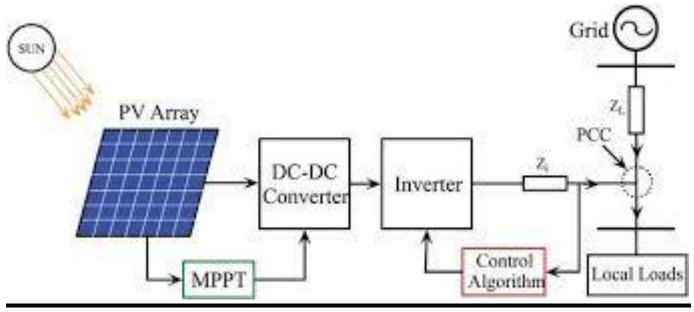


Figure II.1: Key Components of a PV System: From Cells to Grid Integration

II.2.1 Operational Principles

The photovoltaic effect occurs at the p-n junction of a semiconductor, where pho- tons with sufficient energy dislodge electrons, creating electron-hole pairs. This generates a potential difference, driving current through an external circuit. The efficiency of this process depends on the material's bandgap, typically around 1.1 eV for silicon.

II.2.2 Material Types

PV cells are classified based on their material and manufacturing process:

- Monocrystalline Silicon: Offers efficiencies of 15–22% due to its uniform crystal structure but is expensive to produce.
- Polycrystalline Silicon: More cost-effective with efficiencies of 13–18%, though less efficient due to grain boundaries.

- Thin-Film Technologies: Include amorphous silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), with efficiencies of 10– 13% but advantages in flexibility and weight.

II.2.3 Performance Factors

Cell performance is influenced by:

- Irradiance: Higher sunlight intensity increases photocurrent linearly.
- Temperature: Efficiency decreases by approximately 0.5% per 1 ◦C above 25 ◦C.
- Spectral Quality: Variations in sunlight spectrum affect output, particu- larly for thin-film cells.

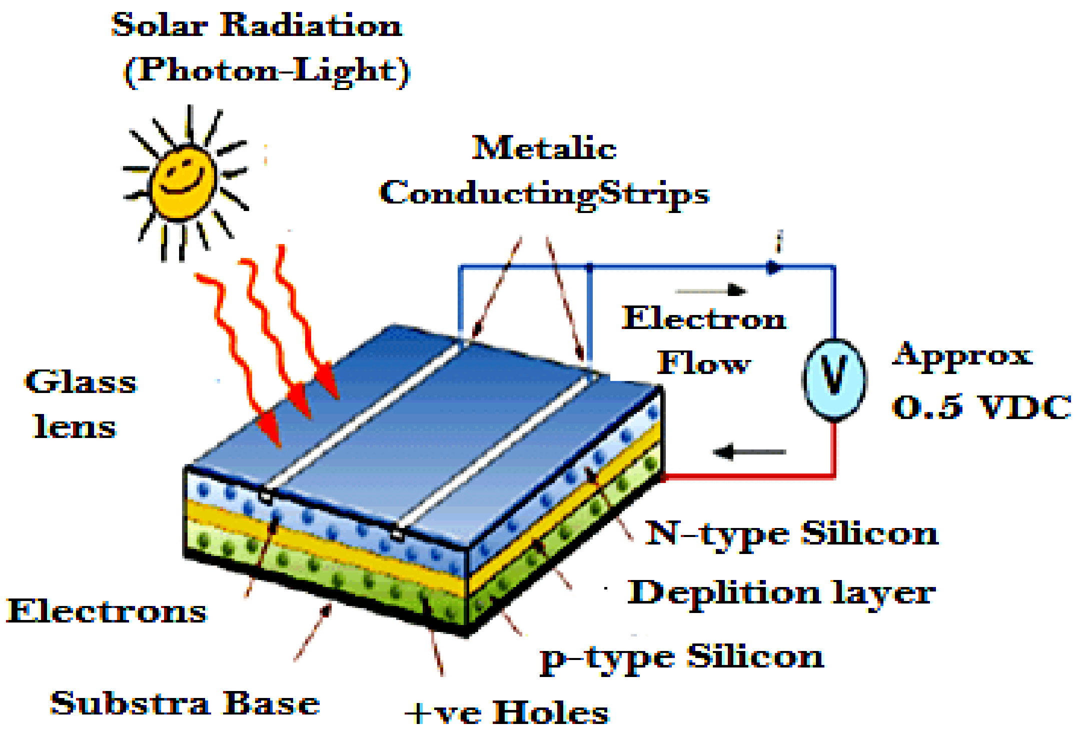


Figure II.2: Structural and Physical Aspects of PV Cell

Table II.1: Comparison of PV Cell Types

Cell Type	Efficiency (%)	Cost	Applications
Monocrystalline	15–22	High	Residential, Commercial
Polycrystalline	13–18	Medium	Large-Scale Installations
Thin-Film	10–13	Low	Portable, Building-Integrated

II.3 PV Generator

A PV generator aggregates multiple PV cells into modules and arrays to deliver the required power output. This section explores the design, electrical configurations, and operational characteristics of PV generators, with emphasis on scalability and system integration. [18]

II.3.1 Configuration Options

PV generators are configured in series to increase voltage or in parallel to boost current. The choice depends on the application, such as standalone systems or grid-connected setups. The power output is given by:

$$P_{out} = V_{oc} \cdot I_{sc} \cdot FF \qquad \text{(II.1)}$$

where Voc is the open-circuit voltage, Isc is the short-circuit current, and FF (fill factor, typically 0.7–0.85) quantifies the cell's quality.

II.3.2 Practical Applications

PV generators are deployed in diverse scenarios:

- Residential Systems: Typically 3–10 kW, powering homes.

- Commercial Installations: 50–500 kW, for offices and factories.
- Utility-Scale Plants: Multi-MW arrays for grid supply

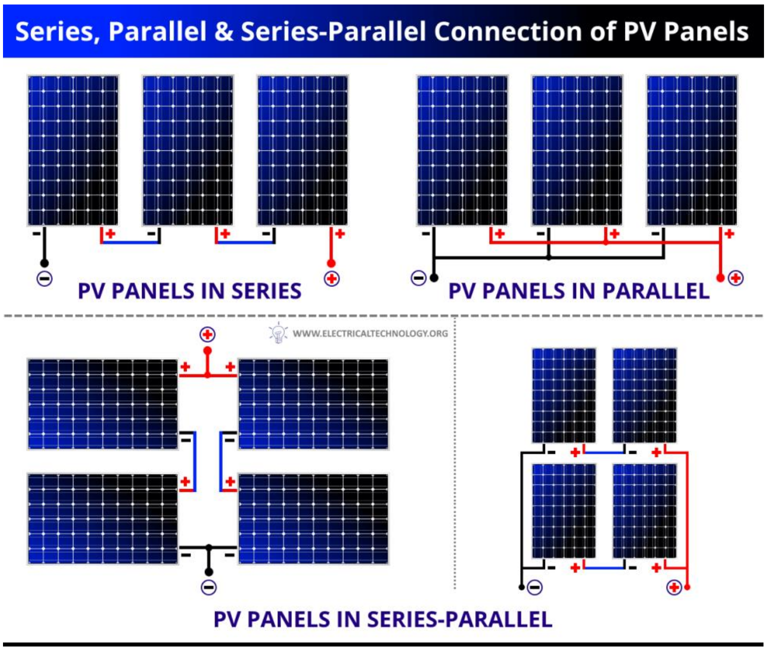


Figure II.3: Series-Parallel Configuration of a PV Generator

II.3.3 Case Study: Utility-Scale PV Generator

Consider a 1 MW PV generator comprising 4000 modules, each rated at 250 W. Arranged in 200 strings of 20 modules in series, the system achieves a nominal voltage of 600 V and current of 1667 A. Such systems require careful design to minimize losses and ensure reliability.

II.4 PV Cell Model

The equivalent circuit model of a PV cell is critical for simulating its electrical behavior. The single-diode model is the most common, but the two-diode model offers greater accuracy under certain conditions. This section provides a de- tailed derivation and comparison. [19]

II.4.1 Single-Diode Model

The single-diode model represents the PV cell as:

$$\mathbf{I} = \mathbf{I}_{ph} - \mathbf{I}_d - \mathbf{I}_{sh} \qquad \text{(II.2)}$$

where:

- I_{ph}: Photocurrent, proportional to irradiance.

- $\mathbf{I_d} = \mathbf{I_O}\left(e^{\frac{q(V+IR_S)}{\ }} - 1\right)$ Diode current, with I_0 as reverse saturation current, q as electron charge, n as ideality factor, k as Boltzmann constant, and T as temperature.

- $I_{sh} = \frac{V+IR_S}{R}$: Shunt current, representing leakage losses.

II.4.2 Two-Diode Model

The two-diode model accounts for recombination losses in the depletion region:

$$I = Iph - Id1 - Id2 - Ish \qquad \text{(II.3)}$$

where Id1 and Id2 represent currents through diodes with different ideality factors. This model is complex but more accurate at low irradiance.

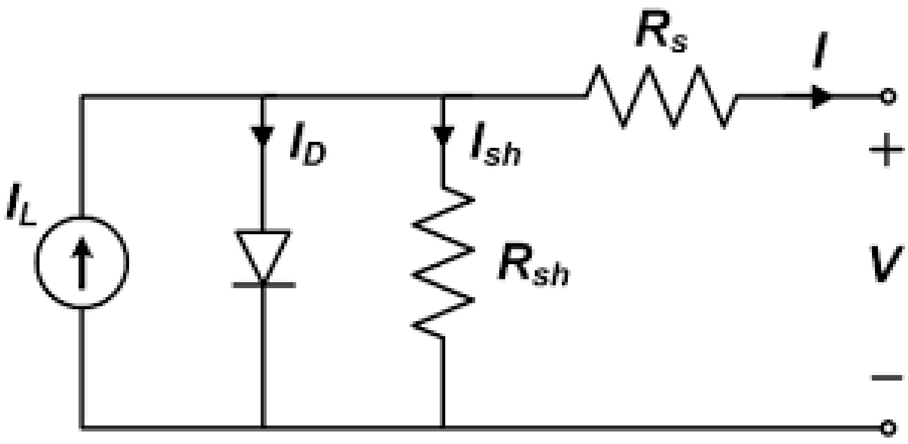


Figure II.4: Single-Diode Equivalent Circuit of a PV Cell

II.4.3 Model Validation

Models are validated by comparing simulated I-V curves with experimental data. Discrepancies highlight the need for accurate parameter estimation, discussed in the next section.

II.5 Identification of PV Model Parameters

Parameter identification is crucial for ensuring model accuracy. This section provides an in-depth analysis of methods, including analytical, numerical, and experimental approaches, with practical examples. [20]

I.5.1 Analytical Methods

These methods use datasheet values (e.g., Voc, Isc, maximum power point) to solve simplified equations.

where Vmp and Imp are the voltage and current at the maximum power point.

II.5.2 Numerical Optimization

Optimization algorithms minimize the error between simulated and measured I-V curves. Common methods include:

• **Newton-Raphson:** Solves nonlinear equations iteratively.

• Particle Swarm Optimization (PSO): Mimics swarm behavior to find global optima.

• **Genetic Algorithms:** Use evolutionary principles to optimize parameters.

II.5.3 Experimental Techniques

Parameters are extracted from I-V curves measured under standard test conditions (STC: 1000 W m−2, 25 ◦C). Advanced setups use variable irradiance and temperature to capture dynamic behavior.

Table II.2: Typical PV Cell Parameters

Parameter	Symbol	Typical Value
Photocurrent	I_{ph}	3–9 A
Series Resistance	R_s	0.01–0.5 Ω
Shunt Resistance	R_{sh}	100–1000 Ω
Ideality Factor	n	1–2

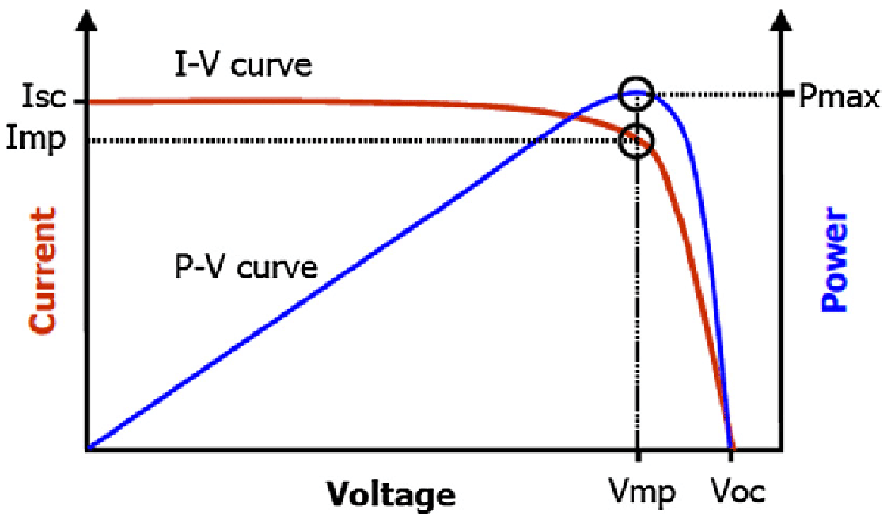


Figure II.5: Typical I-V and P-V Curves for Parameter Extraction

II.6 Photovoltaic Module

A PV module is an assembly of interconnected PV cells, encapsulated to protect against environmental factors. This section explores module design, performance challenges, and optimization strategies. [21]

II.6.1 Construction and Materials

Modules typically consist of:

- **Cells**: 60–72 cells connected in series.

- **Encapsulation**: Tempered glass front, polymer backsheet, and EVA (ethylene- vinyl acetate) encapsulant.
- **Frame**: Aluminum for structural integrity.

II.6.2 Performance Challenges

Key issues include:

- **Partial Shading:** Reduces output due to current mismatch, mitigated by bypass diodes.
- **Temperature Effects:** Power output decreases by 0.4–0.5% per 1 ◦C above STC.
- **Degradation:** Long-term exposure reduces efficiency by 0.5–1% per year.

II.6.3Example: Module Specification

A typical 300 W module has:

- V_{oc}: 39 V
- I_{sc}: 9.8 A
- **Dimensions**: 1.65 m x 1 m

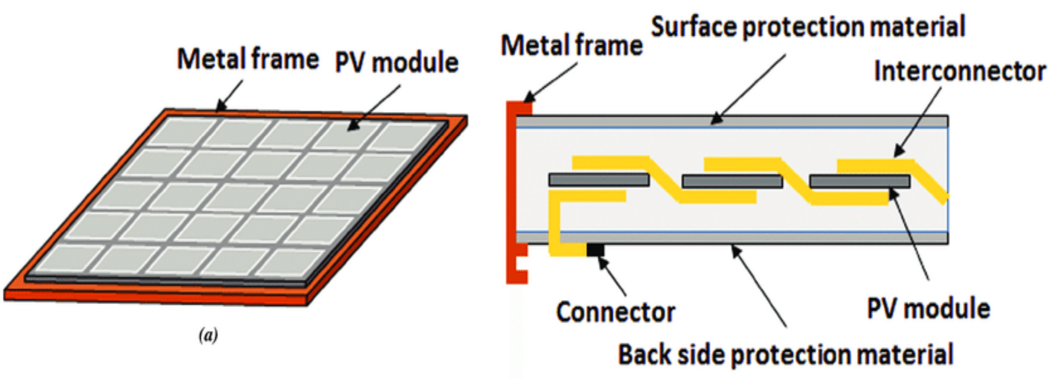


Figure II.6 : Internal Structure and Wiring of a PV Module

II.7 Photovoltaic Array

PV arrays combine multiple modules to meet large-scale power demands. This section covers array design, optimization, and integration with power electron- ics, with a focus on practical implementation. [22]

II.7.1 Design Considerations

Key factors include:

- **Module Arrangement:** Optimized to avoid shading and maximize land use.
- **Wiring Losses:** Minimized through proper cable sizing and inverter placement.
- **Grounding and Safety:** Essential for large arrays to prevent electrical hazards.

II.7.2 Maximum Power Point Tracking (MPPT)

MPPT algorithms, such as Perturb and Observe or Incremental Conductance, ensure operation at the maximum power point under varying conditions. The power output of an array is:

$$P_{array} = N_s \, . \, N_p \, . \, P_{module} \qquad (II.4)$$

where Ns and Np are the number of series and parallel modules.

II.7.3 Case Study: 10 MW Solar Farm

A 10 MW array with 40,000 modules (250 W each) is arranged in 2000 strings of 20 modules. The system uses central inverters with MPPT and achieves an annual energy yield of approximately 15 GWh, depending on location and climate.

II.7.4 Integration with Energy Systems

Arrays are often paired with:

- Inverters: Convert DC to AC for grid compatibility.

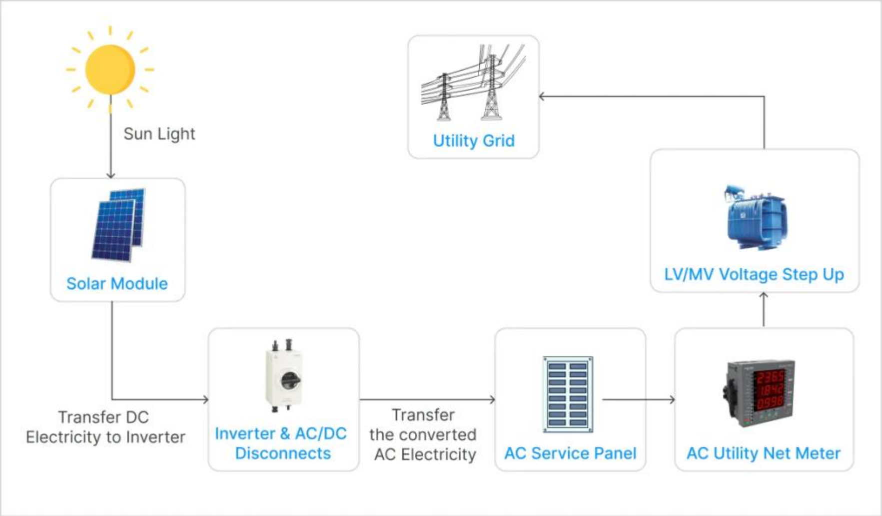


Figure II.7: Layout of a Utility-Scale PV Array

• **Energy Storage:** Batteries store excess energy for use during low irradi- ance.

• **Grid Interface:** Ensures compliance with grid codes and power quality standards.

II.8 Conclusion

The chapter discusses the single diode PV cell model for PV module modeling and parameter identification from datasheets. It highlights how environmental factors, particularly temperature and irradiance, impact PV module performance. The power output is directly proportional to irradiance and inversely proportional to temperature. P-V and I-V characteristics illustrate the effect of temperature variations. Operating at the maximum power point (MPP) is crucial for maximizing power output, but standard test conditions (STC) are rarely met in real environments, leading to suboptimal power delivery if the operating point deviates from the MPP. The next chapter will explore converters designed to track the MPP for optimal power harvesting

.

Chapter III

Field Oriented Control and MPPT

III.1 Introduction

In general, solar power is a limited continuous power source, and its internal impedance varies throughout the day, depending primarily on the level of solar radiation acting on the module's surface and the cell temperature.

A maximum power point tracker (MPPT) is a circuit (usually a DC-DC converter) used in most modern photovoltaic inverters. Its function is to maximize the power available from connected solar module arrays at any given time during operation.

A solar module is a limited continuous power source, and its internal impedance varies throughout the day, depending primarily on the level of solar radiation acting on the module's surface and the cell temperature.

Using an inverter without an MPPT circuit will result in suboptimal or suboptimal operating conditions between any photovoltaic module (or string of modules) and the inverter. Unless the inverter can match the strings to generate maximum power, the result will be less efficient operation of the connected strings.

The MPPT circuit continuously monitors the array's voltage and current, attempting to maximize the inverter's operating point to the array's maximum power point, resulting in the highest energy harvest. Single-channel MPPT inverters only provide monitoring data at the array level.

Whether it's one, two, or four strings, data collection will depend on the total array inputs. With independent dual MPPT channels, the inverter can provide monitoring information at the MPPT channel level.

This results in more accurate monitoring data, such as site status, power production, and troubleshooting data. This is important because, depending on the system design, the loading of the two channels may vary. Therefore, for small systems (with one string per MPPT channel), data collection is primarily at the string level.

For larger residential systems (with a maximum of two strings per MPPT channel), data collection is reported at both string levels. Therefore, in addition to providing the appropriate energy harvest values for each channel, the user can understand what is happening at each input at any given time. This can be useful for troubleshooting abnormal conditions at a particular inverter input.

Understanding all these aspects of MPPT can help provide a better understanding of how energy harvesting works and thus help solar installations become more profitable. [23]

III.2 Maximum power point tracking

The concept of MPPT is explain by considering an example of monocrystalline solar cell Q6LMXP3-G3 made by Q-CELLS. The simulations are conducted with the cell parameters obtained from datasheet Fig. 1 depicts the *I–V* characteristic and power versus voltage curve of a single solar cell. It indicates that the solar PV can give maximum power only at a single point. For extracting the maximum power from the cell the operating voltage or current should be corresponding to the maximum power PV panel power is sent into a DC-DC converter, which is commanded by an MPPT controller that gets the operational parameters in real time. The MPP tracker then uses the built in algorithm and the collected data to determine the MPP related to the operating circumstances and makes the necessary changes to the power converter's duty cycle to keep the system working at peak efficiency. [24]

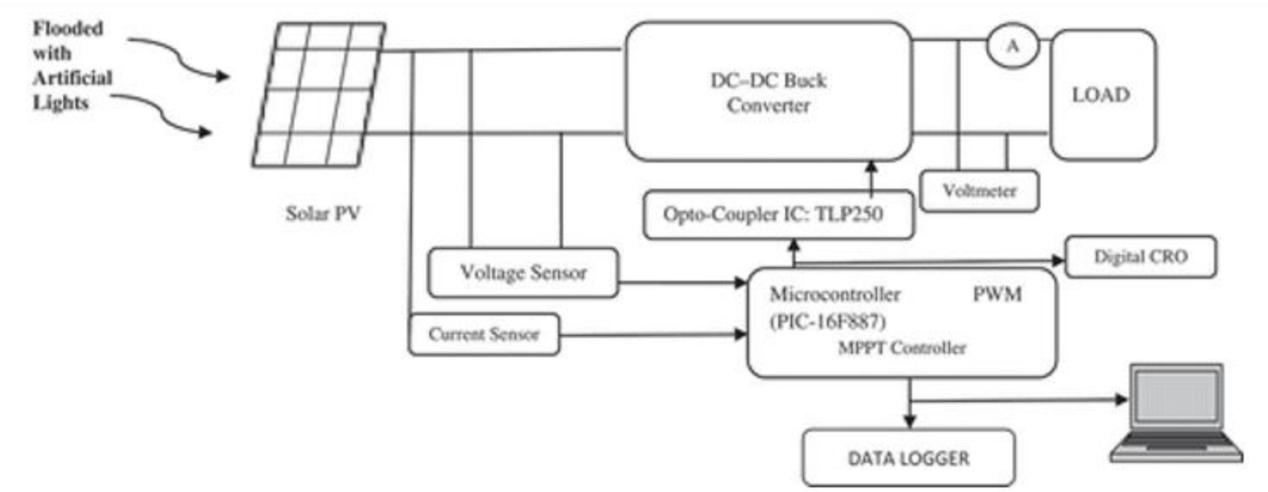


Figure III.1: **Block PV panel power and a DC-DC converter**

III.2.1 Maximum power point tracking algorithms

The noteworthy methods reported in literature are:

III.2.1.1 Comparison and analysis of MPPT methods

Comparison of MPPT methods is done on the basis of following 12 factors:

- 1.Category
- 2.Dependency of PV array
- 3.Implementation methodology
- 4.Sensor required
- 5.Stages of energy conversion
- 6.Partial shading enabled
- 7.Grid interaction
- 8.Analog or Digital
- 9Tracking efficiency
- 10 Tracking speed
- 11.Cost
- 12.Product available in market.

III.2.1.2 DC to DC converter

In this paper a high voltage boost push-pull dc-dc converter for DC load application is proposed. An impedance between the PV panel and load is matched by using DC-DC Push-Pull converter technique. The converter uses high switching frequency of 50Khz which gives high power density, reduces size of components and this reduces the complexity of the circuit. As the power of the PV Panel that is supplied is mainly depends upon the load and the climatic changes, to extract the large amount of power from the source, MPPT technique is used. Here converter duty cycle is varied based on the MPPT, which significantly increases the efficiency of the solar photovoltaic system. The technique used in Maximum power point tracking is perturbation and observation method. In this paper Perturb and observe (P&O) method used and simulations are represented using PSIM environment.

***Figure III.2*:. Block diagram of DC–DC converter.**

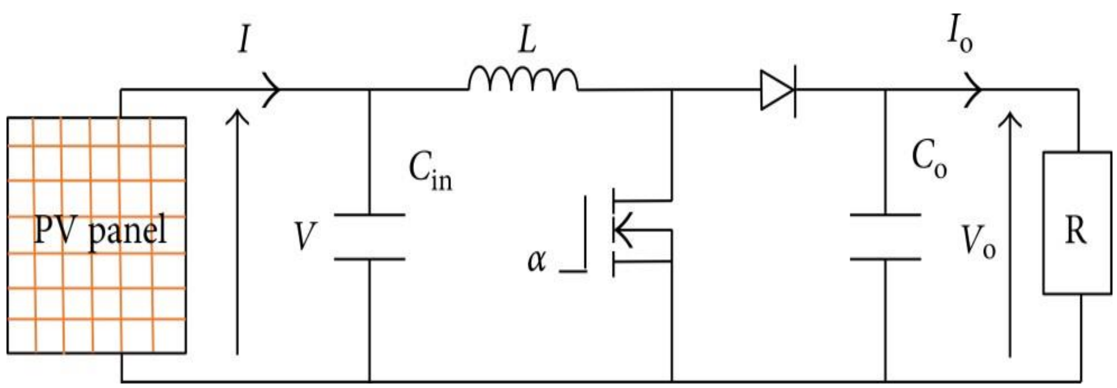


Figure III.3: Boost Converter in an MPPT based PV System

The operation principle of this converter is described by the following equations:

$$V_0 = \frac{V}{1 - D} \quad \text{(III.1)}$$

$$I_0 = I(1 - D) \quad \text{(III.2)}$$

Using these equations, the relationship between the resistance seen by the PV panel (R_{eq}) and the load resistance (R) is given by:

$$R_{eq} = \frac{V}{I} = \frac{V_0(1 - D)^2}{I_0} = R(1 - D)^2 \quad \text{(III.3)}$$

The next equation can be used to calculate the duty cycle required for the MPPT controller to locate and extract the maximum power:

$$D = 1 - \sqrt{\frac{R_{eq}}{R}} \quad \text{(III.4)}$$

Where D is the duty cycle and R is the resistance at which power is at its optimal point:

$$R = \frac{Vmpp}{Impp}$$

III.2.1.3 The P&O algorithm

A key point in the control of photovoltaic (PV) systems is the design of the maximum power point tracking (MPPT) algorithm. Although a huge number of approaches has been proposed in literature, the methods based on the perturb and observe (P&O) technique are the most widely employed in commercial products. The reason is in the fact that P&O can be implemented in cheap digital devices by assuring high robustness and a good MPPT efficiency. The low hardware resources required by the P&O algorithm are especially useful in distributed MPPT architectures, where the cost makes the difference. The performances of the P&O

algorithm implemented in a digital device are affected by the quantization effect and numerical approximations. In this paper the basic P&O algorithm is suitably improved in order to compensate for these effects. A design recipe for choosing the best values of the P&O parameters is also given. The conclusions of the theoretical analysis are validated through simulations and experiments.

Maximum power point tracking (MPPT) algorithms used in traditional photovoltaic systems are based on well consolidated strategies, usually employing perturbative approaches Several papers available in the literature try to define standardized procedures for assessing the MPPT efficiency of these algorithms, and many others propose optimized MPPT approaches, Unfortunately, most of these techniques have a limited field of practical applicability because they require high computational burden and/or expensive hardware resources

Moreover, in many papers the experimental results showing the effectiveness of complex MPPT algorithms are obtained by using high quality measurement sensors and high performance digital controllers. As a consequence, in real commercial applications in which cost, size and weight are the main constraints, many complex methods presented in literature cannot be used. This conclusion holds especially for distributed MPPT (D-MPPT) architectures, where the electronic circuits devoted to the MPPT function are embedded in the PV modules. In this case, the attention must be focused on the minimization of the hardware resources without degrading the MPPT efficiency

An example of how this goal can be achieved is given .where a dc/dc converter regulated by a Perturb and Observe (P&O) algorithm based on the Sliding-Mode Control has been proposed for D-MPPT applications. In it is shown that a high MPPT promptness and the rejection of noises coming from the converter output can be achieved by a very simple control action implemented in a cheap digital device.

Another way of reducing the costs in D-MPPT applications is to use one switching converter per PV module but only one centralized controller in-dimensional multivariable P&O algorithm allows to minimize the number of sensors and requires a simple circuitry and one low cost microcontroller.

In this paper the MPPT efficiency of the P&O algorithm, which is the best candidate for a cheap digital implementation, is studied. The effect of the digital implementation on the P&O performances is analyzed and a novel P&O technique that is able to improve the steady state MPPT efficiency is proposed. The analysis is carried out on a low power converter dedicated to D-MPPT architectures, but the approach has an absolutely general validity.

The proposed method works exactly as the classical P&O one, except when a low MPPT efficiency due to a poor balance of the operating points across the MPP is detected in steady state conditions. In this case, the proposed algorithm temporarily triggers a further perturbation of the controlled variable: this allows to improve the efficiency by balancing the usual climbing taking place around the MPP in the perturbative MPPT method. Some strategies aimed at balancing the steady-state operating points across the MPP have been already proposed in the literature. Techniques employing a parabolic interpolation of the peak region of the power vs. voltage PV curve are very effective and relatively simple. Indeed, near the MPP, the parabola is a good approximation of the curve, so that it can be used for estimating the position of the MPP by using the information coming from the last three operating points settled by the P&O algorithm

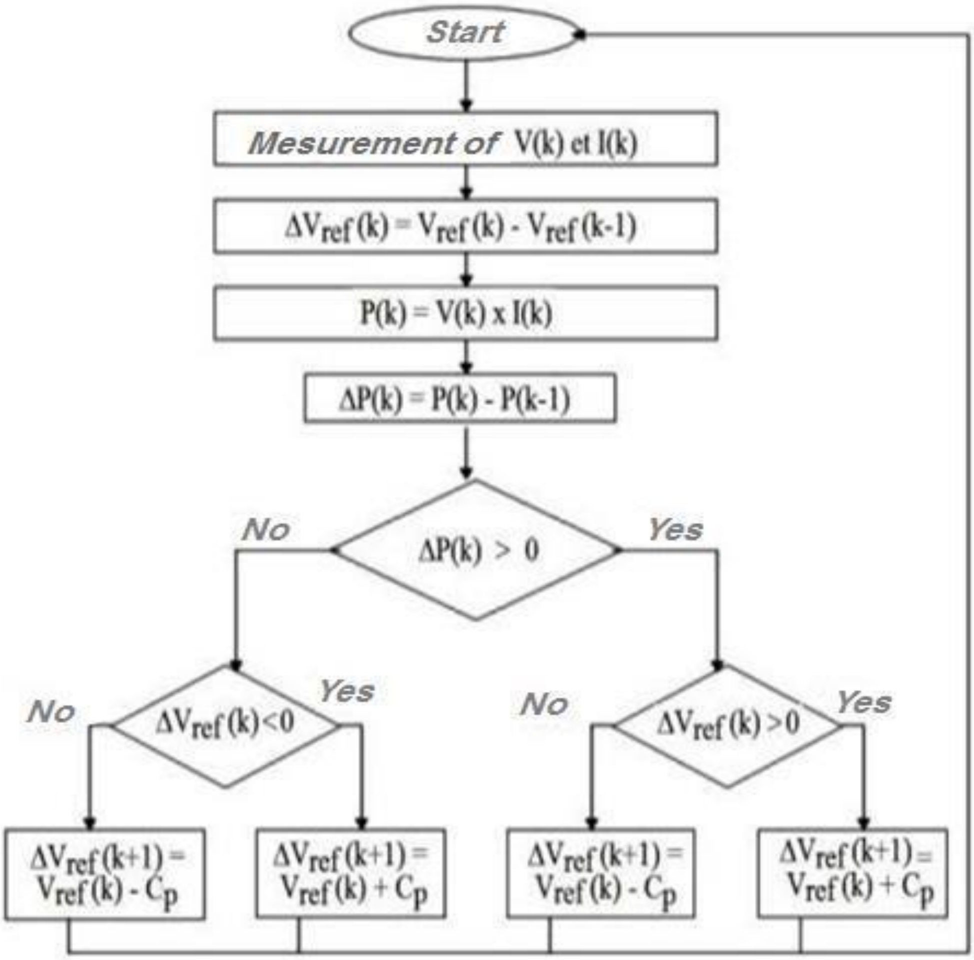


Figure III.4:Flowchart of the Perturb & Observe MPPT algorithm

III.3 Classification of MPPT methods

Recently, a massive number of MPPT algorithms and designs are proposed in the literature. Each approach has its own specifications, limitations, and applications. There is no specific evaluation study that classifies methods since each one can be suitable for an application and not for another. Therefore, there is no unique classification of the MPPT algorithms. In this study, MPPT methods are classified based on different norms such as tracking technique, sensing implementation, and contemporary. Under each of these classifications, there are several sub-categories based on different factors, working principle or implementation. [25]

III.3.1 Based on tracking mechanism

Commonly, the tracking principle of the used MPPT algorithms is different from one to another method. A growing number of MMPT classification of tracking technique classification has been applied to MPPT algorithms. Therefore, in literature, many pieces of research have classified the MPPT algorithms based on their tracking techniques. Some of these methods rely on mathematical calculation, while others rely on trial and error principle and other tracking techniques

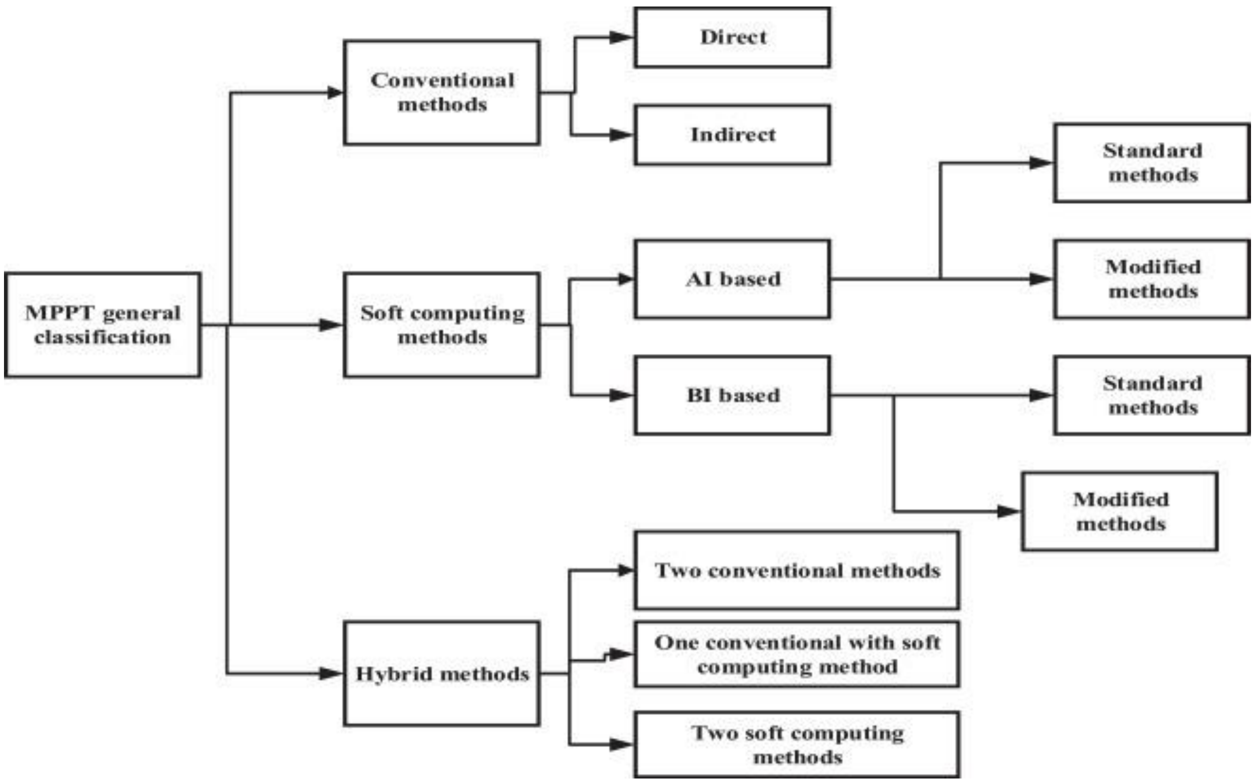


Figure III.5: **General MPPT methods classification**

III.3.2. Based on implementation

MPPT algorithms can be classified into two categories based on the sensing parameters. These sensors can be installed in the PV modules output side or from the DC-DC converter output. The sensors installation is mainly relying on the application and the type of sensor. Each implementation exhibits different implementation speed in deriving the MPPT of the PV. The main two control implementation is known as MPPT control via the input parameters and MPPT control via the output parameters.

III.3.2.1. MPPT control via PV side parameters

Most of the MPPT approaches are using the control variables that sensed from the PV modules output . In this implementation, the power stage input V_{PV} and I_{PV} are used as input to the controller for the MPP tracking controller as shown in Fig. 6

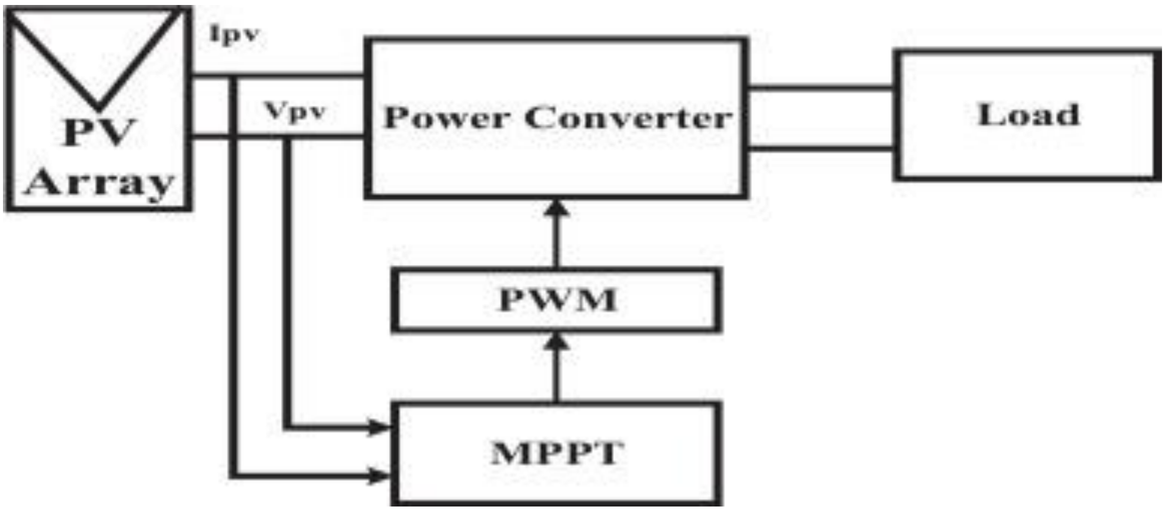


Figure III.6: **MPPT control via input parameters**

III.3.2.2. MPPT Control via load side parameters

The control of MPPT using the output parameters of the converters is been applied in many PV systems . Unlike MPPT control via the input parameter approach, this implementation employs sensors in the output of the DC-DC converter as measured parameters as shown in Fig. 7.

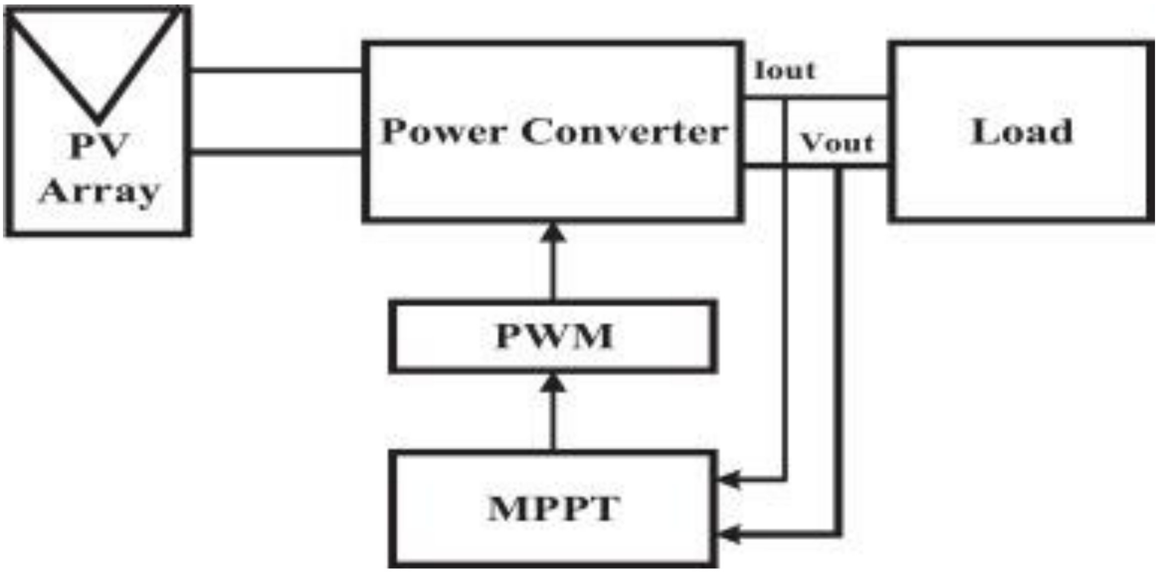


Figure III.7: **MPPT control via output parameters**

III.3.3. Based on Modernity

Since the early use of the PV system as off-grid and grid-connected systems, many researchers have proposed and developed several methods in order to extract the maximum power for the PV panels. Accordingly, the methods have witnessed rapid improvement. Due to that, some researchers have put another classification of MPPT methods based on their modernity. MPPT methods can be classified into two categories based on modernity as conventional methods and advanced methods. Conventional methods are the methods use very simple algorithms employed since the early use of the PV systems. Advanced methods are modern methods that employ different approaches are relatively complex. Contrary to the conventional methods, these methods are relatively complex and require complex computations.

III.3.3.1. Conventional Based Methods

Diverse MPPT conventional techniques are being used since the first use of the PV system. Different conditional MPPT techniques have been proposed during the last decades. Conventional methods rely on very simple algorithms or fractional calculations. They are relatively simple and low cost. These methods are widely used in many PV plants. Their performance mainly varies based on the method selected. There can be defined as the best solution situation to track the MPP under uniform insolation conditions. The most applied conventional MPPT methods are:

III.3.3.1.1. Perturb and Observe (P&O)

Perturbation and observation (P&O) is widely used method This method is based on the property that derivative of the power-voltage of the PV module. The flow chart of the P&O is shown in Fig. 8. The fundamental principle of the P&O method is the voltage is purposely perturbed increase or decrease, then the power is compared to the acquired before to disruption. Extremely, if the power is raised due to disruption will be made in the same direction. And if the power fall, the new perturbation is made in the opposite direction. The P&O always holds(12) ∂PPV∂/VPV=0

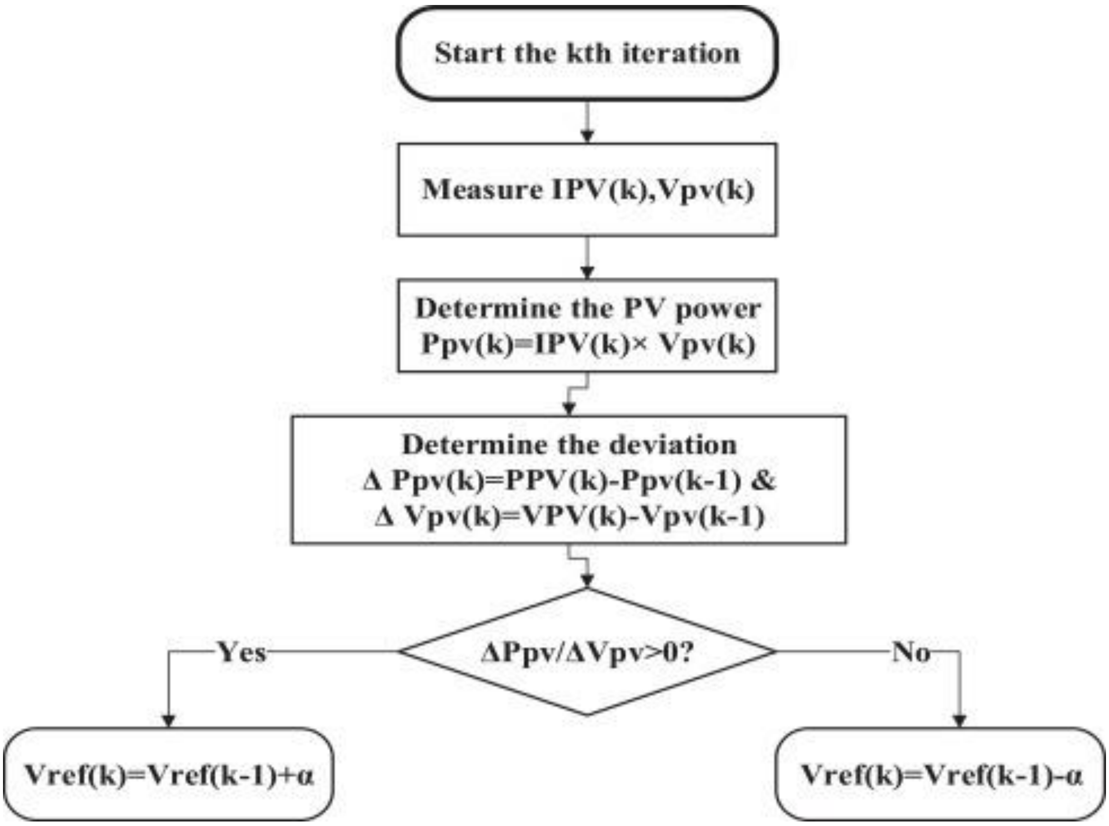


Figure III.8: **Flowchart of P&O MPPT method.**

Where P_{PV} V_{PV} are the PV module output power and voltage, respectively.

Through the implementation procedure, the output current and voltage of the PV module are periodically observed at sequential sampling steps in order to determine the corresponding output power and power derivation with voltage. The MPPT procedure is carried out by adapting the reference signal of the power converter PWM controller, based on the sign of $\partial PPV/\partial VPV = 0,$

III.3.3.1.2. Increment Conductance (INC)

Increment Conductance (INC) MPPT approach is also has been widely applied to the many PV systems. This method is considered as effective method to search efficiently the maximum power point The core idea of this approach mainly relies on power variation. By means, the working principle of this approach is similar to the P&O. The implementation of the INC is illustrated in Fig. 9. INC approach is more complicated compared to the P&O, it can be easily implemented due to the advancements of digital signal processors (DSPs) It has been proposed to enhance the tracking accuracy and dynamic performance under rapidly varying conditions. The implementation of the former is done by applying the individual measurements of the PV module output current and voltage, not requiring the determination of the corresponding output power. At MPP of the PV source, it holds that(15) $\frac{\partial Ppv}{\partial Vpv} = 0 \Longrightarrow \frac{\partial(Ipv \times Vpv)}{\partial Vpv} = \frac{Ipv + \partial Ipv}{\partial Vpv \times Vpv} = 0 \Longrightarrow \frac{\partial Ipv}{\partial Vpv} = \frac{-Ipv}{Vpv}$

where I_{pv} is the PV array output current.

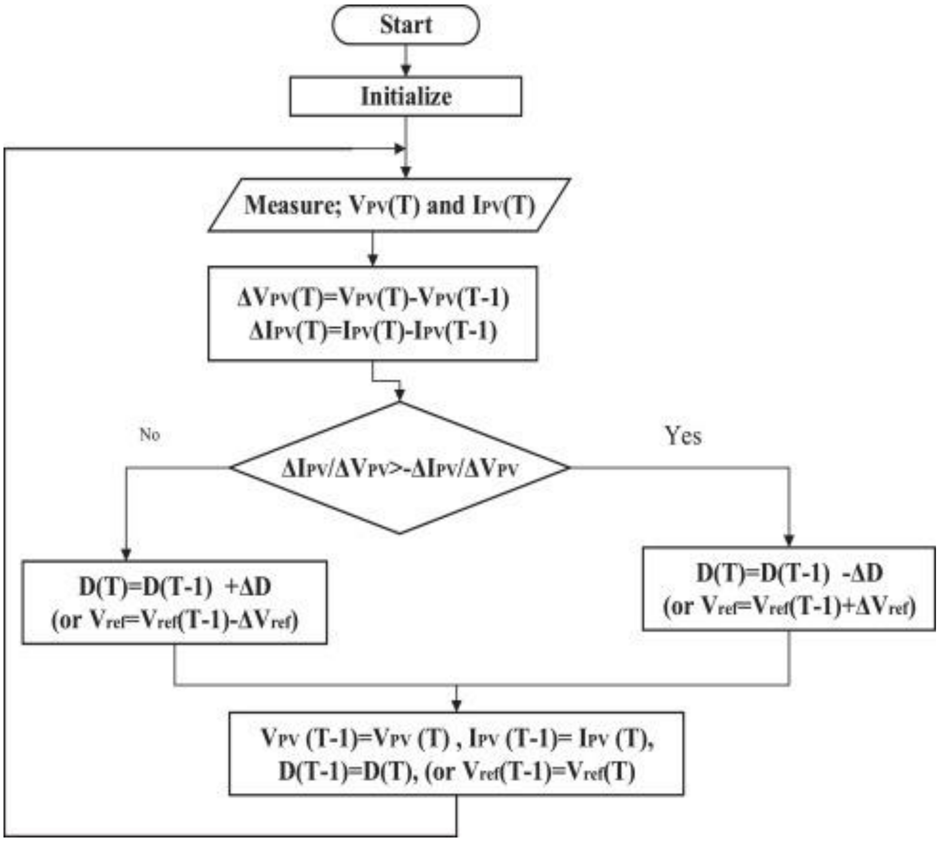


Figure III.9: **Flowchart of INC MPPT method.**

Many researchers show that the INC algorithm provides better performance than the P&O algorithm during fast changing weather conditions. This is commonly intellect to be according to the INC algorithm exhibiting lower confusion during these conditions [INC approach also has better noise rejection and less confusion due to system dynamics. INC suffers some drawbacks which can be concluded as the implementation is often complicated and requires a high computation capacity, which raises the system control period .

III.3.3.1.3. Parasitic Capacitance (PC)

The implementation of this approach is similar to INC method], except that the effect of the solar cells parasitic junction capacitance C_p, which models charge storage in the p-n junctions of the solar cells, is included. By adding this capacitance to the lighted diode equation, the PV module can be represented

$$I = IL - Io[\exp(VP + RSIa) - 1] + CPdvPdt = F(vP) + CPdvPdt$$

III.3.3.1.4. Hill Climbing (HC)

The working principle of this method is similar to the P&O method. The only difference between these two methods is the duty cycle is perturbed rather than perturbing the current or voltage to update the operating point of the PV panel. If increase in duty cycle leads to increase in increase in output power, duty cycle will be further increased otherwise duty cycle will be decreased This method also suffers from oscillations around the MPP which expressively reduces efficiency of PV systems. To overcome this obstacle an adaptive perturbation has been proposed The proposed method is used to reduce the occurred oscillation and the perturbation size is adapted as follows(19) $s = \frac{\Delta P}{\frac{\Delta \mathrm{dP}}{\mathrm{d}}}$

where *s* denotes to perturbation step size

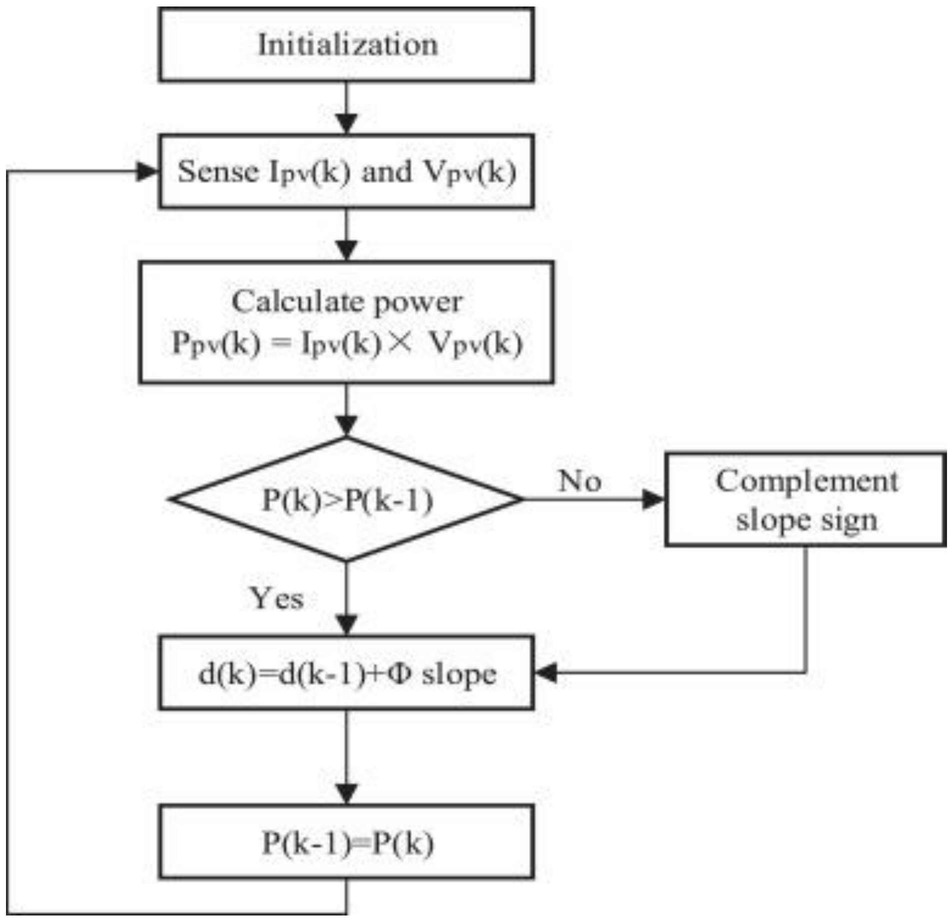


Figure III.10: **Flowchart of the conventional HC method.**

III.3.3.1.5. Constant voltage (CV)

The constant-voltage is referred to as fractional open-circuit voltage MPPT method which is an offline method. In other words, it is a ratio of the MPP to the PV module open circuit V_{OC} as follows(21)

$$Vrev = KV \times VOCIMPPVOC \cong KV < 1$$

where V_{MPP} is the maximum voltage, V_{OC} is the open circuit voltage, and K_V is the constant value and ranges from 73 to 80% 11 illustrates the flow chart of the constant voltage implementation. To achieve the open-circuit voltage of any power converter load should be disconnected resulting zero output current, thus, the open circuit-voltage can be obtained. The PV modules open-circuit voltage is measured by interrupting the normal operation of the system, with a certain frequency, storing the measured value. After that, the MPP is calculated, according to, and the operation voltage is regulated to the maximum voltage point. This process will be repeated periodically.

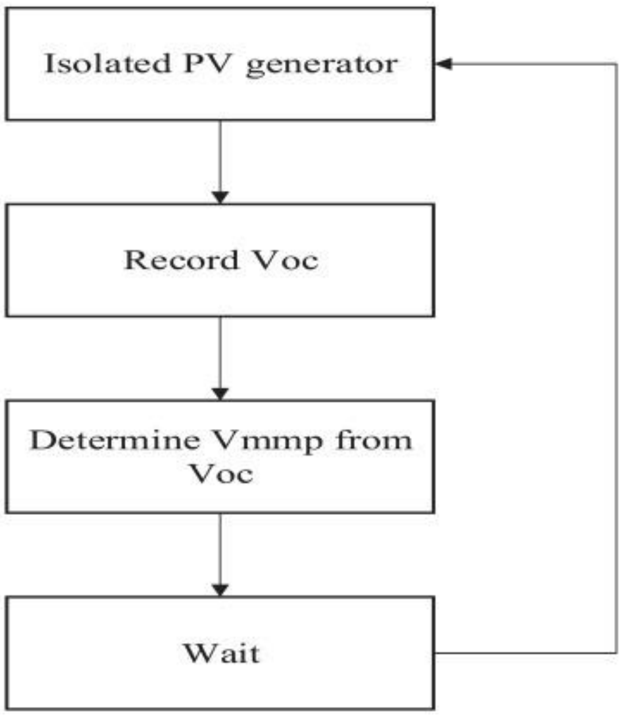


Figure III.11: **Flowchart of Constant voltage MPPT method.**

III.3.3.1.6. Constant Current (CC)

The working principle of the short circuit current MPPT approach is similar to open circuit voltage MPPT method. Which is a fractional to short-circuit current MPPT method. The assumption of the MPPT is proportional to the short circuit current I_{sc} as follows(22)

$$Irev = Isc \times KIIMPPISC \cong KI < 1$$

where I_{MPP} is the maximum current, I_{SC} is the short-circuit current, and K_I is the constant value. Where K_I values ranging from 78 to 92% The constant current implementation can be depicted in flow chart as shown in Fig. 12. The PV modules short-circuit current is measured by interrupting the normal operation of the system, with a certain frequency, storing the measured value. After that, the MPP is calculated, according to), and the operation current is regulated to the maximum current point. This process will be repeated periodically.

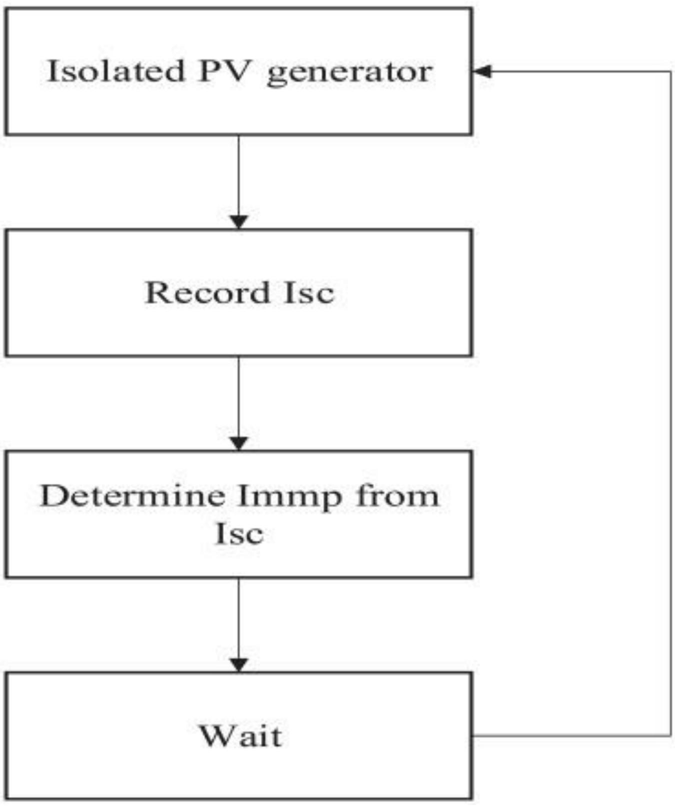


Figure III.12: **Flowchart of Constant Current MPPT method.**

In this approach, the accuracy of the tracking MPP is affected by the accuracy of knowing the value of the proportionality factor of the short-circuit current. With the corresponding value at the MPP for the specific PV module used in each installation, as well as their variation with irradiance and aging. The pros and cons of this approach is similar to the constant voltage MPPT approach.

III.3.3.2. Conventional methods classification

Generally, conventional methods can be classified into two subcategories as direct based methods and indirect based methods. Direct methods mainly rely on measurement. Contrary, indirect methods are mainly based on the fraction calculations of the open circuit voltage, short circuit current, or comparison to saved data. Both of these categories can achieve good performance under specific conditions.

III.3.3.2.1. Indirect methods

The operating point, where the PV system works with maximum power, is predicted either measuring current, voltage and radiation values or with numerical approximations-mathematical expressions using experimental data . This approach also called offline method. In the indirect MPP tracking approach, the duty ratio is controlled only to extract the maximum power from the PV system for a specific operating condition which is time-variant Constant current and the constant voltage methods are the popular indirect MPPT algorithms that produce the control signal using empiric data or mathematical expressions with numerical corrections and approximations. The advantage of the methods described above is their very simple structures, but they only give an estimation for optimum operating point. They are not sensitive to changes due to aging and contamination of cells. In literature, the most commonly used indirect methods can be summarized as CC, CV, curve fitting, and lookup table.

III.3.3.2.2. Direct methods

Direct MPPT approaches employ the instantaneous values of PV voltage (V_{PV}) or PV current (I_{PV}) to search the MPP by observing the sense of the variation of the PV power. This methods are generally known as online methods. Commonly, the voltage can be easily measured, for instance through a resistive divider, while the current measurement is more complicated . Direct methods provide more accurate tracking and reach the MPP by periodically perturbing PV voltage (V_{PV}) or duty ratio in steps. Therefore, these methods affected the performance changes in time due to various reasons and can make a more accurate tracking . In literature, the most commonly used direct methods can be summarized as P&O, INC, and PC. These methods can guarantee a higher energy conversion efficiency and do not need periodical tuning of the parameter, as in the cases of the fractional techniques.

III.4.Model of the DC-DC converter with MPPT

A unified circuit model of three basic DC/DC converters has been built and a MPPT control strategy which has the ability to track the MPP more rapidly has been proposed for PV systems with DC bus. In these studies, the focuses are to build the unified circuit of three DC/DC converters and to find out the relationship between control signal and external weather parameters. Meanwhile, studying how the proposed MPPT strategy is influenced by non-uniform irradiance and temperature is [26]

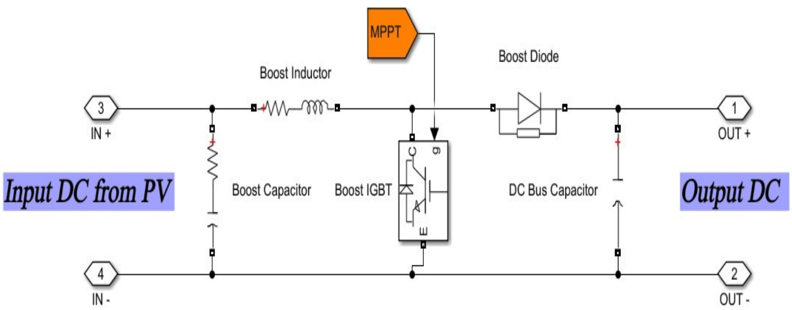


***Figure III.13:* DC-DC converter circuit**

III.5. Field Oriented Control of SynRM

Simulation studies of three synchronous reluctance motor (SynRM) control strategies are presented: field-oriented control (FOC), direct torque control (DTC), and finite-set model-predictive control (FS-MPC). FOC uses linear controllers and pulse-width modulation to control the fundamental components of the load voltages vectors. In contrast, DTC and FS-MPC are nonlinear strategies wherein the voltage vectors are directly generated in the absence of a modulator. Theoretical operating principles and control structures of these control strategies are presented. Moreover, a comparative analysis of the static and dynamic performance of the control strategies is conducted using Matlab/Simulink to identify their advantages and limitations. It is confirmed that each of the control strategies has merits and that all three of them satisfy the requirements of modern high-performance drives.

The well-designed synchronous reluctance motor (SynRM) has recently attracted the attention of the industrial and scientific communities because it has a lower cost, a higher density, and simpler control than the induction motor. Furthermore, the SynRM is seen as a better alternative to permanent-magnet synchronous motors and induction motors for applications such as fans, washing machines, and electric vehicles . Additionally, owing to the absence of the winding and magnet in the rotor, it exhibits a higher energy efficiency and field-weakening capability

High performance, a fast transient response, and appropriate control flexibility of electric drives are essential requirements for various industrial applications. Two control techniques that have been widely investigated and reported for SynRM drives are field-oriented control (FOC) and direct torque control (DTC) FOC is a linear strategy that uses linear controllers and a pulse-width modulator to generate the voltages to be applied to the motor. Because FOC exhibits good performance under both steady-state and transient operating conditions, it has been widely used in electric drive systems The control strategies for the SynRM drive based on FOC can be divided into three main categories: constant d-axis current control, current angle control (CAC), and active flux control. These categories mainly differ in the method of generating the reference value of the currents in the. rotor refrence frame. Maximum torque per ampere control can be considered a type of CAC; the objective of this control strategy is to maximize the electromagnetic torque for a given motor supply current. This is equivalent to the minimization of the motor copper losses for each torque value, which results in a high efficiency of the drive system . Despite FOC providing a good dynamic torque and flux response, its structure is complex owing to the use of proportional- integral (PI) controllers and a modulator block, and tuning is necessary to achieve good performance. [27]

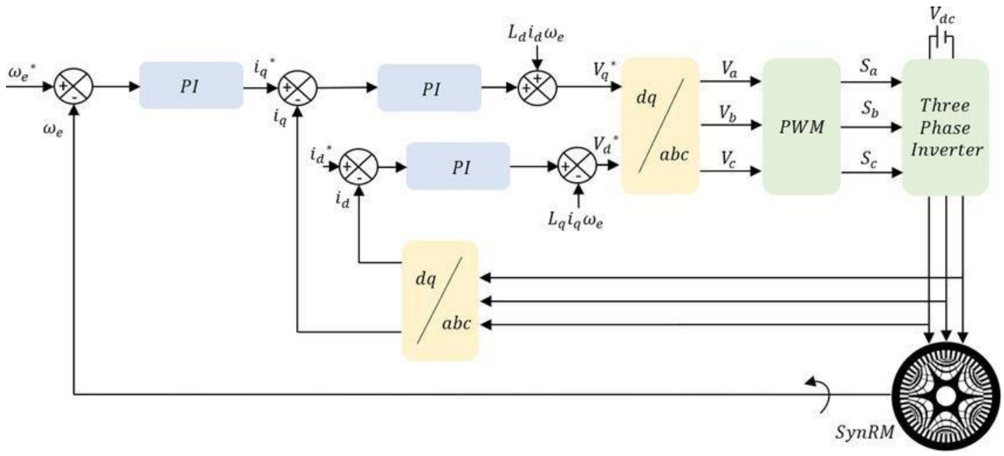


Figure III.14: Overall field oriented control schematic of Syn-RM.

Voltage references V_d^*, V_q^* , are generated as,

$$V_d^* = i_d^* R_s - w_e i_q^* L_q \qquad (III.5)$$

$$V_q^* = i_q^* R_s - w_e i_d^* L_d \qquad (III.6)$$

where, i_d^*, i_q^*, are current controllers commands. Inverse Park's transformation expressed in (*iii*) is used to transform the voltage reference quantities V_d^*, V_q^*, into stator reference quantities V_a ,V_b ,V_c in Eq. (III. 8) in order to be applied to the PWM block.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = M_p^{-1} \begin{bmatrix} V_d^* \\ V_q^* \end{bmatrix} \qquad \textit{(III.7)}$$

$$M_p^{-1} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e & 1 \\ \cos\left(\theta_e - \frac{2\pi}{3}\right) & -\sin\left(\theta_e - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_e + \frac{2\pi}{3}\right) & -\sin\left(\theta_e + \frac{2\pi}{3}\right) & 1 \end{bmatrix} (iii) \quad \textit{(III.8)}$$

III.5.1 Rotor field-oriented control

In this control technique, the indirect method is limited.

By applying the principle of vector control (id=idr), and after arrangements necessary, we will have the following system of equations:

$$R_s I_d + L_d \frac{dI_d}{\mathrm{dt}} = V_{sd} - wL_d I_q \qquad R_s I_q + L_q \frac{dI_q}{\mathrm{dt}} = V_{sq} - wL_q I_d \qquad \textit{(III.9)}$$

These equations show that V_{sd} and V_{sq} depend on both the currents on the axes d and q We are therefore led to implement a decoupling as for the asynchronous machine supplied with voltage.

III.5.1.1. Decoupling by compensation

The principle of this decoupling amounts to defining two new control variables V_{d1} and V_{q1}

$$V_{sd1} = V_{sd} + e_q \qquad \textit{(III.10)}$$

$$V_{sq1} = V_{sq} + e_d \qquad \textit{(III.11)}$$

Such that (e_d , e_q) represents the disturbances to be compensated.

The effectiveness of the engine control system is highly dependent on the mathematical model chosen for this engine and the exact knowledge of its parameters. In the case of synchronous machine drives, Park's reference system is adopted because it is widely used in control and command [14].

$$e_d = wL_dI_q \qquad (III.12)$$

$$e_q = wL_qI_d \qquad (III.13)$$

$$V_{sd} = V_{sd1} - e_q \qquad (III.14)$$

$$V_{sq} = V_{sq1} - e_d$$

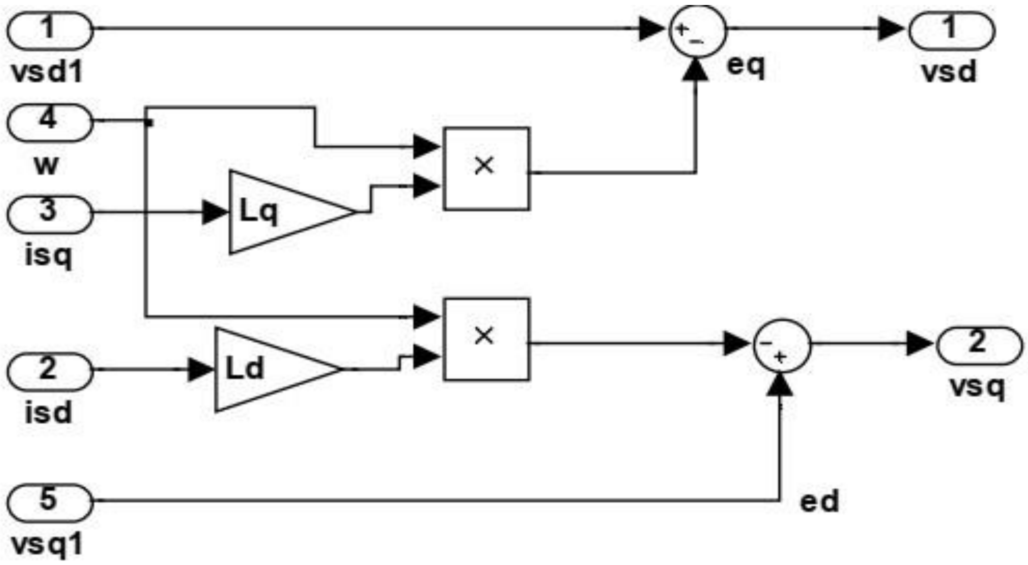


Figure III.15:Compensation block scheme

III.6. structure of the proposed pumping system

The solar-powered water system under consideration, basically and as shown by figure. 1, consists of a solar panel, a power converter, a motor pump, and a storage tank for the pumped water. The considered pumping system consists of connected asynchronous machine (*AsM*) and a centrifugal pump. The *AsM* is often used for speed control operation because it has a frequency converter power supply

For voltage-fed three-phase asynchronous motors case, the stator voltage components U_{ds} and U_{qs} and the rotating field speed

On the other hand, the current through the diode I_D is explained in the following relationship [28]

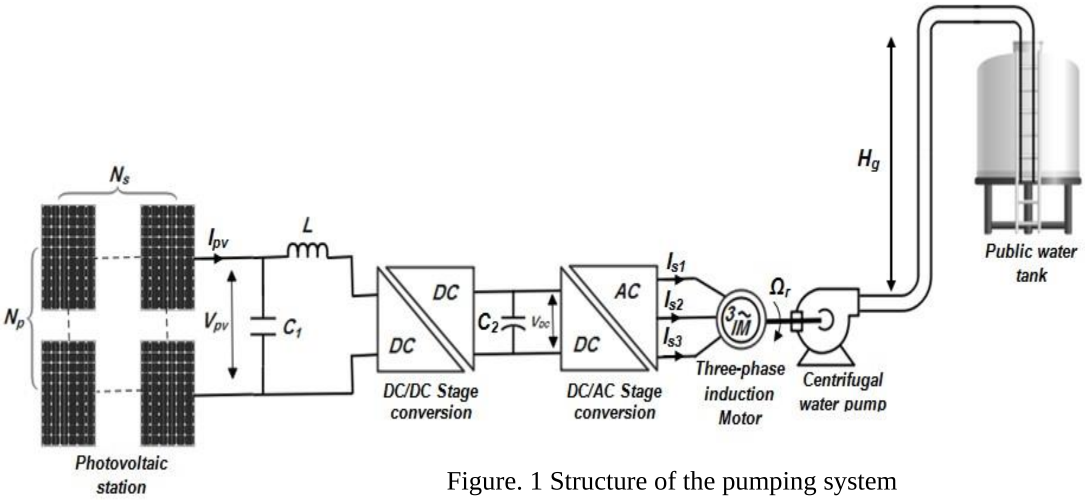


Figure. 1 Structure of the pumping system

$$I_{sh} = [\frac{V+IR_s}{} \qquad (6)$$

III.6.1. Modelling of The Pumping System

Since, the stator voltages (U_{ds} and U_{qs}) and the speed of the rotating field are the control variables of the three-phase voltage-fed asynchronous machine, and the resistant torque C_r is the disturbance variable, the AsM state model can be expressed by the flowing expression [15].

$$\dot{X} = A.X + B.U \qquad \text{(III.15)}$$

With;

$$\dot{X} = A\begin{bmatrix} di_{ds} \\ di_{qs} \\ d\phi_{dr} \\ d\phi_{qr} \end{bmatrix} \qquad \text{(III.16)}$$

and,

$$X = \begin{bmatrix} di_{ds} \\ di_{qs} \\ d\phi_{dr} \\ d\phi_{qr} \end{bmatrix} \quad and \quad B = \begin{bmatrix} \frac{1}{\delta L_s} & 0 \\ 0 & \frac{1}{\delta L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad (III.17)$$

and the control variable matrix U:

$$U = \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} \qquad (III.18)$$

We can also express the mecanical equations for both torque and speed by:

$$\begin{cases} C_e = \frac{3PM}{2L_r}\left(\left(\phi_{dr} - i_{qs}\right) - \left(\phi_{qr} i_{ds}\right)\right) \\ \frac{d\Omega_r}{dt} = \frac{1}{j}\left(C_e - C_r - \left(K_f \Omega_r\right)\right) \end{cases} \qquad (III.19)$$

Where;

$$T_r = \frac{L_r}{R_r} \qquad (III.20)$$

$$\delta = 1 - \frac{M^2}{L_s L_r} \qquad (III.21)$$

$$K_s = \frac{M}{\delta L_s L_r} \qquad (III.22)$$

$$\lambda = \frac{R_s}{\delta L_s L_r} + \frac{R_r M^2}{\delta L_s L_r^2} \qquad (III.23)$$

As a definition, centrifugal pump is a hydraulic machine that transfers energy to fluids (especially liquids) by centrifugal force. These types of pumps differ in design, but the principle of operation is the same and the fluid dynamics are always the same. The main purpose of centrifugal pumps is to increase pressure and pump liquids [16].

As a physic definition, centrifugal pump is a hydraulic machine that transfers energy to fluids (especially liquids) by centrifugal force. These types of pumps differ in design, but the principle of operation is the same and the fluid dynamics are the same. The main purpose of centrifugal pumps is to increase pressure and pump liquids [7].

Centrifugal pumps are designed for a relatively fixed full load (HMT). Pump displacement (Q) varies proportionally with engine speed. Its torque increases very rapidly at this speed and the head is a function of the square of the motor speed. Therefore, very high engine speeds are required to ensure good flow. Besides, the energy consumption, which is proportional to Q and HMT, changes proportionally to the cube of the velocity. Centrifugal pumps are typically used at medium or shallow depths (10-100 meters) with high flow rates [9].

The operation of the centrifugal pump involves her three parameters: Lift, flow rate and speed.

$$f(H, Q, P) = 0 \qquad \text{(III.24)}$$

During pump operation, the main types of losses are noted, in particular the normal pressure drop and the singular pressure drop, each of which is mathematically represented by the relationship:

$$\Delta H_1 = \lambda \frac{V^2}{2.g} . \frac{L}{D} \qquad \Delta H_2 = \varepsilon \frac{V^2}{2.g} = \varepsilon \frac{8Q^2}{\pi^2 D^2 g} \qquad \textit{(III.25)}$$

With;

H: Total head achieved by the pump [m];

Hm: Maximum head [m];

N(t): Instantaneous speed [rpm];

Nm: Maximum speed [rpm];

Q(t): Instantaneou flow rate [m3/s]; Qm: Maximum flow rate [m3/s]; ρ: Density of the liquid [kg/m3]; g: Acceleration of gravity [m/s²].

The centrifugal pump parameters introduced from our work are defined in the table below.

Nominal speed *Ωn*	**1500 *tr/min***
Nominal frequency *Fn*	50 *Hz*
Stator resistance *Rs*	4.850 *Ohm*
Rotor resistance *Rr*	3.805 *Ohm*
Cyclic stator inductance *Ls*	0.274 *H*
Cyclic rotor inductance *Lr*	0.274 *H*
Mutual inductance *M*	0.258 *H*
Moment of inertia *J*	0.031 *Kg.m²*
Viscose friction coefficient *Kf*	0.00114 *N.m.s/rd*
Maximal flow *Qm*	0.001 *m3/s*
maximum height *Hm*	35 *m*
Nominal speed *Nm*	2800 *tr/min*
density of the liquid *ρ*	1000 *kg/m3*
acceleration of gravity *g*	10 *m/s²*

Table III.1: AsM and pump parameters

Solar cells generate low voltage (approximately 0.5*V*) and consume little power, so multiple cells must be combined. So, to form a solar panel, multiple cells are connected in series, parallel, or series-parallel (mixed) combinations to form a photovoltaic generator. When constituting of a solar panel, the model considers the number of cells grouped according to the formula.

III.7. System Simulation and Results

III.7.1 MATLAB/Simscape Environment

MATLAB has long been a useful tool for engineers and scientist for complex numerical computations. Its native programming environment is based on the C language; however, it has a graphic editor called Simulink. An additional toolbox for Simulink known as Simscape provides the fundamental building blocks to create simulation in common physical domains such as electrical hydraulic, and pneumatic, among others.

In addition to providing base building blocks, Simscape allows users to create their own custom defined blocks. These custom defined blocks are programmed similarly to MATLAB language. Its main advantage is the integration of a common engineering tool, MATLAB/Simulink. It also has the ability to be used in conjunction with multi domain environments [15].

III.7.2 System Simulation

In order to evaluate the effectiveness of the proposed system, a simulation study was conducted under MATLAB/Simscape environment.

The PV array consists of six panels connected in series that has been simulated using the solar cell blocks. For the synchronous reluctance motor, there is no available block in Simscape, and so a customized machine block was developed by programming the Eqs. For the centrifugal pump a customized block was also developed based . Figure 16 shows the overall system layout. [29]

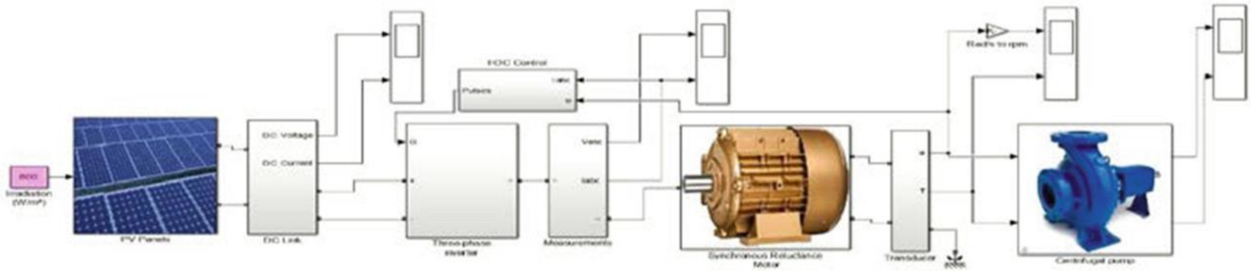


Figure III.16: **System implementation in MATLAB Simscape**

III.7.3 Simulation Results and Discussion

After a simulation during 2 s in Simscape environment, the following results have been

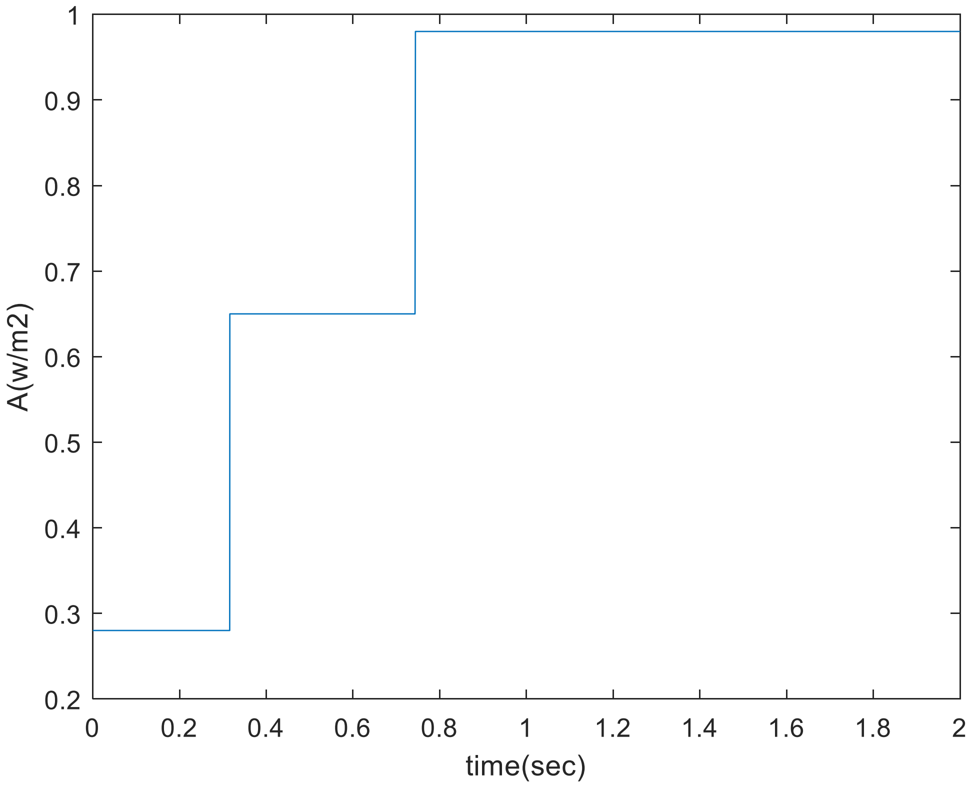


Figure III.17**: Solar irradiation**

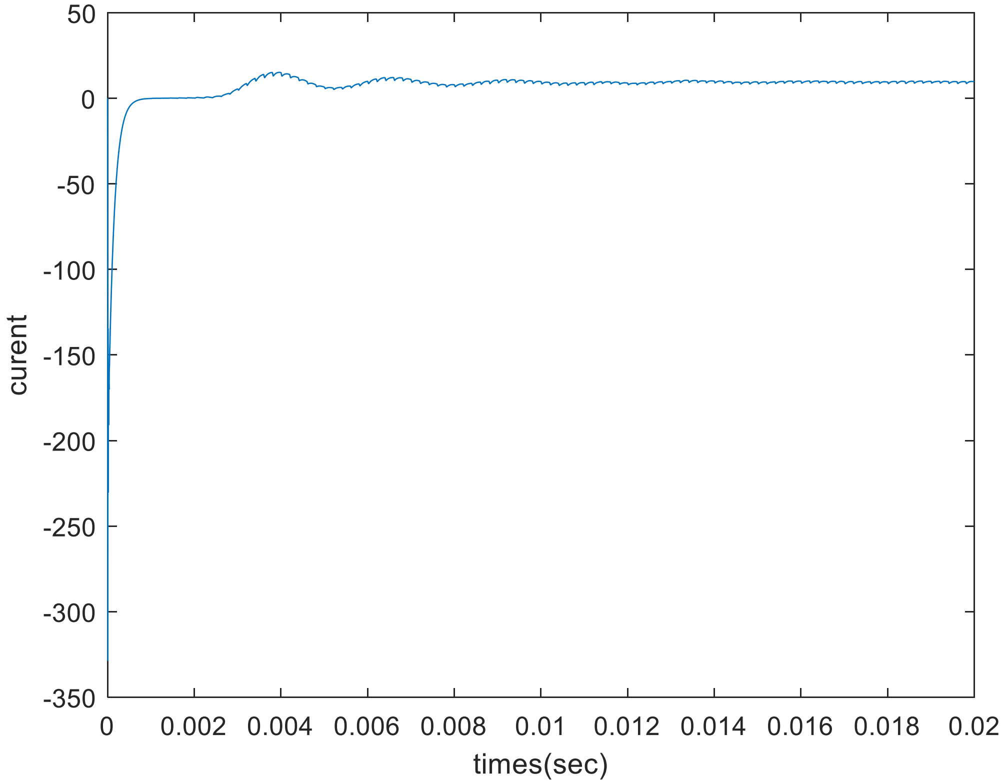


***Figure III.18*: DC bus current**

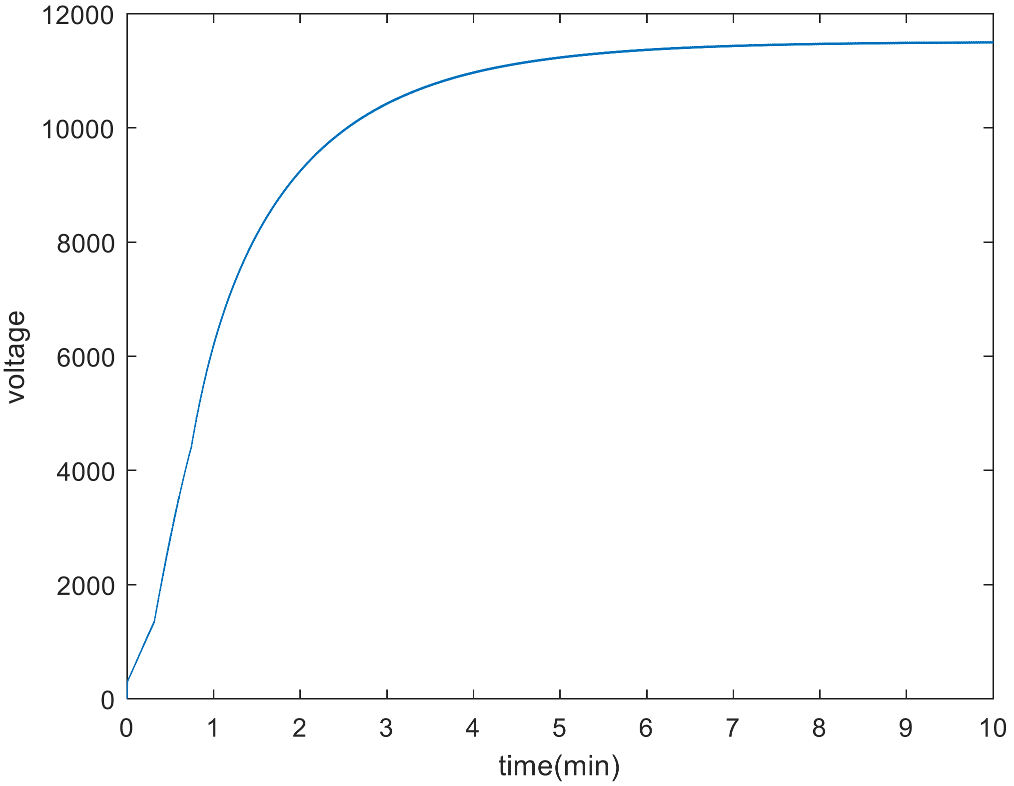


***Figure III.19*: DC bus voltage**

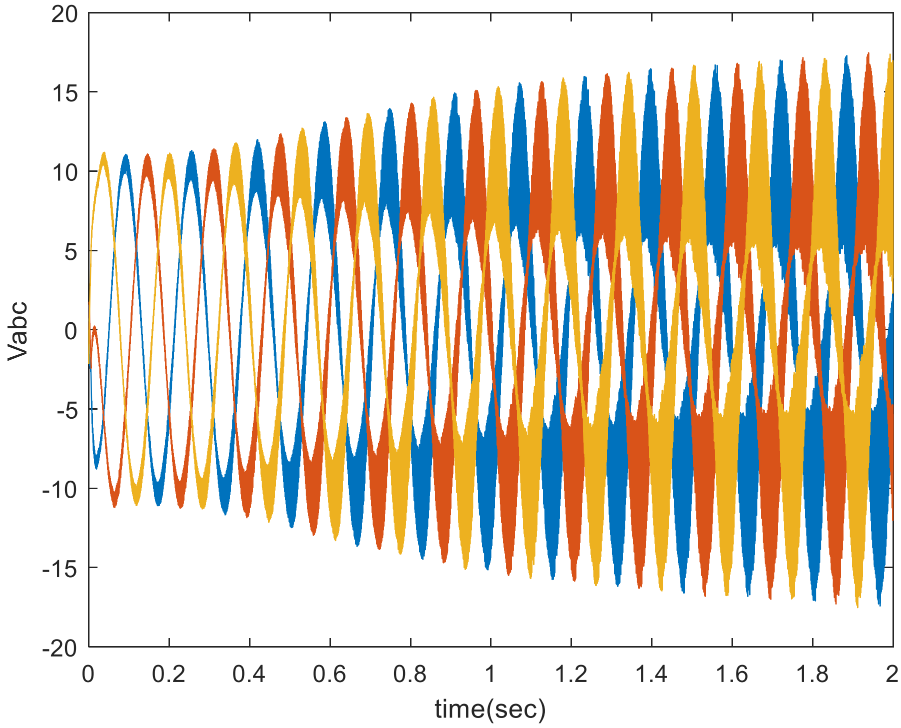


***Figure III.20*:Three phase voltages**

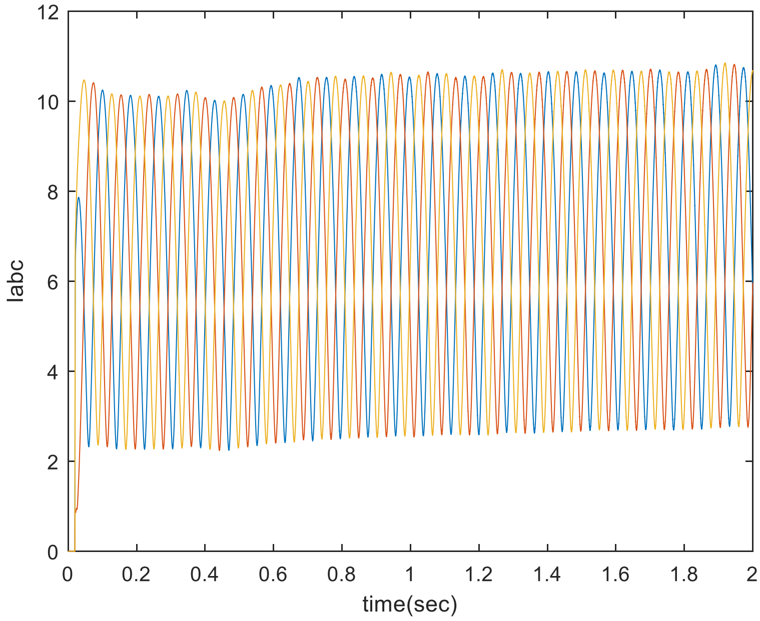


***Figure III.21*:Three phase current**

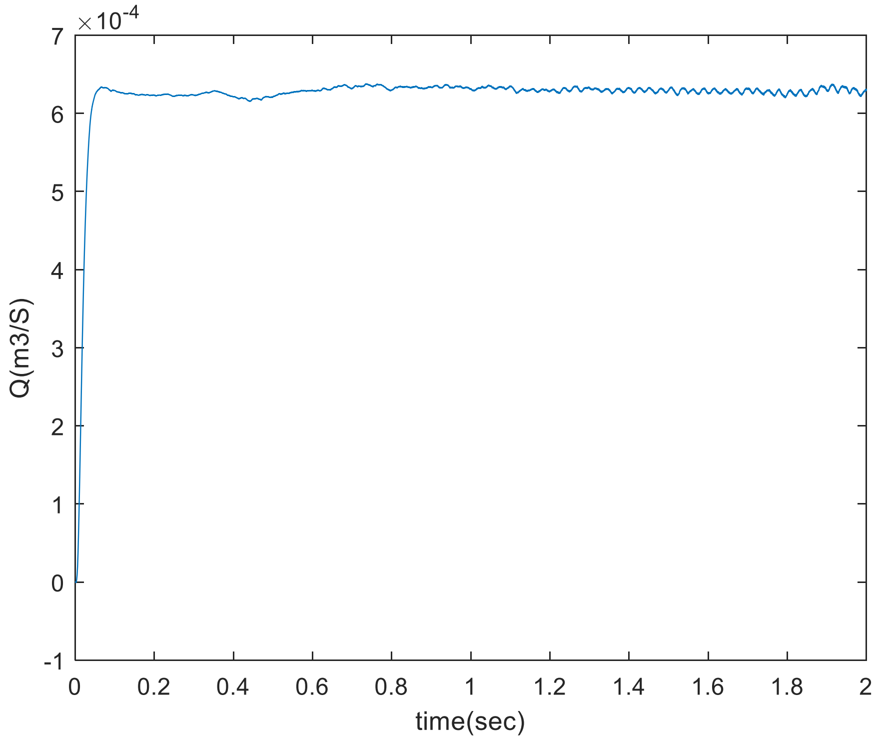


Figure III.22 **:Water flow rate**

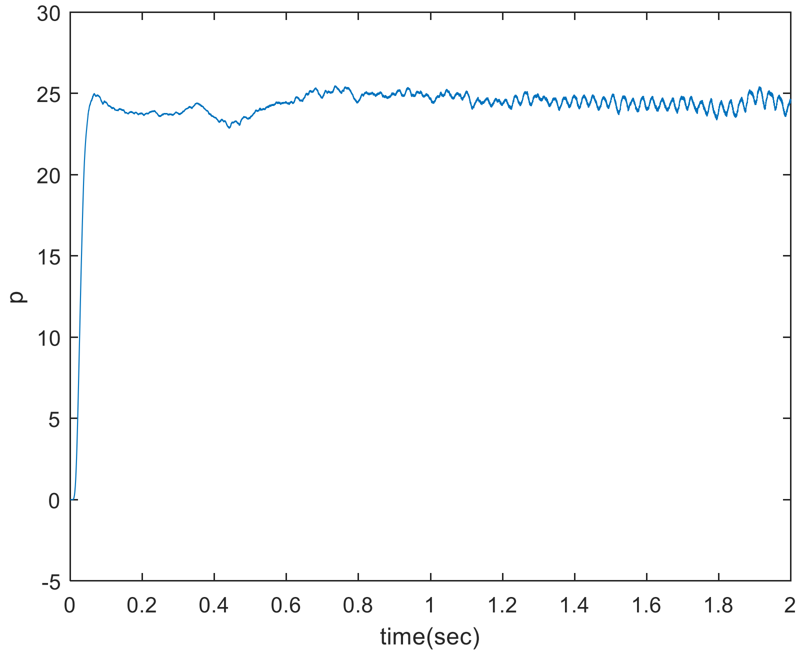


Figure III.23**:P water la pump**

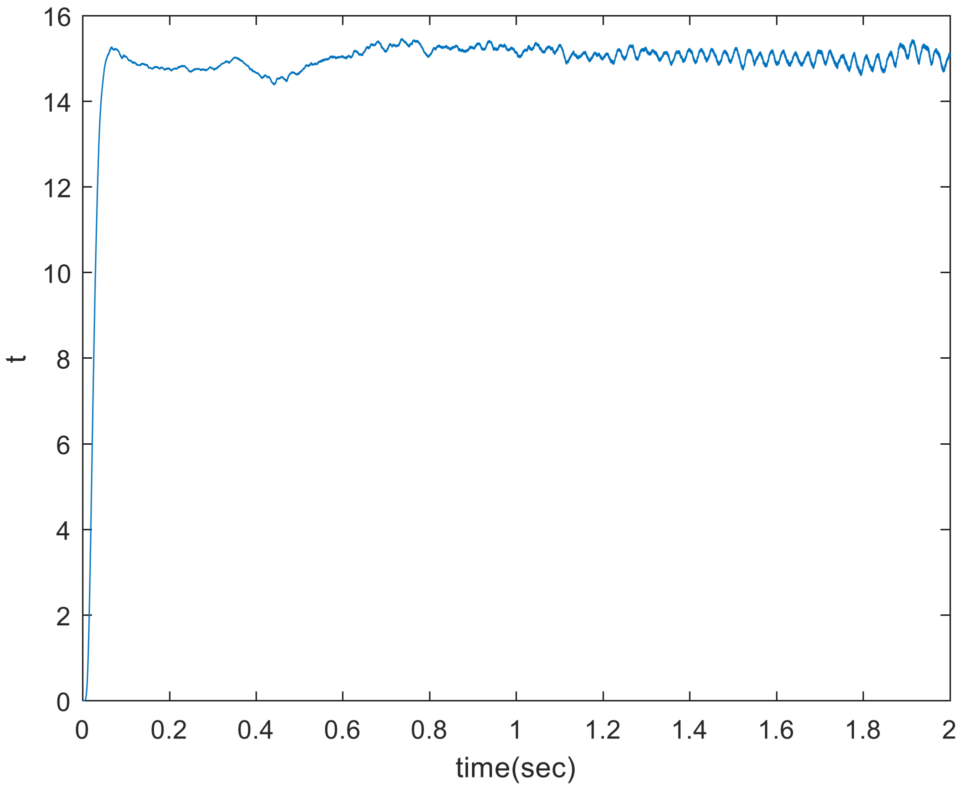


Figure III.24 **:turque the pump**

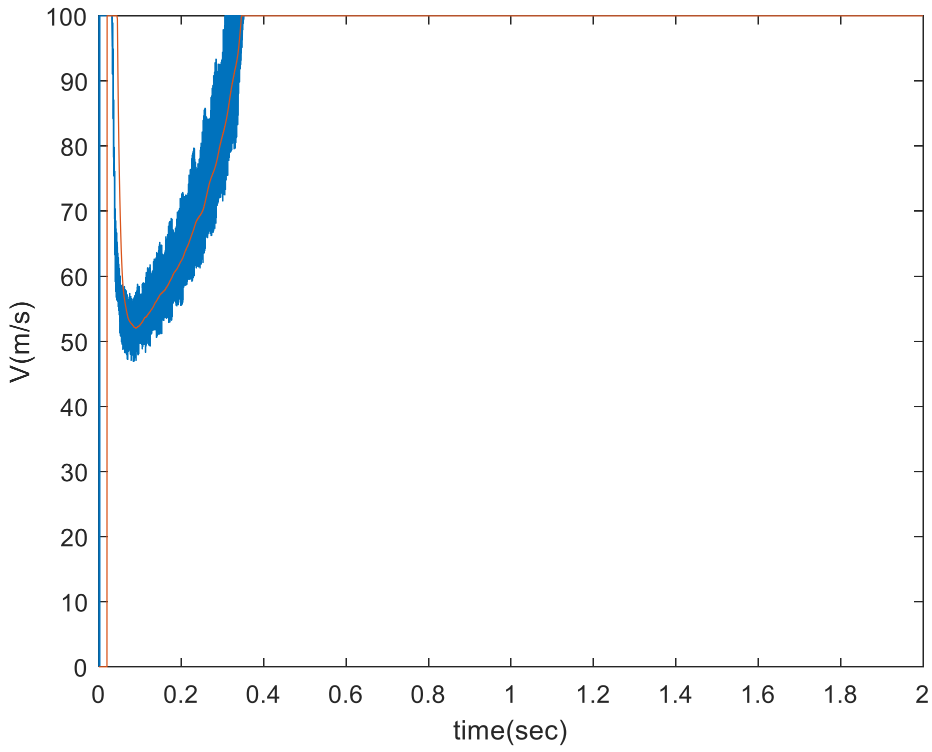


Figure III.25**: speed the motor (SymRM)**

The sun irradiation and DC bus voltage are depicted in Figures (17) and (19) and(20), respectively. At the DC bus, an amplitude of 13 V DC was measured at an irradiation of 1000 W/m^2.

The three phase voltages and currents supplied by the inverter are shown in Figures (18) and (21).

The water flow rate and SynRM angular velocity at the centrifugal pump's output are displayed in Figures(22) and (23).

Friction is one of the main factors that slow down the motion of objects, as it works to reduce the speed of a moving object over time unless this loss is compensated by additional energy. Without friction, objects would not be able to stop or change their speed easily, but its presence makes it possible to control motion and bring objects to a stop.

III.8. Conclusions

Accurate and rapid tracking of solar power parameters (MPP) under varying solar radiation conditions and load variations is a challenging task for researchers. The proposed MPPT scheme offers a solution to improve existing methods. The proposed scheme may help achieve accurate and rapid response in stand-alone and grid-connected solar photovoltaic (PV) energy conversion systems. It can be applied in regions with rapidly changing solar radiation where PV is used. The proposed method's shortcoming is its inability to be evaluated under partial shading conditions

General Conclusion

General Conclusion

In conclusion, this memo underscores the critical importance of advancing control methodologies for photovoltaic (PV) pumping systems integrated with Synchronous Reluctance Motors (SynRM). Such systems represent a sustainable and energy-efficient solution for water pumping applications, particularly in regions reliant on solar energy. By adopting enhanced control strategies, including Maximum Power Point Tracking (MPPT) algorithms optimized for dynamic solar conditions and adaptive motor control techniques, these systems can achieve unparalleled efficiency, reliability, and adaptability.

The analysis highlights that SynRM's inherent advantages—such as high torque density, low rotor losses, and robustness—make it an ideal candidate for PV-powered systems. However, maximizing its potential requires sophisticated control frameworks capable of addressing two key challenges:

.1 Environmental Variability: Fluctuations in solar irradiance and temperature demand real-time adjustments to maintain optimal energy harvesting and motor performance.

.2 Load Dynamics: Variations in water demand and pump load necessitate adaptive torque and speed regulation to prevent energy waste or system instability.

To overcome these challenges, the memo proposes integrating intelligent control systems, such as:

- Predictive Control Models for anticipating solar and load changes.
- Hybrid MPPT Algorithms combining perturb-and-observe (P&O) methods with AI-driven optimization.
- Sensorless Control Techniques for SynRM to reduce hardware costs and enhance durability in harsh environments.

Key Recommendations for Future Work:

1. Advanced Algorithm Development: Prioritize research into AI-based hybrid control systems (e.g., machine learning-enhanced MPPT or neural network-driven torque controllers) to improve system responsiveness and autonomy.

2. Field Validation: Conduct large-scale pilot projects in diverse geographic and climatic conditions to test system resilience, scalability, and cost-effectiveness. Metrics such as energy conversion efficiency, water output per kWh, and system lifespan should be rigorously evaluated.

3. Cross-Disciplinary Collaboration: Foster partnerships between renewable energy researchers, motor design engineers, and IoT specialists to innovate integrated solutions (e.g., smart grid compatibility, remote monitoring via IoT platforms.(

4. Policy Advocacy: Encourage governments and NGOs to subsidize PV-SynRM pumping systems in rural and off-grid areas, aligning with global sustainability goals such as the UN’s SDG 6 (Clean Water) and SDG 7 (Affordable Clean Energy.(

By implementing these strategies, PV-SynRM pumping systems can become a cornerstone of sustainable water and energy management. Their deployment not only addresses water scarcity but also reduces carbon footprints, empowers rural communities, and accelerates the transition to a circular economy. Future advancements in material science, digital twins, and edge computing could further revolutionize this field, unlocking new frontiers in renewable energy utilization.

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