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**Echahid Hamma Lakhdar University of El-Oued**

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**For obtaining the**

# MASTER DEGREE

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**THEME**

# Development of synchronous Reluctance motor associated to pumping water well related to PV panels

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﴿ رَبَّنَا لاَ تُؤَاخِذْنَا إِن نَّسِينَا أَوْ أَخْطَأْنَا رَبَّنَا وَلاَ تَحْمِلْ عَلَيْنَا إِصْرًا كَمَا حَمَلْتَهُ عَلَى الَّذِينَ مِن قَبْلِنَا رَبَّنَا وَلاَ تُحَمِّلْنَا مَا لاَ طَاقَةَ لَنَا بِهِ وَاعْفُ عَنَّا وَاغْفِرْ لَنَا وَارْحَمْنَا أَنتَ مَوْلاَنَا فَانصُرْنَا عَلَى الْقَوْمِ الْكَافِرِينَ﴾ **سورة البقرة : الآية286 .**

**" صدق الله العظيم"**

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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.

Accordingly, in this research we studied and modeled a pumping system connected to a synchronous reluctance motor.



**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..

وعليه قمنا في هذا البحث بدراسة ونمذجة نظام الضخ متصل بمحرك ممانعة متزامن.



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

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# Field Oriented Control and MPPT

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# Abbreviations

# Abbreviations

Voc : The diameter of the equivalent antenna surface
Rsh : Cell parallel (shunt) resistance [Ω].
Rs Cell series resistance [Ω].
Iph : is the distance between the elements .
IL : represents the light-generated current in the cell.
Ish : represents the current lost due to shunt resistances.
ID : is modelled using the Shockley equation for an ideal diode.
Isc : The short circuit current.
Ia:Output current of PV array[A].
Io:Diode saturation current [A].
Iph:Panel photocurrent [A].
Ir:Rotor current [A].
Is:Stator current [A].
K:Boltzmann constant [J K − 1].
Kp:Proportionality constant.
L s :Stator inductance [H].
L r :Rotor inductance [H].
M:Mutual inductance [H].
Ns:Number of modules connected in series.
Np:Number of modules connected in parallel.
p:Pole pair number.
P, H, Q:Characteristics of the pump for rotation speed[N].
P′, H′, Q':Characteristics of the pump for rotation speed [N′].
q:Electron charge [C].
Rr:Rotor resistance [Ω].
R:Series resistance [Ω].
Rsh:Shunt resistance [Ω].
Rs:Stator resistance [Ω].
Sa, Sb, Sc:Switching states
T c :Cell temperature [K].
Va:Panel output voltage [V].
ws, wr:stator and rotor pulsations.
w m :rotor mechanical angular velocity [rad/s].
Isa , Isb, Isc:Stator phase currents of the machine.
Fsa ,Fsb ,Fsc :Flow of the stator phases of the machine.
f : Flux of magnets.
Vsa ,Vsb ,Vsc:Stator phase voltages.
Ids , Iqs :Stator currents of direct axis and quadrature.
Te :Electromagnetic torque.
TL : Load Torque.
f :Coefficient of friction.
Ω : Rotor rotation pulse
Ts:sampling period
Rs : Stator resistance
P:Number of pole pairs.
M :Cyclic inductancemutual stator-rotor
J :Moment of inertia of rotor masses.
Ld , Lq : Direct and quadrature component of inductance in Park's model

$U_c$ : DC voltage at the inlet of the inverter.
D : Direct axis index
Q : Index of the axis in quadrature
$\omega$ : Stator voltage pulsation.
$\tau$ :Electric time constant.
ABC:Index corresponding to the three phases of the stator
d q:Axis corresponding to the reference frame related to the rotating field
H: Total head achieved by the pump [m];
Hm: Maximum head [m];
N(t): Instantaneous speed [rpm];
Nm: Maximum speed [rpm];
Q(t): Instantaneous flow rate [m3/s];
Qm: Maximum flow rate [m3/s];
ρ: Density of the liquid [kg/m3];
g: Acceleration of gravity [$m/s^2$].
λ: Coefficient of linear pressure drop;
D: Internal diameter of the pipe [m];
V: Average velocity of the fluid [m/s];
g: Acceleration of gravity [m/s2];
L: Length of the pipe [m];
ε: Coefficient of local pressure drop
Q: Volume flow [m3/h].

# Abbreviations

DTC:Direct Torque Control
SynRM :Synchronous reluctance motors
IM:Induction motor.
MPPT:Maximum Power Point Tracking.
$MPP$: Maximum Power Point
P & O:Perturb and observe.
PV:Photovoltaic.
Kp , Ki : Proportional-integral coefficient
DC : Direct Current.
AC : Alternative Current.
FOC : Field Oriented Control.
IGBT: Insulated Gate Bipolar Transistor.
Vmpp : maximum voltage
SVPWM: Space Vector Pulse Width Modulation.

# General Introduction

# General Introduction

Nowadays, considerable effort has been devoted to finding a source of production of electrical energy without yielding $CO_2$ emissions to the environment [1]. Solar photovoltaic (PV) is one of the well-known sources of renewable energy which can be considered the best solution to produce clean electrical energy [2]. PV water pumping system is considered one of the most popular applications of PV power systems, particularly in remote area. Water pumping based on PV technology is a promising alternative to conventional pumping systems based diesel because there is no carbon emission or noise generation and it has a low maintenance cost.

Solar Photovoltaic Water Pumping Systems (SPVWPS) offer a promising solution, providing reliability, performance, and acceptability for irrigation, livestock, and residential use in remote areas. SPVWPS can withstand harsh weather conditions and can be adjusted according to water demand and solar power availability. DC motor powered PV pumps are widely used, but brushless motors offer a more appealing solution due to fewer maintenance issues and lower costs. Induction motor-based PV pumping systems, permanent magnet synchronous motors, and synchronous reluctance motors are other alternatives being explored.

In this thesis, the objective of our study is the modelling and simulation of a cost effective directly coupled solar photovoltaic powered pumping system based on a synchronous reluctance motor. The synchronous reluctance motor is directly connected to the PV panels through an inverter, and therefore no DC/DC converter is used. Using a of the MPPT technique (Maximum Power Point Tracker) to maximize the extraction of power, The machine is controlled using a Filed Oriented Control (FOC) method.

The present work is structured as follows:

In the first chapter, we present a theoretical overview of the photovoltaic and pumping systems, where we present some methods and techniques that allow us to extract the available maximum power that can be produced taking into account the influences of the temperature and insolation variation on the efficiency of the PV systems.

In the second chapter, we present the modelling of the essential parts of the studied system starting from the synchronous reluctance motor (SynRM). Inverters are important in electric motor speed drives as they convert DC power into AC power with variable frequency and amplitude. Moreover, we will present the Inveret model. Furthermore, the equation and the modeling of the synchronous reluctance motor (SynRM) However, controlling SynRMs is challenging due to their complex, multi-variable nature. In addition to modelling of The Pumping System.

In the third chapter, we present the using a of the MPPT technique (Maximum Power Point Tracker) to maximize the extraction of power, The machine is controlled using a Filed Oriented Control (FOC) method.

Field-oriented control (FOC) was proposed to address this, allowing independent control of magnetic field and torque components. FOC initially faced implementation difficulties but became popular with the advent of microcontrollers and signal processing devices, leading to increased research and applications in the field. Finally, we close this chapter by implementing the FOC technique using Simulink/Matlab with the discussion of the obtained results.

Finally, we conclude our work with a general conclusion and perspectives.

# Chapter I

## State of the art Photovoltaic

## I.1. Introduction

Because solar energy is readily available and sustainable, its many features make its application in the industrial sector imperative. Creating methods to use these energies in place of conventional energy is the difficult part.

One method of making use of solar resources is the photovoltaic process, which turns solar radiation into energy. Clean energy generation has emerged as a basic requirement in a society where pollution and the greenhouse effect are major threats [1].

PV, or photovoltaics, is a clean, limitless energy source. It is a crucial part of renewable energy sources, which may help the world fulfill its expanding energy demands while containing the rise in greenhouse gas emissions and lowering pollution in the environment.

In other words, photovoltaics is an intermittent energy source. It is an attractive solution as a replacement or complement to conventional sources of electricity supply due to its numerous advantages [2]:

- It is a reliable means that requires little maintenance.
- It provides electricity using free and renewable solar energy.
- It does not require any fuel.
- It is silent and environmentally friendly, with no pollution.
- It has a lifespan of approximately 25 years.

In this chapter, we will present some generalities about photovoltaic systems. We will briefly describe the most commonly used solar cells and the combination of photovoltaic cells.

Next, we will present and elaborate on different models of a PV system, then select the most suitable model and describe the various equations governing it. Finally, we will simulate this model with varying sunlight and a fixed temperature, and with fixed sunlight and a variable temperature.

## I.2.What is photovoltaics?

Photovoltaic solar energy comes from the conversion of sunlight into electricity using semiconductor materials such as silicon, the raw material for photovoltaic solar panels.

The name Photovoltaic comes from the Greek, it is composed of two parts:

- **Photos**: Light.
- **Volt**: Electrical voltage unit, named Alessandro Volta.

## I.3.History of photovoltaics

Some important data in photovoltaics [3].

- 1839: French physicist Edmond Beckerel discovers the photovoltaic effect.
- 1875: Werner von Siemens published an article on Photovoltaic effect in semiconductors.
- 1954: Three American researchers Chapin, Psion and Prince built a cell Photovoltaic.

  1958: Battery with 9 c/o efficiency; first cell powered satellite Solar energy is sent into space.
- 1973: The first house powered by photovoltaics is built University of Delaware.
- 1983: The first photovoltaic-powered car travels long distances 4000km in Australia.

## I.4.Photovoltaic phenomenon and physics of PV cell

Temperature is a large factor in the performance of a solar cell. The maximum allowable voltage across a solar cell is equal to the bandgap voltage, this occurs when the temperature of the cell is at almost 0 Kelvin [4]. As temperature increases, the bandgap and voltage across the cell decreases. Since the bandgap has decreased, it takes less light energy to free electrons from the solar cell and there will be a slight increase in the output current. However, a more drastic decrease in the output voltage occurs with increasing temperature and the overall output power of the solar cell decreases. A solar cell's output power increases as irradiance increases and temperature decreases. Therefore, ideal locations for PV panels are in cold climates that receive lots of sunlight [3].

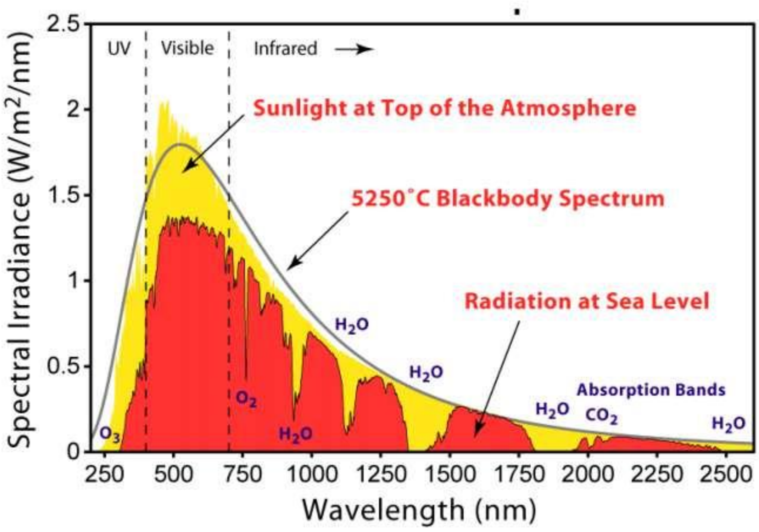



***Figure I.1: Solar Radiation Spectrum [5]***

## I.5.Solar energy

The solar constant is the density of solar energy that reaches the outer boundary of the atmosphere facing the sun. The value of the illumination is commonly taken equal to 1360W/2m.

At ground level, the solar energy density is reduced to 1000 W/2m because of absorption into the atmosphere. Albert Einstein discovered while working on the effect Photoelectric that light did not have only a wave character, but that its energy is carried by particles, photons. The energy of a photon being given by the relation [5]:

$$E = (h.c)/\lambda \tag{I.1}$$

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

C: the speed of light [m. s^ (-1)].

λ: the wavelength [m].

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

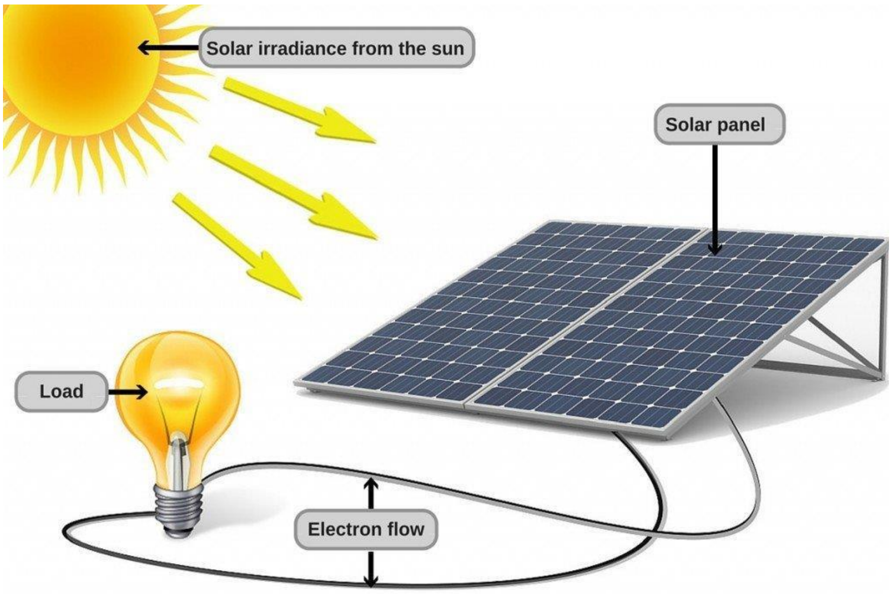



***Figure I.2: Solar energy[1].***

### 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 solar 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]

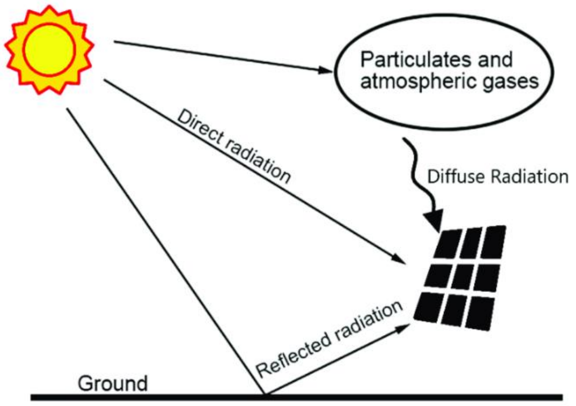



***Figure I. 3: Types of solar radiation (Direct, Diffuse and Reflected). [6]***

## I.6.Operating Principles of a cell

A photovoltaic cell PV, also known as a solar cell, is the combination of two semiconductors, one doped P and the other doped N. At the junction of the two layers, an electric field is formed. This field exists even when the cell is in the dark. Under varying levels of sunlight, photons or light particles, carrying sufficient energy, collide with the atoms of the crystal (Figure I.4). They have the ability to transfer electrons from the semiconductor material's valence band to its conduction band, forming electron-hole pairs in the process. These couples gather on the P and N zone's outer faces when the potential barrier is present [2] .

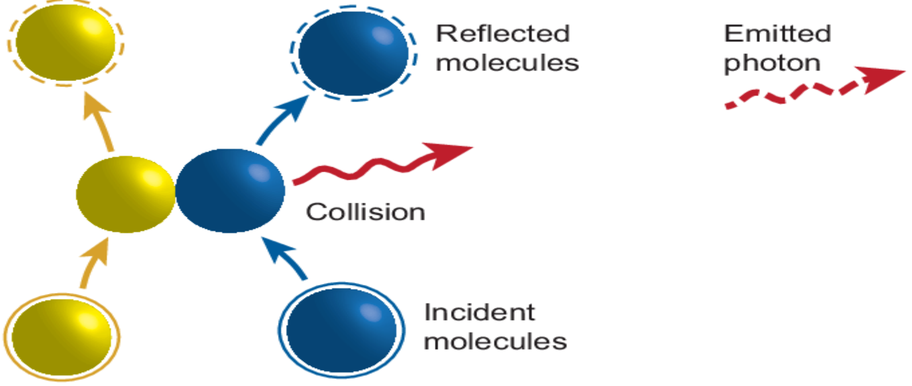



***Figure I.4: Collision between a photon and an atom. [2]***

Thus, a potential difference is created between the two faces of the cell. The metallic grids on the front and back of the PV cell collect the electrons and holes, which provide the generated electric current to an external circuit (Figure I.5) [5]. If the photon is highly energetic, it can still only extract a single electron. The excess energy is lost as heat. The N region is covered by a metallic grid that acts as the cathode, while a metal plate (back contact) covers the other face of the crystal and serves as the anode. The total thickness of the crystal is in the order of millimeters.

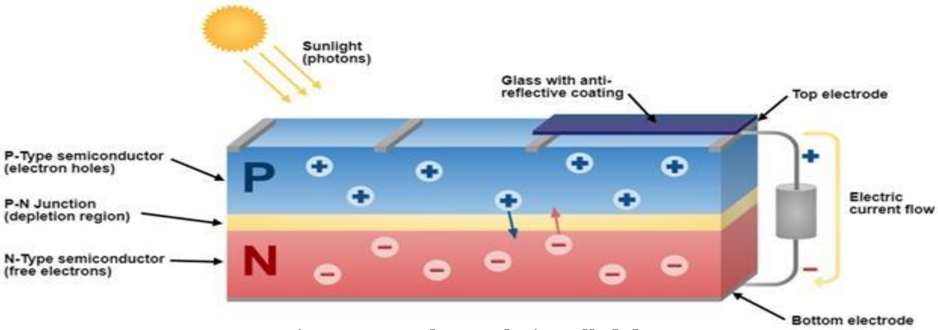



***Figure I.5: Photovoltaic cell. [5]***

### I.6.1. Types of Extrinsic Semiconductors

#### I.6.1.1. P-type semiconductor

A P-type semiconductor is a type of extrinsic semiconductor, which is obtained by adding a trivalent impurity in an intrinsic (or pure) semiconductor. The examples of trivalent impurities are aluminum, gallium, indium, etc. When the trivalent impurity is added to an intrinsic semiconductor, it provides extra holes and these impurities are also known as acceptor impurities. Therefore, the majority charge carriers in the P-type semiconductor are holes. [7]

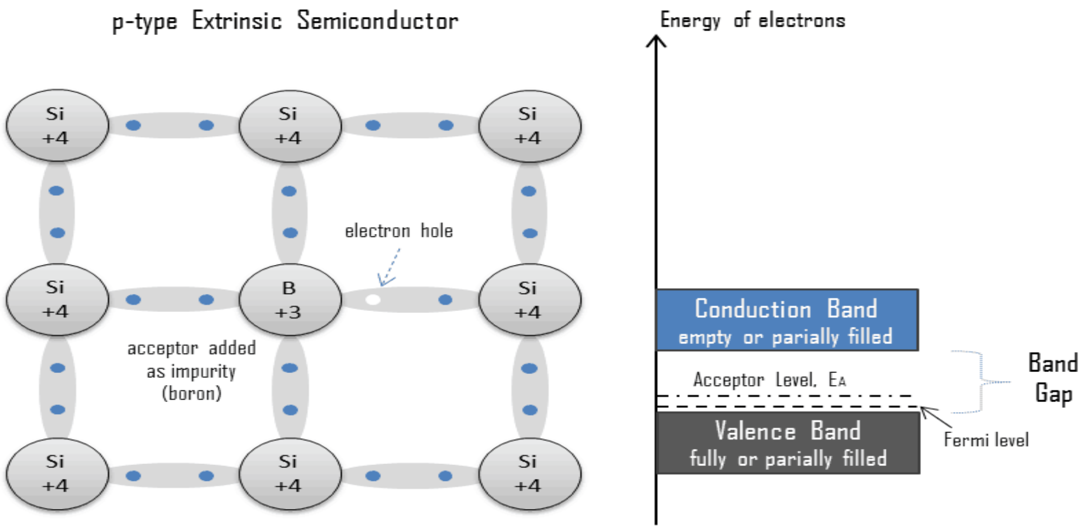



***Figure I.6: Structure of p-type semiconductor[7]***

### I.6.1.2. N-type semiconductor

An N-type semiconductor is also a type of extrinsic semiconductor, which is obtained by adding a pentavalent impurity in an intrinsic semiconductor. The common examples of pentavalent impurities are antimony, arsenic, bismuth, etc. When the pentavalent impurity is added to a pure semiconductor, it provides extra electrons and thus these are also known as donor impurities. In case of N-Type semiconductor, the majority charge carriers are electrons. [7]

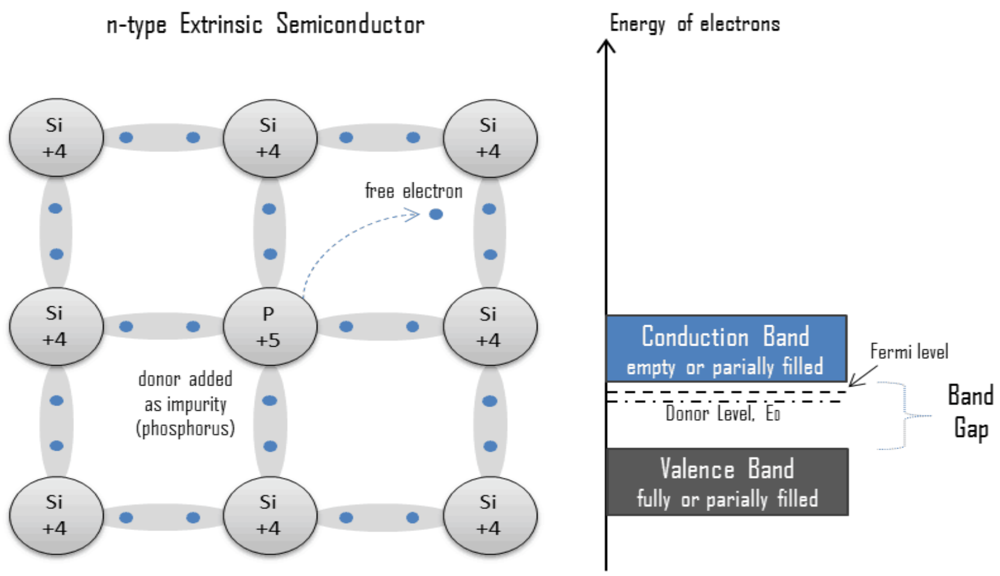



*Figure I.7: Structure of n-type semiconductor[7]*

## I.7. Structure of photovoltaic

PV systems are rated based on their PV modules (cells) maximum DC power output under Standard Test Conditions (STC). Standard Test Conditions include a module (cell) operating temperature of 25°C, incident solar irradiance of 1000 W/m2, and spectral distribution of Air Mass 1.5. Since these circumstances are not typically indicative of how PV modules and arrays behave in the field, real performance is usually about 85% of the STC rating.

To reach larger voltages, currents, and power levels, photovoltaic cells are electrically connected in series and/or parallel circuits. Photovoltaic modules are the main components of PV systems, which are constructed of PV cell circuits sealed in an environmentally friendly laminate. In photovoltaic panels, one or more PV modules are structured as a pre-wired field-installable unit. [5]

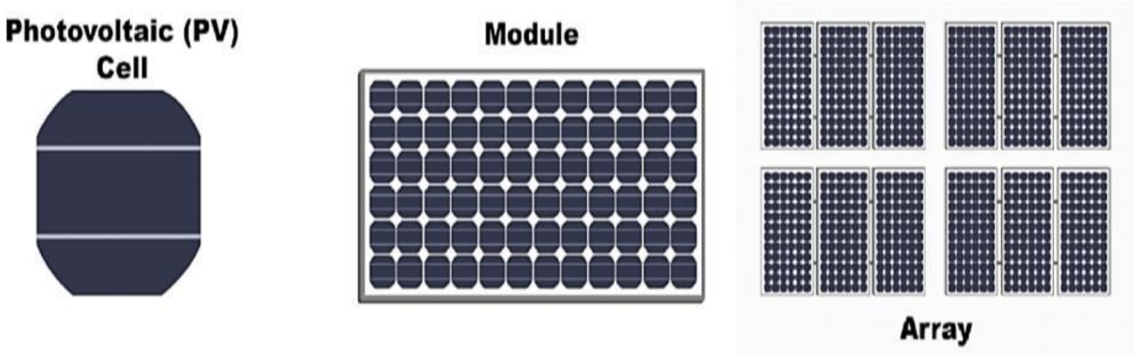



*Figure I.8: photovoltaic cell, module and array[5]*

## I.8. Generations of Photovoltaic

Photovoltaic (PV) cells can be categorized by four main generations: first, second, third, and fourth generation. Each generation has its own characteristics, advantages, and disadvantages.

### I.8.1. First Generation

The most prevalent kind of solar cell in use today, crystalline silicon (c-Si) solar cells, fall within this group. They are produced by melting and crystallizing silicon to produce exceedingly pure silicon wafers. First-generation solar cells are renowned for having a long lifespan (more than 25 years) and high efficiency (between 15 and 20%). However, because of the high cost of silicon and the energy-intensive manufacturing process, they are also the most costly form of solar cell to create.

### I.8.2. Second Generation

Second-generation solar cells, also known as thin-film solar cells, are designed to be a lower-cost alternative to crystalline silicon cells. They are made from a thin layer of photovoltaic material deposited on 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. Second-generation solar cells are generally less efficient than first-generation cells (around 10-15%) but are also less expensive to produce.

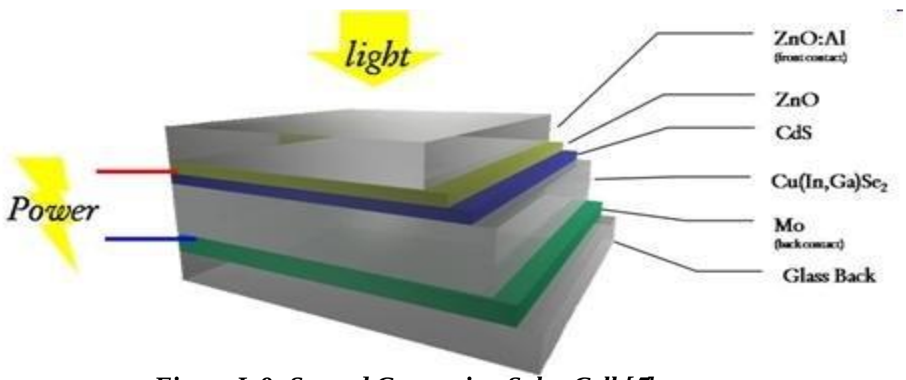



*Figure I. 9: Second Generation Solar Cell [7]*

### I.8.3. Third Generation

Third-generation solar cells are still under development but have the potential to be even more efficient and lower-cost than first and second-generation cells. They include a variety of new materials and technologies, such as organic solar cells, dye-sensitized solar cells, and perovskite solar cells. Third-generation solar cells are still in the early stages of development, but they have the potential to revolutionize the solar industry. [6]

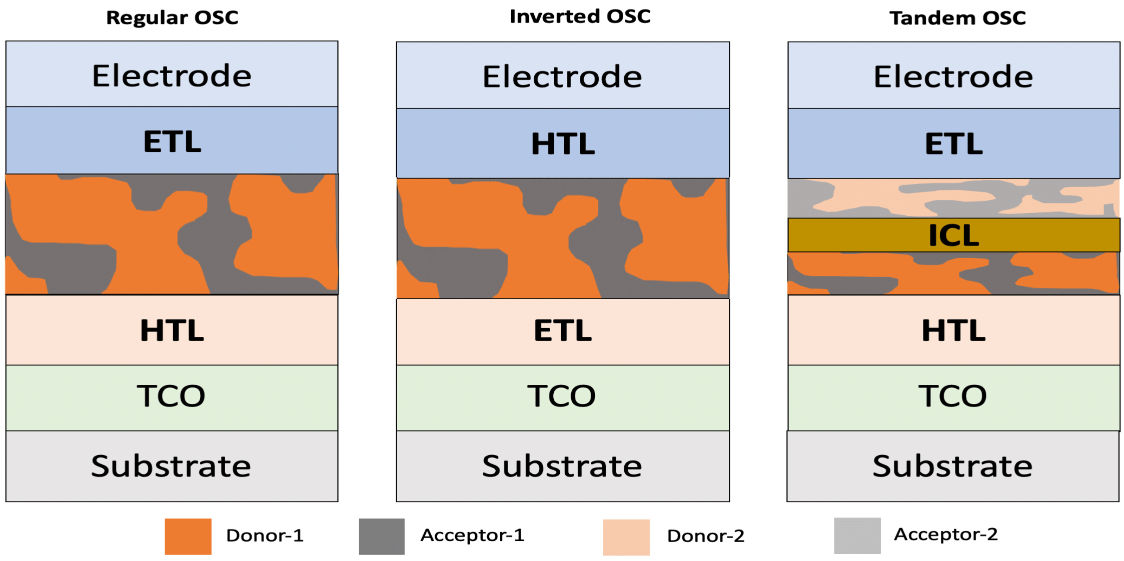



*Figure I.10: Schematic diagram of typical BHJ-OSC (Regular OSC, inverted OSC and tandem OSC) [6]*

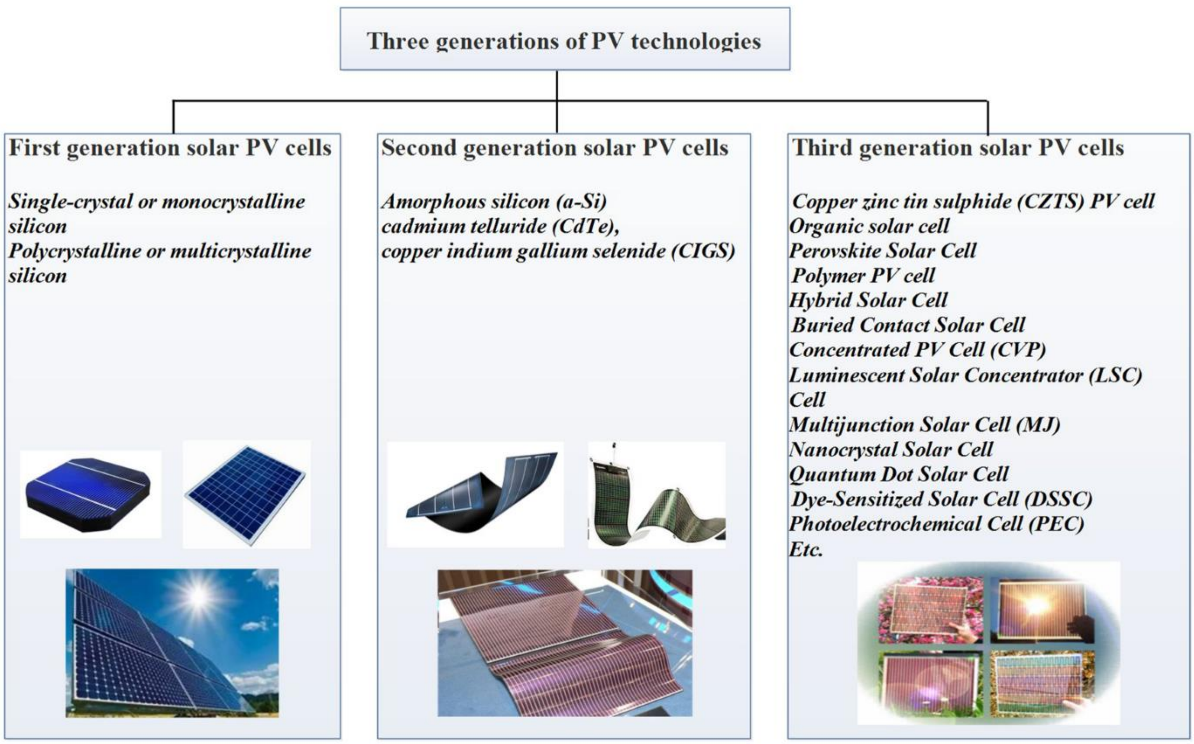



*Figure I.11: The three generations of solar photovoltaic (PV) cells. [6]*

## I.9. Synoptic diagram of the photovoltaic conversion chain

The photovoltaic (PV) conversion chain can be illustrated using a synoptic diagram, which is a simplified block diagram highlighting the main components and their interactions. Here's a breakdown of the key elements[8]:

- **PV Panel:** This is the core element, consisting of interconnected solar cells that convert sunlight (photons) into direct current (DC) electricity through the photovoltaic effect.
- **Maximum Power Point Tracking (MPPT) Unit (Optional):** This electronic device optimizes the output power from the PV panel by adjusting its operating voltage and current to reach the maximum power point (MPP) under varying conditions like sunlight intensity and temperature.
- **DC-DC Converter (Optional):** In some systems, a DC-DC converter might be used to adjust the voltage level from the PV panel to match the voltage requirements of the inverter or the connected load.
- **DC-AC Inverter:** This converter transforms the DC electricity from the PV panel (or DC-DC converter) into AC electricity usable by appliances or for feeding into the power grid.
- **Load:** This represents the device or system that utilizes the generated AC electricity, such as household appliances, lighting, or the electric grid.

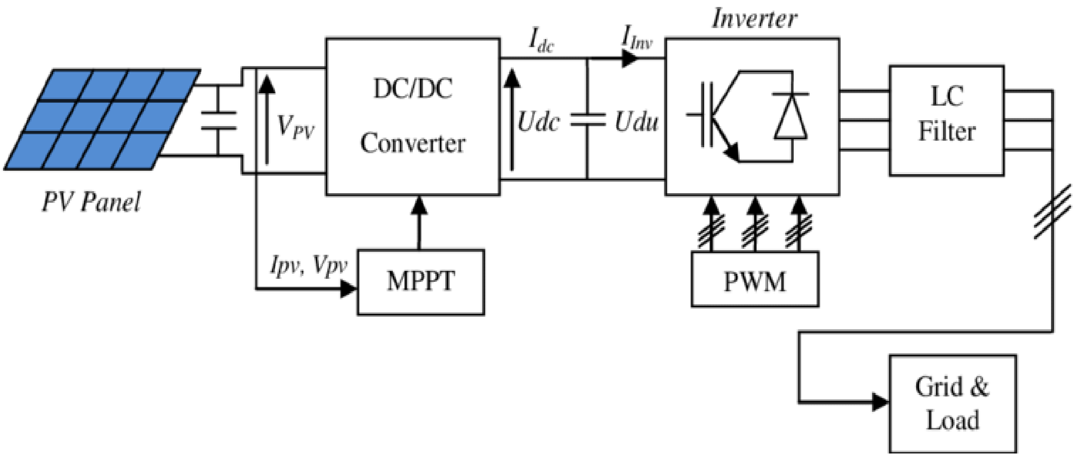



***Figure I.12: Synoptic diagram of the photovoltaic conversion chain. [9]***

## I.10. Photovoltaic cell

Photovoltaic cells (photon: a unit of light energy and volt: a unit of electrical potential) are electronic components made of semiconductor materials, commonly silicon in its various forms.

They directly convert light energy into electricity through the photovoltaic effect. Since sunlight is the source of light energy, these cells are commonly referred to as solar cells.

## I.11. Photovoltaic module

Due to low power ratings of each individual PV cell, the cells are connected in seriesparallel configuration form a PV module in order to produce the required power. Usually, the PV module is rated by its DC output power under standard test conditions (STC) and commercially STC is specified at an irradiance of 1000 W/m2 and a 25°C PV cell temperature [5]. Figure I.38 shows the equivalent circuit of a PV module. The nonlinear current-voltage characteristic of the PV module is modeled by the following equation where all cells are identical [5]:

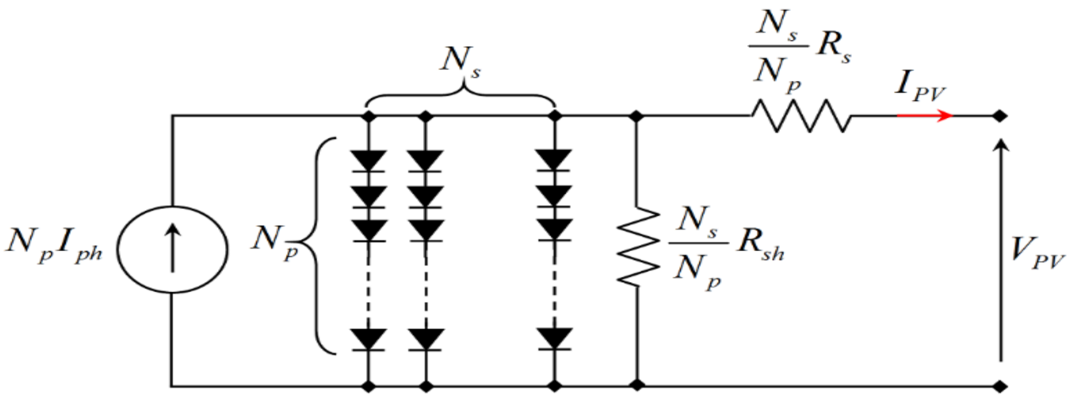



***Figure I.13: The equivalent circuit of a PV module.***

Where:

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

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

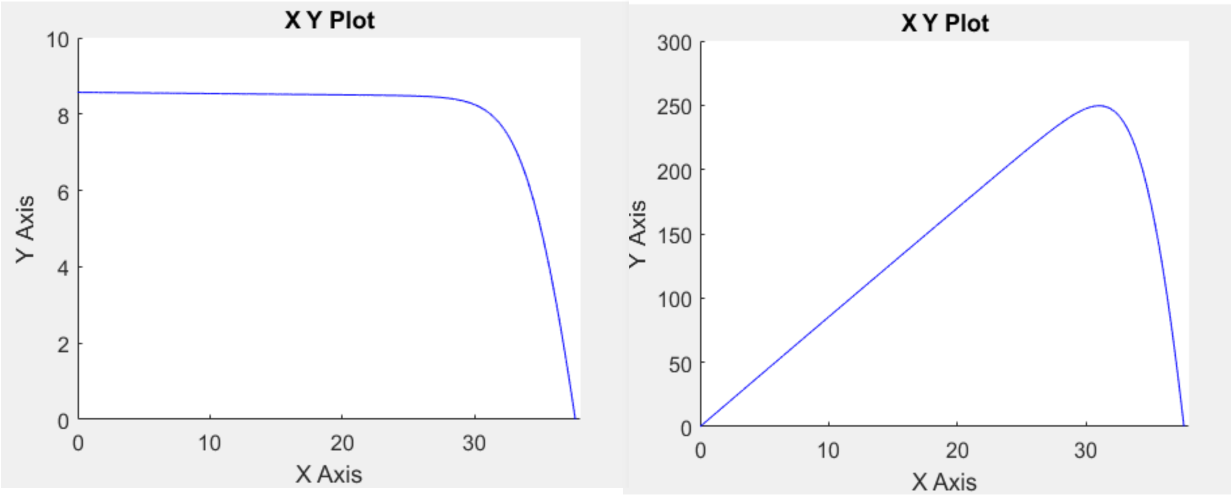
$N_s$: is the number of cells connected in series

$N_p$: is the number of cells connected in parallel

The PV module considered for this thesis is Trina Solar TSM-250PA05.08 PV model. The power versus voltage (P-V) and the current versus voltage (I-V) characteristics of Trina Solar TSM-250PA05.08 PV model under STC are shown in Figure I.14. A PV module can produce the power at a point, called an operating point, anywhere on the I-V curve. Three operating points on the I-V curve are important in defining the performance of a PV module, i.e., the maximum power point, short-circuit current and the open-circuit voltage.

- The maximum power point (MPP) is the point on the I-V curve at which the PV module works with maximum power output.
- The short-circuit current point characterized by a zero voltage at the PV module terminals and by a short-circuit current ($Isc$).

- The open-circuit voltage point characterized by a zero current in the PV panel terminals and by an open-circuit voltage ($VOC$).




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

***Figure I.14: (a) I-V and (b) P-V characteristics of the solar Trina Solar TSM-250PA05.08 PV model under 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].

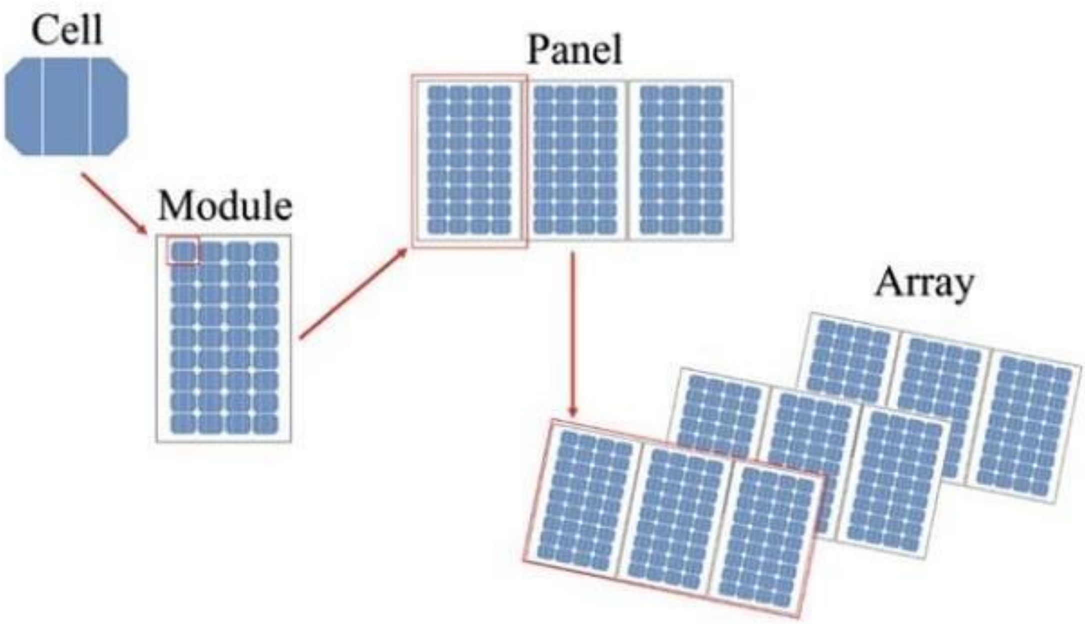



***Figure I.15: The Composition of a Solar Cell. [10]***

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

The solar cell, which can be round or square in shape, is the basic building block of a solar system. A collection of cells forms a solar module, where the cells are electrically interconnected and encapsulated to protect them from external factors. Multiple modules make up a solar panel.

Several panels together form a solar system or solar array, which may include additional components such as protective devices, a regulator, an energy storage system (battery), as well as monitoring and measurement devices [3].

The power provided by a single solar cell is very low, so several cells with similar characteristics need to be electrically connected and encapsulated in plastic to form a PV module. In the following, the different possible groupings of solar cells are presented.

### I.13.1. Series Connection

In a series connection, the cells are traversed by the same current, as shown in Figure.I.16. The resulting characteristic of the series connection is obtained by adding the voltages at a given current.

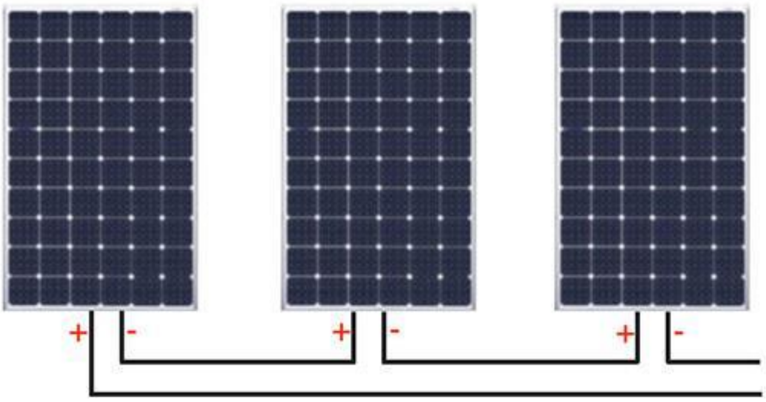



*Figure I.16: Series Connection of cells. [7]*

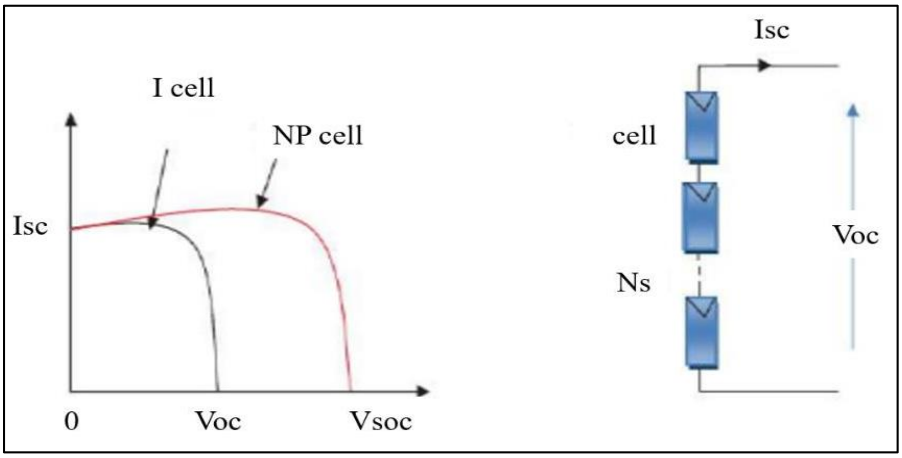



*Figure I.17: Characteristics resulting from a grouping of Ns cell in series [3]*

### I.13.2. Parallel Connection

The properties of parallel connection of cells are the dual of those in series connection. In a parallel grouping of cells, the voltage across each cell is the same, as shown in Figure I.18 which also represents a 2 series-strings in parallel (Mixed connection).

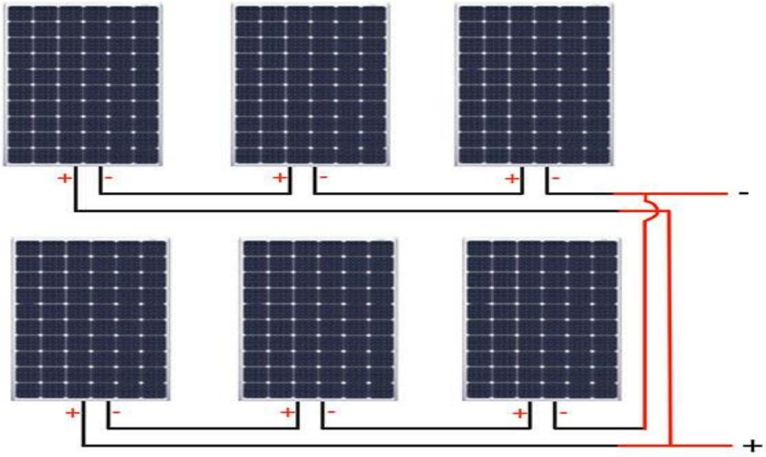



*Figure I.18: Parallel Connection of cells. [7]*

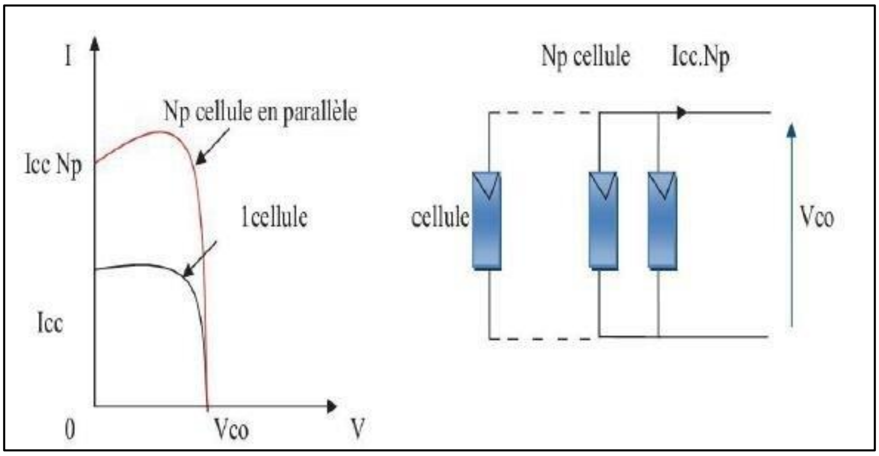



*Figure I.19: Characteristics resulting from a grouping of Np cells in parallel [3]*

## 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).

Inclination of 90° in relation to the sun's rays (in the center) = optimal production. [8]

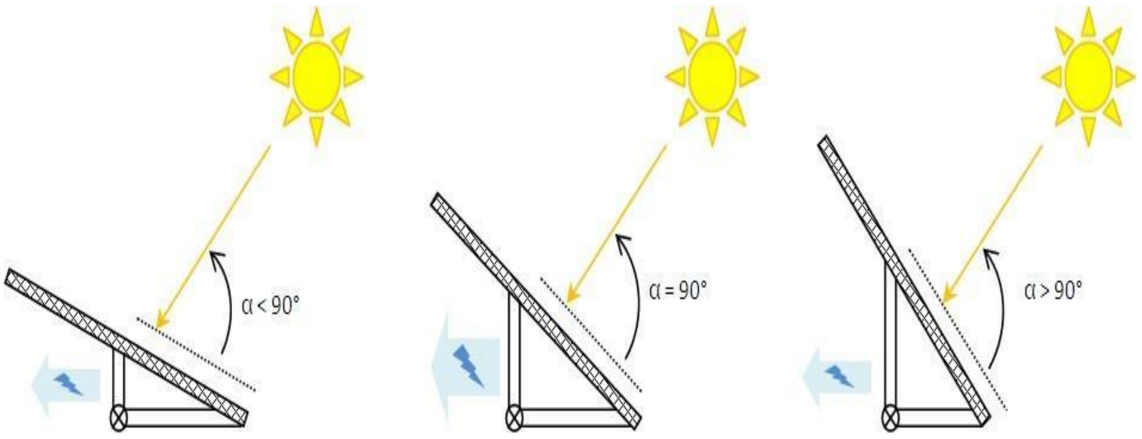



***Figure I.20: Tilt of solar panel. [8]***

**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;
- The inverter transforms direct current into alternating current to supply the AC receivers;
- The batteries are charged by day to be able to supply power at night or on bad 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).

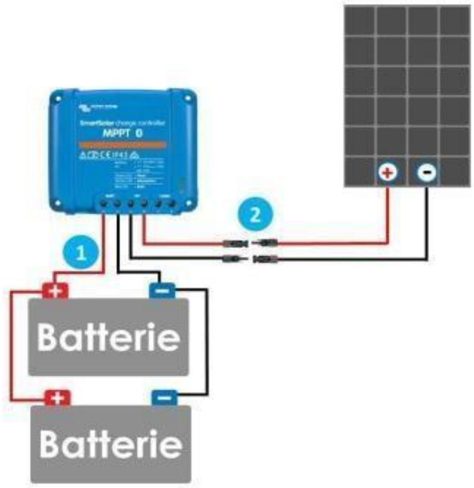



***Figure I.21: Connection to the regulator. [8]***

**b. Panel**

Cover the panel with protection to prevent any production of electricity. Connect the 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**

The energy produced supplies one or more consumer appliances (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 will ensure the protection of people and equipment: the structure of the 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]

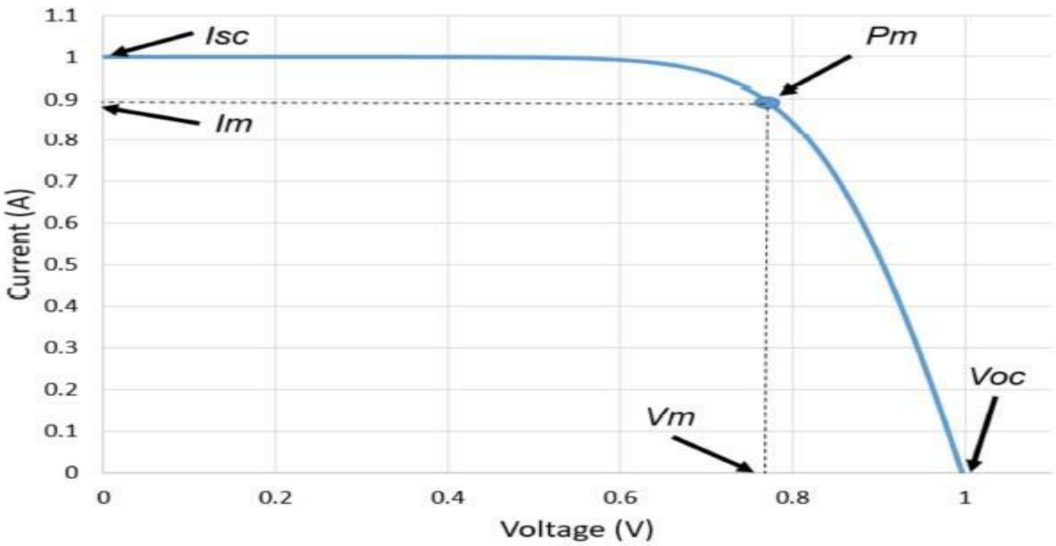



***Figure I.22: I-V characteristic curve.***

### 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,

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

**b. Short-Circuit Current Isc:**

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

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

**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).

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

**d. Fill Factor FF:**

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

$$FF = \frac{Power\ at\ mpp}{Theoritical\ maximum\ power} = \frac{I_{mp}.V_{mp}}{I_{SC}.V_{OC}} \qquad (I.5)$$

**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 the maximum power point, Pmax, divided by the input light irradiance (G, in W/m²) in the standard test conditions (STC) and the surface area of the solar cell (Ac in m²)[11].

$$\eta = \left(\frac{P_m}{P_i}\right) = \frac{I_m.V_m}{P_i} = \frac{I_{SC}.V_{OC}}{P_i} * FF \qquad (I.6)$$

Pi: incident light power,

Pm: the maximum power converted into electricity.

## 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.

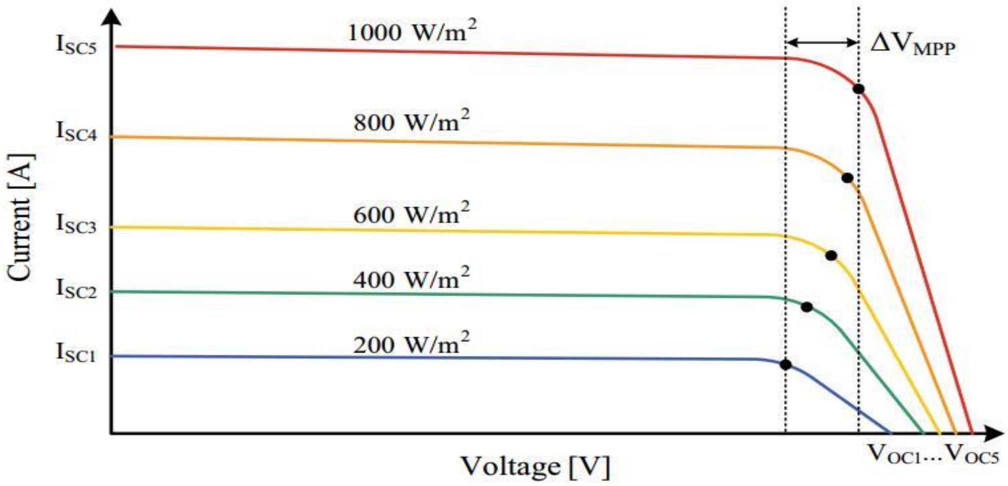



***Figure I.23: I–V Characteristic curve of a PV module [12].***

### 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.

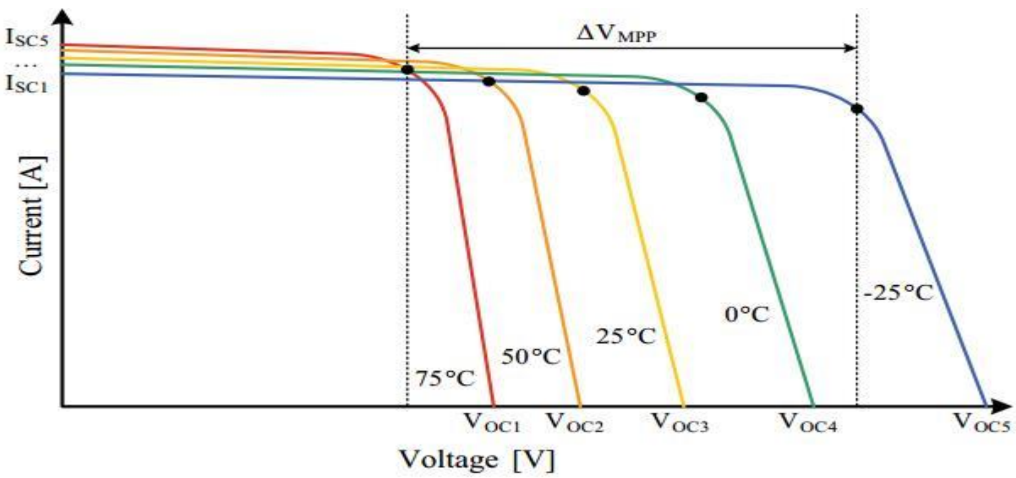



***Figure I.24: I–V Characteristic Curve of a PV Module at Constant Received Solar Radiation and Variable Temperature [12].***

# 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.

***Figure I.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]

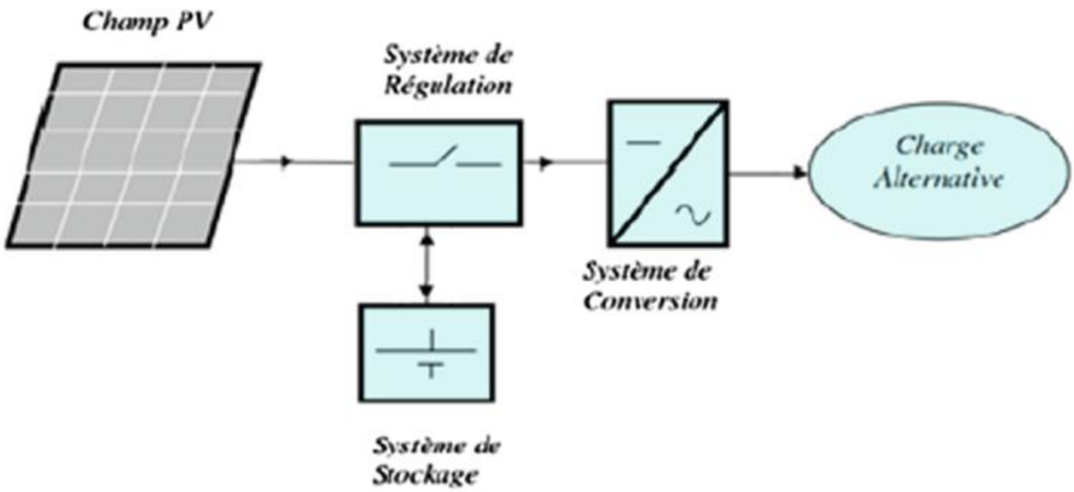



***Figure I.26: Simplified diagram of an autonomous photovoltaic installation[5]***

### I.18.2. Grid-Connected Photovoltaic 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.

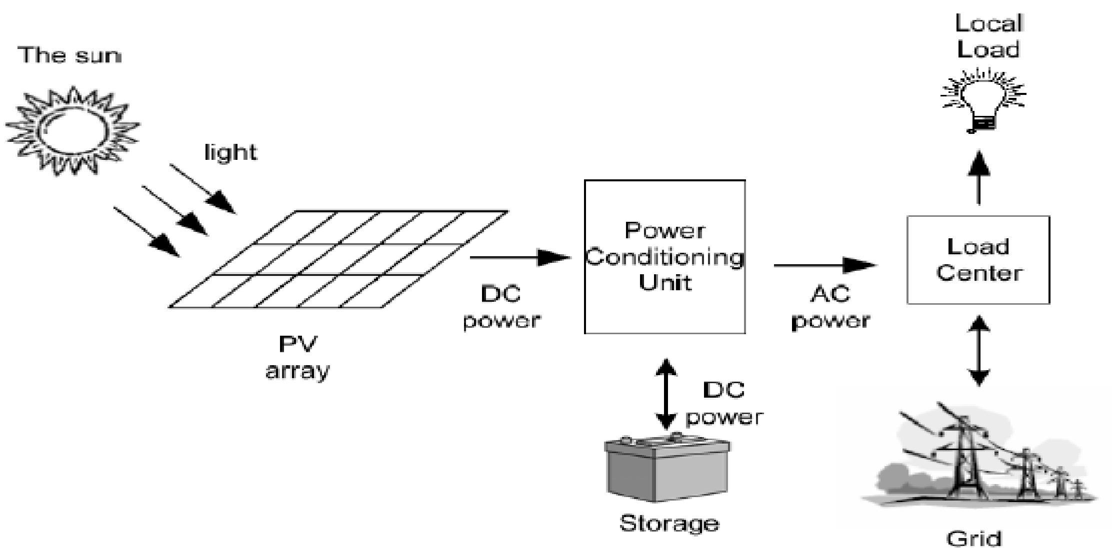



***Figure I.27: Grid-Connected Photovoltaic Systems[13]***

### 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]

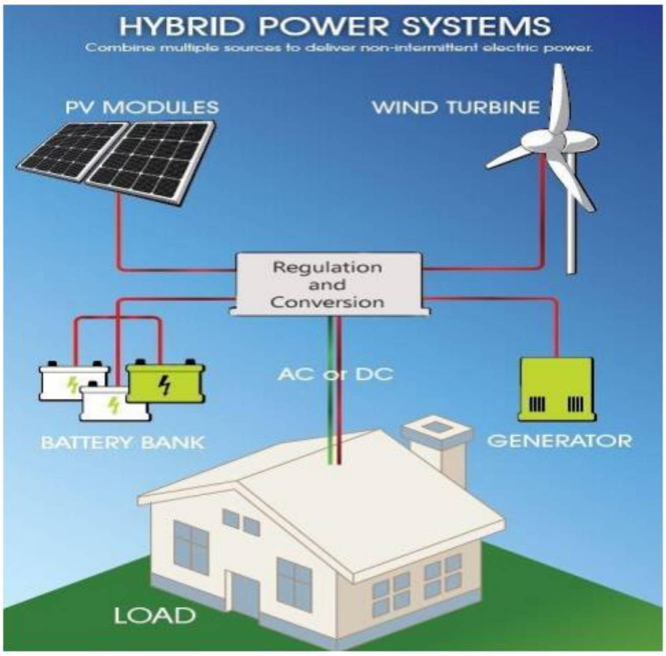



*Figure I.28: Hybrid photovoltaic systems[13]*

## 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.

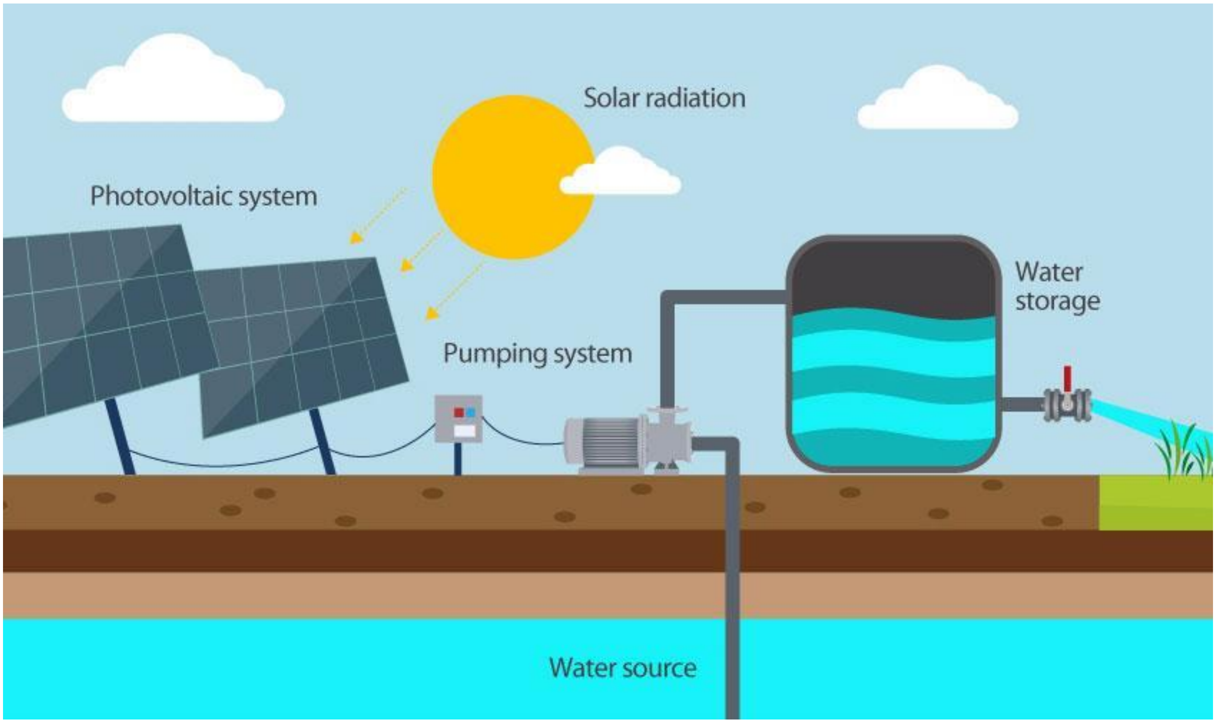



***Figure I.29: Photovoltaic Water Pumping System [7].***

### 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 up to 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]

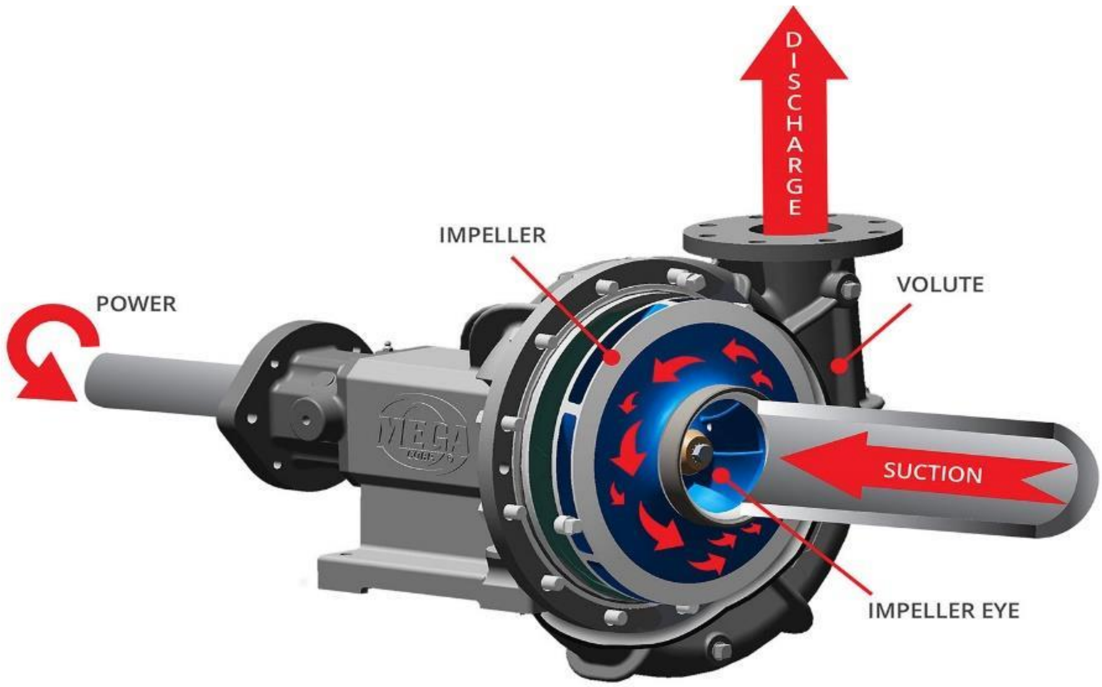



*Figure I.30: Centrifugal Pump. [9]*

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:

$$T_L = K_p \Omega_r^2 \tag{I.7}$$

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

$$K_p = P_{np}/\Omega_{rn}^3 \tag{I.8}$$

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]:

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

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

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

### 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

## Modelling of the system

## II.1. Introduction

Water pumping worldwide is generally dependent on conventional electricity or diesel generated electricity. The continuous exhaustion of conventional energy sources and their environmental impacts have created an interest in choosing renewable energy sources such as solar-photovoltaic, solar-thermal, wind and biomass to power water pumping systems. The need for the optimum utilization of water and energy resources has become a vital issue during the last decade, and it will become even more essential in the future [14].

Nowadays, the utilization of Photovoltaic PV conversion of solar energy to power water pumps is an emerging technology with great challenges.

A synchronous reluctance motor (SynRM) fed by a PV generator represents a brushless scheme that merits to be studied in detail. However, PV pumping systems based on SynRMs motor have not garnered any significant attention from researchers until to date [11].

## II.2. Model of the system components

This section deals with MATLAB/SIMULINK modeling of the system components based on the description, circuits and equations that will be presented in this chapter.

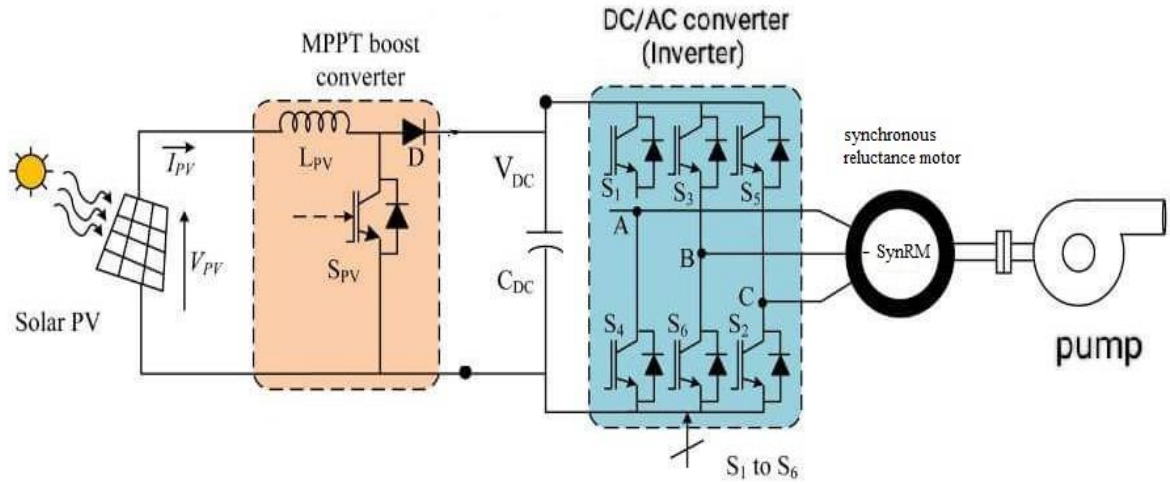



*Figure II.1: Schematic diagram of the PV Water Pumping System*

### II.2.1. PV array model

The PV array is represented by the model illustrated in the following diagram. The array creates a direct current (dc) proportional to irradiance, temperature, and the number of parallel and series linked modules per string.

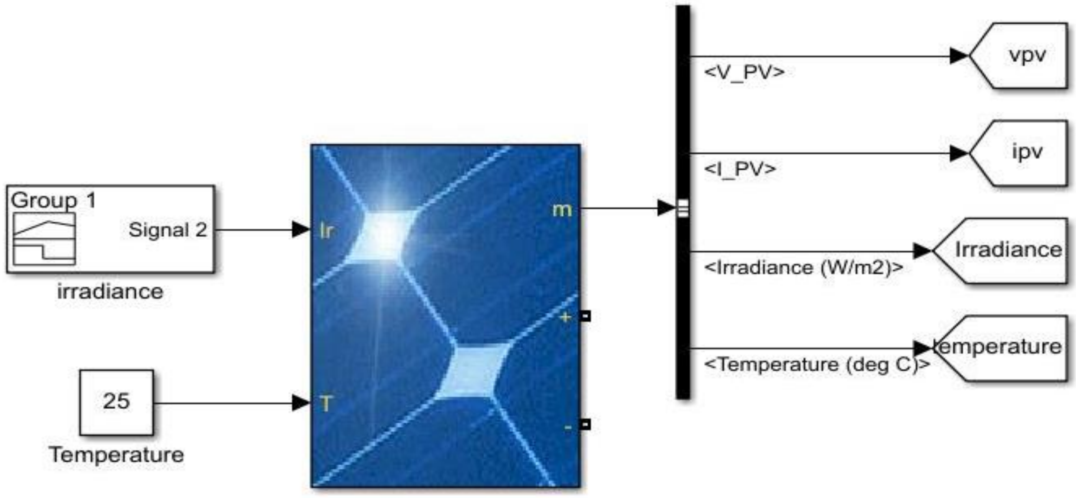



***Figure II.2: PV panel model.***

The general current-voltage characteristic of a PV panel based on the single exponential model is:

$$I = I_{ph} - I_0\left(e^{\left(\frac{V+IR_s}{n_s V_t}\right)} - 1\right) - \left(\frac{V + IR_s}{R_{sh}}\right) \tag{II.1}$$

$$V_t = \frac{AkT_{stc}}{q} \tag{II.2}$$

Where:
– STC - Standard test conditions (A = 1000 W/m2; T = 25 °C; AM = 1.5)
– $I_{ph}$ - the photo-generated current under STC
– $I_0$ - dark saturation current under STC
– $R_s$, $R_{sh}$ - panel series resistance panel; parallel (shunt) resistance
– A - diode quality (ideality) factor.

are the five parameters of the model, while K is the Boltzmann’s constant, and q is the charge of the electrons.

the following equation can be used to describe the I(V) relationship:

$$I = I_{ph} - I_0 e^{\left(\frac{V+IR_s}{n_s V_t}\right)} - \frac{V + IR_s}{R_{sh}}\left(1 + a\left(1 - \frac{V + IR_s}{n_s V_{br}}\right)^{-m}\right) \tag{II.3}$$

### ❖ Photovoltaic module inputs/outputs:

The array has two inputs; the temperature and the irradiance. A positive and negative terminals output voltage and also an output m which is a bus that contains four parameters:

- The PV voltage
- The PV current
- The input temperature
- The input irradiance

***Note:*** The irradiance and temperature can be constants or variables depending on the study.

### ❖ Photovoltaic module identification:

For the simulation, a **1Soltech 1STH-215-P** Photovoltaic module is selected, the chosen module is provided by simscape library in SIMULNIK/MATLAB 2020. The characteristics and parameters of the chosen module are shown in the next table:

| ***Module data*** | | | |
|---|---|---|---|
| ***Module*** | ***1Soltech 1STH-215-P*** | | |
| *Maximum Power (W)* | ***213.15*** | *Cells per module (Ncell)* | ***60*** |
| *Open circuit voltage Voc (V)* | ***36.3*** | *Short-circuit current Isc (A)* | ***7.84*** |
| *Voltage at maximum power point Vmp (V)* | ***29*** | *Current at maximum power point Imp (A)* | ***7.35*** |
| *Temperature coefficient of Voc (%/deg.C)* | ***-0.36099*** | *Temperature coefficient of Isc (%/deg.C)* | ***0.102*** |

***Table II.1: PV panel characteristics***

Using the PV model, it is possible to plot its P-V and I-V characteristics. Hence, the effect of variable irradiance and temperature on the electrical characteristics can easily be observed. Different values of irradiance have been applied to the system from 200 W/m2 to 1200W/m2, for a constant temperature of 25°C.

I-V and P-V curves for the PV array are shown in figure below:

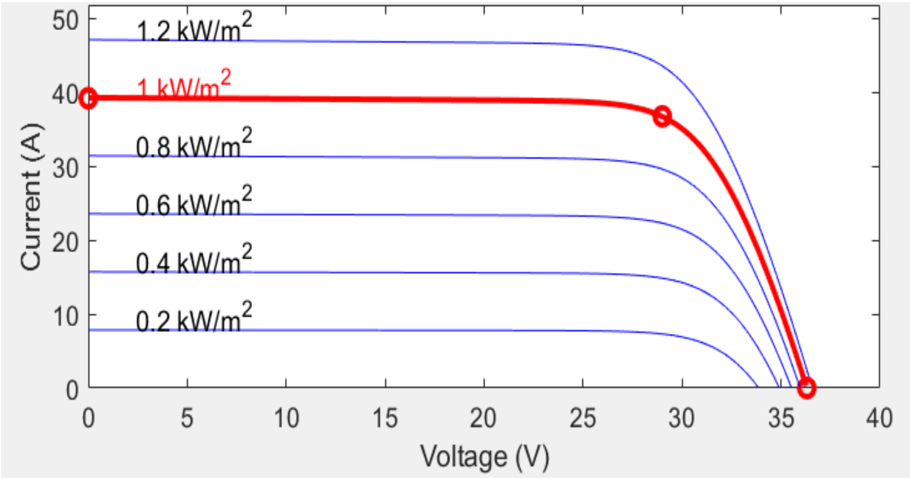



***Figure II.3: PV array: I-V characteristic curve***

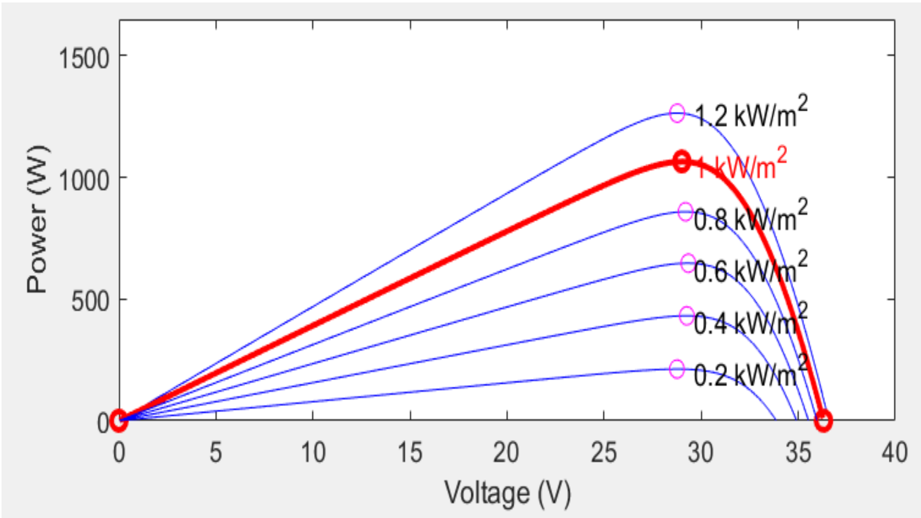



***Figure II.4: PV array: P-V characteristic curve***

It is evident from the two graphs that the panel's features are impacted by the irradiance. The output current is exactly proportional to the irradiance change since it is very sensitive to it. As the irradiance declines, so does the output current. On the other hand, the voltage remains around the open circuit value when the current reaches zero.

The P-V characteristic graph maintains its form throughout a range of irradiances; nevertheless, as with the I-V characteristic, the relationship is directly proportional as the highest power point, shown by circles on the graph, falls with irradiance. Additionally, the open circuit voltage, or $V_{oc}$, is the location where power drops to zero.

**II.2.2. Electrical equivalent circuit of the photovoltaic cell**

From the literature, there are few types of equivalent circuit models to represent PV cells. A well-known circuit model is the generic model which has single diode with a series resistance and a shunt resistance [17, 18]. As shown in Figure II.5, the amount of electrical energy produced by PV is represented by the current Iph, which is proportional to the solar irradiation. The series resistor represents an internal resistance while the shunt resistance represents the leakage current.

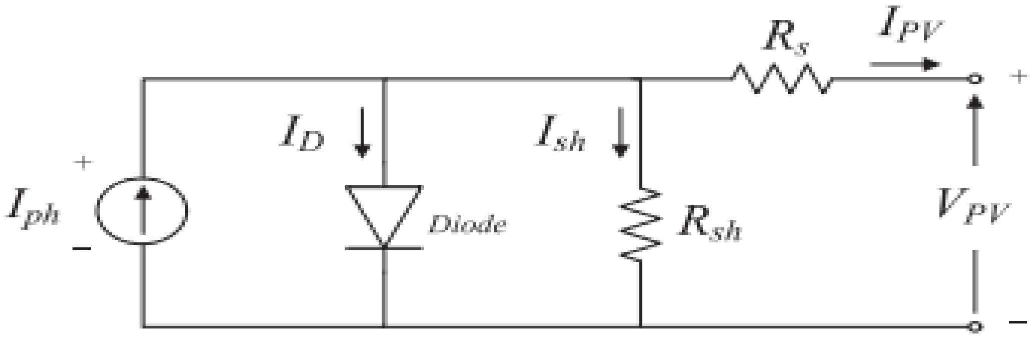



***Figure II.5: The single diode model of PV cell [9]***

The mathematical equation that expresses the PV cell is given in as follows:

$$I_{PV} = I_{ph} - I_D - \frac{V_D}{R_{sh}} \quad \text{(II.4)}$$

Or,

$$I_{PV} = I_{ph} - I_s \left[ exp\left( \frac{q(V_{PV} + R_s I_{PV})}{AKT} \right) - 1 \right] - \frac{V_{PV} + R_s I_{PV}}{R_{sh}} \quad \text{(II.5)}$$

Where:

$I_{ph}$: is the light-generated current of the elementary solar cell.

$I_d$: is the current of the parallel diode.

$I_s$: is the reverse saturation current of the diode.

$I_{pv}$, $V_{pv}$: are the output current and voltage of the PV cell respectively. q: is the electron charge (1.60217662 × 10-19 C).

A: is the diode ideality factor and depends on the PV cell technology. K: is the Boltzmann constant (1.38064852 × 10-23 J/K°)

$T$: is the temperature of the p-n junction in unit Kelvin.

## II.3. General information on Synchronous Reluctance Motor

The Synchronous Reluctance Motor is structurally a synchronous machine with poles without excitation. Its stator is identical to that of ordinary alternating current machines. The electromagnetic torque consists exclusively of the the salient torque. The energy conversion in the machine is done by variation of the inductances of its phase windings due to the rotation of a rotor magnetically dissymmetrical between the direct axes (of minimal reluctance) and in quadrature of maximum reluctance. It is indeed a variable reluctance machine and more precisely a polyphase pure reluctance machine with a smooth stator and a sinusoidal supply. As the machine rotates synchronously with its supply and as it the name "Synchronous Reluctance Motor" has been chosen. The variable reluctance synchronous machine is therefore suitable for high power applications is therefore suitable for high power and high-speed applications, a field largely occupied by the occupied by the asynchronous machine. But the latter presents Joule and iron losses at the rotor in steady state. The synchro-reluctant machine is therefore a real competitor on this point. a real competitor of the asynchronous machine on this point [2].

**II.3.1. Operating principle of synchro-reluctant machine**

The stator of the variable reluctance synchronous machine is wound in the same way as that of ordinary synchronous machines. of the ordinary synchronous machines. It is a three-phase winding with p even poles fed by a balanced three-phase system of currents of pulsation ω . The three-phase winding then creates a rotating magneto-motive force (m.m.f.) with an angular velocity $\frac{\omega}{P}$.

Its rotor is protruding: it presents an "asymmetry" between the direct axis and the axis in quadrature axis. The rotor is positioned in relation to the rotating f.m.m. so that the that the reluctance crossed by the magnetic induction flux in the air gap is the smallest that the load it is driving allows. As it rotates, the magnetomotive force thus drives the rotor at the same speed $\frac{\omega}{P}$.

The angle between the maximum of the magnetomotive force and the angle between the maximum of the magnetomotive force and the axis d of the rotor is called "load angle"[1].

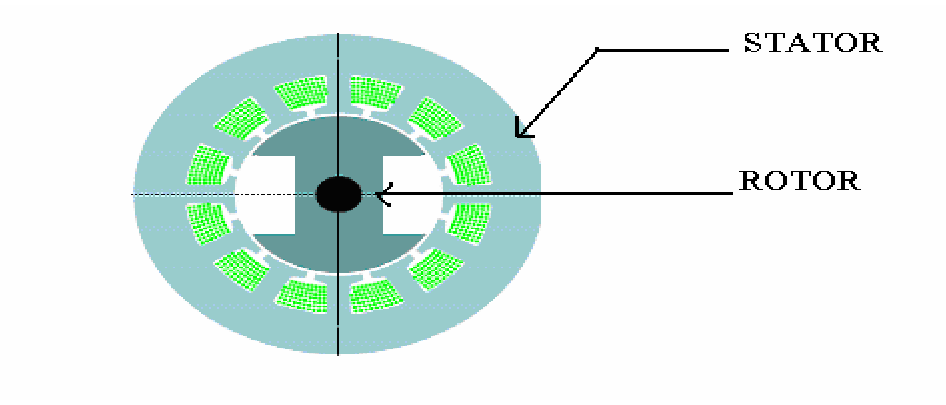



***Figure II.6: SynRM stator and rotor.***

### II.3.2. The different rotor structures of a Synchronous Reluctance Motor

There are currently five main structures of the synchronous machine rotor with variable reluctance, simple, with flow barriers and axially laminated, magnet assisted and superconducting [3].

#### II.3.2.1. Simple rotor

If the starting point in the development of rotor models the latter was under formed by a stack of electromagnetic laminations.

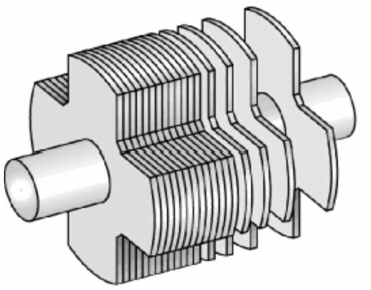


***Figure II.7: Single rotor of the SynRM***

#### II.3.2.2. Rotor with flux barriers

Flux barriers are one of the devices that allow to increase the salinity ratio ($L_d/L_q$) (up to about 13). The salience ratio is increased mainly by the reduction of the inductance $L_q$ , i.e. by increasing the reluctance q of the path of q in the rotor. The rotor then becomes an assembly of ferromagnetic segments flux and non-magnetic segments. The salience ratio is adjusted by adjusting the relative widths of the segments.

The flux barriers can be made of air (holes in the rotor). A is then necessary to ensure the solidity of the rotor and the reduction of the reduction of the q-axis flux. To preserve the mechanical balance of the rotor, the flux barriers can also be can also be made of non-magnetic steel. A robust assembly technique (explosion welding) is then essential to allow the rotor to operate at high speed [4].

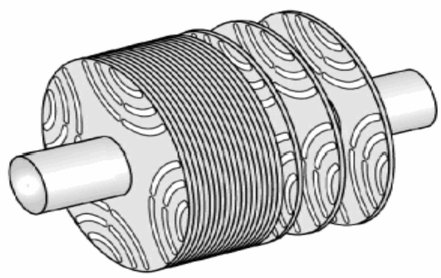


***Figure II.8: Rotor with flux barriers***

### II.3.2.3. Axially laminated rotor

A second device to increase the salience ratio is the axial lamination of the rotor. non-magnetic sheets. The rotor then behaves like a homogeneous anisotropic material. It is this anisotropy of the rotor material that ensures the asymmetry between the direct axis and the quadrature axis. The gloss ratio is adjusted by adjusting the relative thicknesses of the sheets.

It is possible to reach a gloss ratio of about 20 in two poles and 10 in four poles [2].

Note that this structure is generally used for synchro-reluctant machines with four poles. The assembled sheets are then shaped like hyperbolas as shown in figure (II.9). Because of the high number of assembled elements and the relatively low mechanical mechanical strength, this structure is limited to low speeds (less than 5000 rpm) and low (below 5000 rpm) and low power (below 2kW) but it has higher performances than the first two. higher performance than the first two.

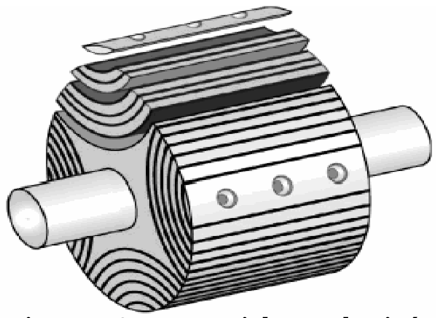


***Figure II.9: Rotor axialement laminé***

### II.3.2.4. Magnet assistance

In order to further reduce the q-axis flux, permanent magnets can be used housed in the flux barriers. In contrast to an ordinary excitation, the flux created by the magnets opposes the quadrature flux. Most of the torque remains due to the to the salience of the rotor. This technique allows to improve the performance in terms of torque, power factor and efficiency.

But because of the polarity of the magnets, the machine loses its reversibility and the direction of direction of rotation. Of course, the use of magnets increases the cost of the machine[5].

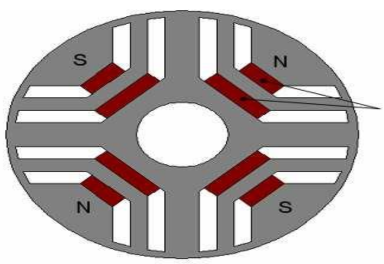



***Figure II.10: Magnet assistance of a synchro-reluctant machine. Four-pole configurations***

### II.3.2.5. Use of superconductors as magnetic insulators

The high-temperature superconductor is by far the best device to reduce the q-axis flux. reduce the q-axis flux. It is used as a magnetic insulator. It can be used to It can be used to enclose a solid rotor or instead of flux barriers as shown in figure (II.11)

The introduction of flux barriers made of superconducting material has the advantage of considerably reduce $L_q$ while preserving a high value of $L_d$.

The magnetic isolation leads to a considerable increase of the and consequently a significant improvement of the power factor. In contrast to magnet assistance, the use of superconductors allows to the reversibility of the machine with respect to the direction of rotation. But it has two major disadvantages: the cost of the superconducting material and the complexity of the structure and implementation [1].

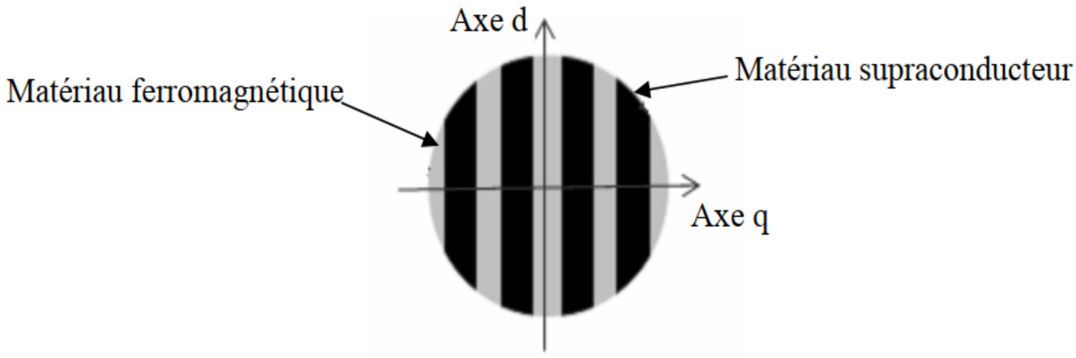



***Figure II.11: Rotor of a superconducting variable reluctance machine.***

The rotor in this type of motor is made up of several layers, interposing ferromagnetic and high-temperature ferromagnetic layers and layers of superconductor at high critical temperature, this configuration. This configuration allows to have a reluctance difference along the axes d and q axes of the rotor figure (II.11).

The rotor is cooled with nitrogen. The power of the variable reluctance motors realized and tested tested vary between 0.75 and 10 kW. These motors have a power density 4 to 7 times higher than that of non-superconducting variable reluctance motors [4].

### II.3.3. Influence of the parameter ($L_d/L_q$) on machine performance

An in-depth study of the influence of the ratio ($L_d/L_q$) on the performance of the variable reluctance synchronous machine.

We will recall the main results of this study.

The expression of the electromagnetic torque developed by this type of machine in steady state is given by the relation.

$$C_e = \frac{3}{2} p(L_d - L_q) I_d I_q \quad \text{(II.6)}$$

We have defined in Figure (II.12), the angle $\theta$ identifying the position of the current vector stator $I_s$ with respect to the d-axis. In steady state, this vector is fixed.

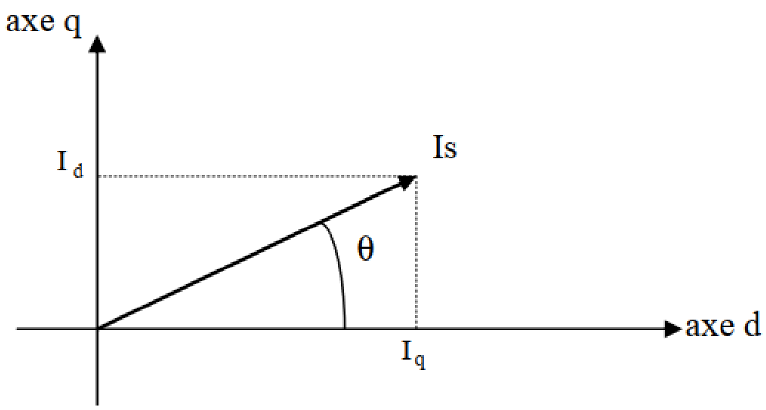



***Figure II.12: Position of the stator current in the coordinate system (d-q).***

The value of the modulus of the stator current is given by the following relationship

$$I_s = \sqrt{I_d^2 + I_q^2} \quad \text{(II.7)}$$

The electromagnetic torque can be expressed as a function of θ and the stator current

$$C_e = \frac{3}{2} p(L_d - L_q) I_s^2 \sin 2\theta \quad \text{(II.8)}$$

It is shown from the two previous relations that for a given value of the stator current, the torque is the torque is maximum when $\theta = \pi/4$ which corresponds to impose $I_d = I_q$ .

This mode of operation corresponds to a particular control strategy.

By setting $\theta = \pi/4$ in equation (II.8), we obtain equation (II.9). We see appearing in this equation, the salience ratio $L_q/L_d$.

$$C_e = \frac{3}{2} p L_d I_s^2 \left( 1 - \frac{1}{\left(\frac{L_d}{L_q}\right)} \right) \quad \text{(II.9)}$$

We can define the power factor of the machine which corresponds to the phase shift between the fundamental of the line current and the corresponding simple voltage. This factor also represents the ratio between the active power and the apparent power absorbed by the machine. It is important that this ratio is as close as possible to 1 to limit the power of the source feeding the machine. By neglecting the losses in the model of the machine, we obtain a simple expression for the power factor [6]:

$$\cos\varphi = \frac{\left(\frac{L_d}{L_q} - 1\right)\sin\theta}{\left(\frac{L_d}{L_q}\right)^2 + \tan^2\theta} \quad \text{(II.10)}$$

The power factor is maximized and depends only on the ratio $L_d/L_q$ for / $\sin(\theta) \approx 1$.

The expression for the power factor is then given by the following relationship:

$$\cos\varphi = \frac{\frac{L_d}{L_q} - 1}{\frac{L_d}{L_q} + 1} \quad \text{(II.11)}$$

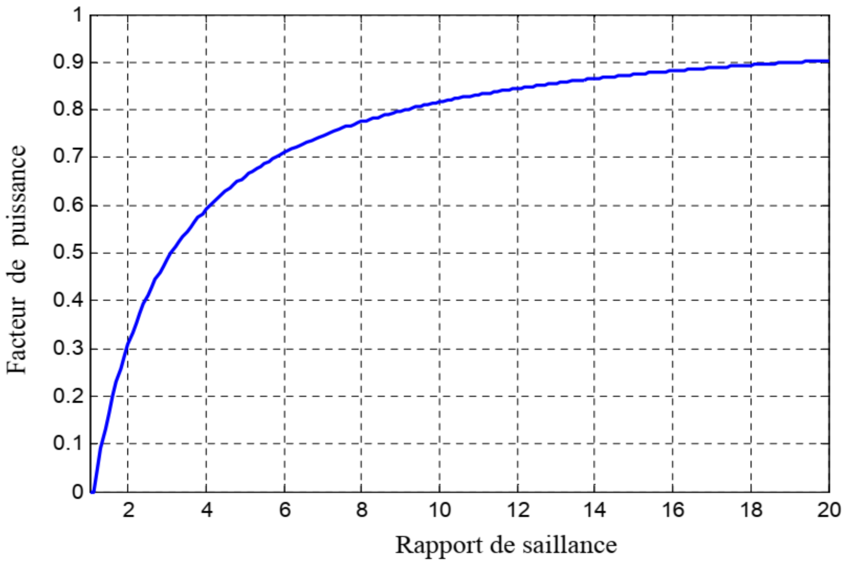



***Figure II.13: Power factor as a function of salience ratio.***

We have represented on figure (II.13), the variations of the power factor as a function of the salience ratio $L_d/L_q$. We can observe on this figure that the power factor starts to become interesting for power factor starts to become interesting for salience ratios higher than 6. Taking into account the electrical losses (Joule losses and iron losses) increases this power factor slightly increases this power factor [7].

Equations (II.9) and (II.11) show that in order to optimize machine performance, a rotor structure must be designed such that the inductor $L_d$ has the greatest possible value and the ratio ($L_d/L_q$) is as large as possible. This is a problem of optimization of an electromagnetic structure with two constraints. The search for an optimal rotor structure can be solved using the finite element method applied to magnetic field calculation.

### II.3.4. Healthy Model of the SynRM in the abc frame

The three-phase voltage of the SynRM can be represented in the a,b,c axis stationary reference frame as follows which was used in[14]

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad \text{(II.12)}$$

Where $V_a$, $V_b$, $V_c$ are the phase voltages, $R_s$ is the stator winding resistance $i_a$, $i_b$, $i_c$ are stator currents, where $L_{aa}$, $L_{bb}$ and $L_{cc}$ are the a,b and c phase self-inductances .$L_{ab}$, $L_{ac}$, $L_{ba}$, $L_{ca}$, $L_{ba}$ and $L_{cb}$ are the mutual inductances between the stator windings. Assuming that the stator windings are sinusoidally distributed windings, the self and mutual inductances of the SynRM can be expressed as:

$$L_{aa} = L_{1s} + L_A + L_B \cos(2\theta_e)$$

$$L_{bb} = L_{1s} + L_A + L_B \cos(2\theta_e + \frac{2}{3}\pi)$$

$$L_{cc} = L_{1s} + L_A + L_B \cos(2\theta_e - \frac{2}{3}\pi) \quad \text{(II.13)}$$

$$L_{ab} = L_{ba} = -\frac{1}{2} L_A + L_B \cos(2\theta_e - \frac{2}{3}\pi)$$

$$L_{bc} = L_{cb} = -\frac{1}{2} L_A + L_B \cos(2\theta_e)$$

$$L_{ca} = L_{ca} = -\frac{1}{2}L_A + L_B\cos(2\theta_e + \frac{2}{3}\pi)$$

Where L1sis the leakage inductance, LAis the parameter which is unrelated to the rotor position, LBis the parameter which is related to the rotor position and θeis the electrical rotor position of the motor. The SynRM's back EMF caused by mutual inductances and also saliency effect. The back EMFs of Synchronous Reluctance machines are called extended back EMF [15]. The electromagnetic torque is indicated as:

$$T_e = \frac{3}{2}p\left(L_d - L_q\right)i_d i_q \quad \text{(II.14)}$$

$L_d$ and $L_q$ are the direct and quadrature axes inductances respectively in the function of $i_d$ and $i_q$ currents as stated in [18]. Generally speaking, in order to enhance the control algorithm, the id may be defined as a constant current; the electromagnetic torque would then be reduced to:

$$T_e = K{i_d}^*{i_q}^* \quad \text{(II.15)}$$

The motor dynamic equation is expressed as:

$$T_e = J\frac{d\omega_m}{dt} + B_m\omega_m + T_L + T_k \quad \text{(II.16)}$$

Where $T_L$ is the load torque, $J$ the inertia moment of the system rotating parts, $\omega_m$ is the motor mechanical speed, $B_m$ the viscous friction coefficient, $T_k$ the constant friction load and $p$ the number of pole pairs.

The electrical rotor speed and position are expressed as:

$$\omega_e = \frac{p}{2}\omega_m \quad \text{(II.17)}$$

$$\theta_e = \frac{p}{2}\theta_m \quad \text{(II.18)}$$

In order to simplify the equation, the electrical angle can be neglected in all previous inductances in (2) where the inductances will be as follows.

$$L_{aa} = L_{1s} + L_A + L_B \cos(2\theta_e)$$

$$L = L_{1s} + L_A + L_B \qquad \text{(II.19)}$$

$$L_{aa} = L_{bb} = L_{cc} = L$$

The whole of the mutual becomes as:

$$M = -\frac{1}{2} L_A + L_B \qquad \text{(II.20)}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad \text{(II.21)}$$

The motor model will be in frame dq0 as in (22) after applying Park transformation to (21)

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q + \Delta v_{df}$$

$$v_d = R_s i_d + L_q \frac{di_q}{dt} - \omega_e L_d i_d + \Delta v_{qf}$$

$$\text{(II.22)}$$

$$\Delta v_{df} = -\frac{2}{3} v R_s i_f \cos\theta - \frac{2}{3} v L_d \cos\theta \frac{di_f}{dt} + \frac{2}{3} v \omega e^i f \left(L_d - L_q\right) \sin\theta$$

$$\Delta v_{qf} = -\frac{2}{3} v R_s i_f \sin\theta - \frac{2}{3} v L_q \sin\theta \frac{di_f}{dt} + \frac{2}{3} v \omega e^i f \left(L_d \sin\theta - L_q \cos\theta\right)$$

The inductances of the dq will be as (23), like[15]and by the transformation of the park.

$$L_{dq} = p L_s p^{-1} = diag\{L_d L_q L_{1s}\}$$

$$L_d = L_{1s} + \frac{2}{3}(L_A + L_B) \qquad \text{(II.23)}$$

$$L_q = L_{1s} + \frac{2}{3}(L_A - L_B)$$

### II.3.5. Benefits of SynRM

The main motivations that make the SynRM competitive with other machines are:

- ✓ The improvement of the saliency ratio makes the SynRM competitive with the asynchronous machine, especially in terms of power factor and power absorbed power.
- ✓ Small and medium-sized drives can have simpler control by using SynRM compared to using the SynRM compared to the vector control of the asynchronous machine. asynchronous machine.
- ✓ The SynRM has stable operation at low speeds and full load unlike an asynchronous motor. unlike an asynchronous motor which can have problems with overheating. overheating.
- ✓ The SynRM has no magnets which is an advantage over the permanent magnet machine in permanent magnet machine in high temperature applications. Therefore, it does not have demagnetization problems.
- ✓ It is very simple to build and very robust.

## II.4. Inverter-SynRM modeling

### II.4.1. Static DC-AC converter

A method for adjusting the electrical energy supply to a specific receiver is called a static converter. The invention of power electronics in the middle of the 20th century allowed for the creation of electrical power converters that did not require revolving gear. The technology of the components used (semiconductors) is constantly evolving [11]:

- Low cost;
- High switched powers
- Ease of control.

**a. Definition of the inverter**

The inverter is a static converter that can convert AC power continuously. Thanks to semiconductors, we may link a voltage—sometimes positive, sometimes negative—to each terminal of the receiver if the input is a direct voltage.

It is therefore feasible to generate an alternating voltage with an average value of zero at the inverter's output by properly sequencing the control of the semiconductors. Depending on whether it is a pulse width modulation control or an alternating one-slot control, this voltage may consist of one or more alternating slots [12].

There are several types of inverters:

- According to the source :
  - Voltage inverters,
  - Current inverters;
- Depending on the number of phases (single-phase, three-phase, etc.),
- Depending on the number of levels (2.3, etc.).

**b. Voltage Inverter Modeling**

The voltage inverter powers the SYNRM can ideally be represented according to (Figure II.8), where Ti and T'i (i = a, b, c) are MOSFET transistors, Si and Si' are the logical commands associated with them such that:

• if Si = 1, the switch Ti is passed and T'i is open,

• if Si = 0, the switch Ti is opened and T'i is passing.

The network-side converter consists of a three-phase diode rectifier and a filter, and the converter on the machine side, and a three-phase voltage inverter.

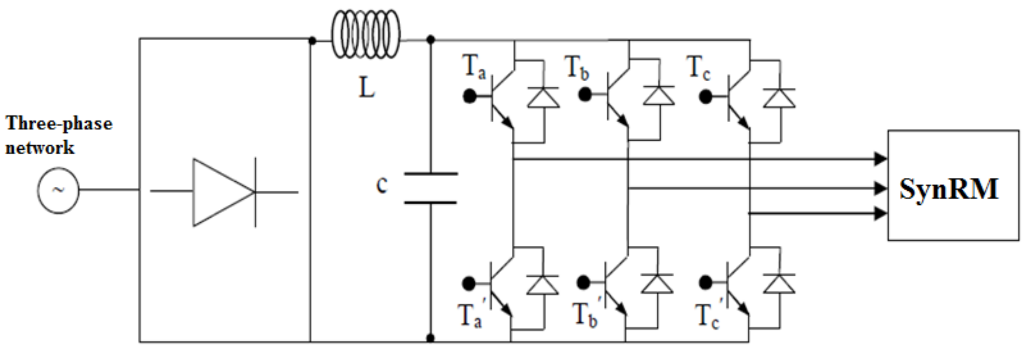



***Figure II.14: Diagram of the association synchronous machine-voltage inverter[9]***

It is believed that the inverter's power supply, which consists of two generators with f.e.m. equal to $U_0/2$ linked to one another via a point designated $n_0$, is a perfect source. Each of the three arms that make up the inverter has two transistors in it.

whose sequence is symmetrical. Recovery diodes shift the transistors. As seen in (Figure II.15), each arm of the inverter can be provided by a switch with two states.

The synchronous machine is connected in a star, $U_0$ is the DC voltage feeding the voltage inverter.

The compound voltages are obtained from the outputs of the inverter [9]:

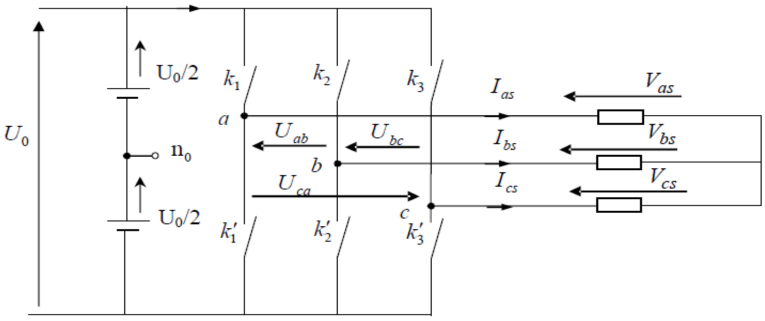



***Figure II.15: Equivalent diagram of the inverter[9]***

The line voltages delivered by the inverter are:

$$U_{ab} = V_{as} - V_{bs} = U_0(S_a - S_b) \tag{II.24}$$

$$U_{bc} = V_{bs} - V_{cs} = U_0(S_b - S_c) \tag{II.25}$$

$$U_{ca} = V_{cs} - V_{as} = U_0(S_c - S_a) \tag{II.26}$$

The voltages Vas, Vbs and Vcs form a balanced three-phase voltage system then:

From (II.24) and (II.26) :

$$V_{as} = \frac{U_0}{3}(2S_a - S_b - S_c) \tag{II.27}$$

From (II.24) and (II.25) :

$$V_{bs} = \frac{U_0}{3}(2S_b - S_a - S_c) \tag{II.28}$$

From (II.27) and (II.28) :

$$V_{cs} = \frac{U_0}{3}(2S_c - S_a - S_b) \tag{II.29}$$

Therefore:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \frac{1}{3}U_0 \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{II.30}$$

In our work, the Pulse Width Modulation (PWM) approach is used to regulate the inverter. It entails applying machine terminal voltages that are chopped at a set frequency and change based on voltage references that are acquired from current regulators. To find the switching and conduction periods of each inverter switch, these voltages are modulated in pulse width using a triangle signal known as a carrier. Each arm has two switches, one of which is in conduction and the other blocked at any given time.

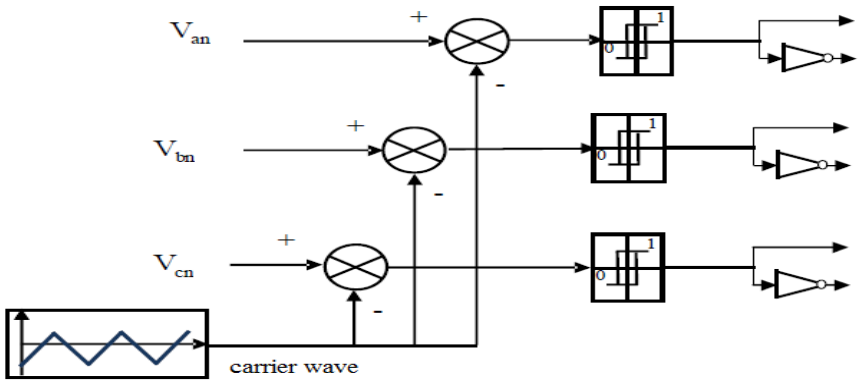



***Figure II.16: Schematic diagram of the triangle-sinusoidal technique[14]***

### II.4.2. Modeling of the Voltage Inverter- SynRM association

These days, alternating current machines and voltage inverters are often utilized in industrial driving systems. First of all, the production of ever-more-efficient static converters has been made feasible by advancements in semiconductor technology. Second, real-time execution of intricate converter control algorithms is now feasible due to the advancement of digital technology, namely the ever-growing usage of signal processors (DSP, or "Digital Signal Processing") [14].

#### a. Filter modeling

In order to enhance the quality of the DC voltage source, a smoothing inductor $L_f$(internal resistance $R$) is placed in series with the inverter's input capacitance $C_f$. This inductance reduces the ripple of current I and safeguards the inverter against the critical growth rate of current. Together, L-C and Cf form a low pass filter 24, which eliminates sudden variations in $U_{dc}$ during switching [10].

To get rid of high frequencies, a low-pass filter (LC) is placed in between the voltage inverter and the rectifier. This is the sample diagram (Figure.II.17).

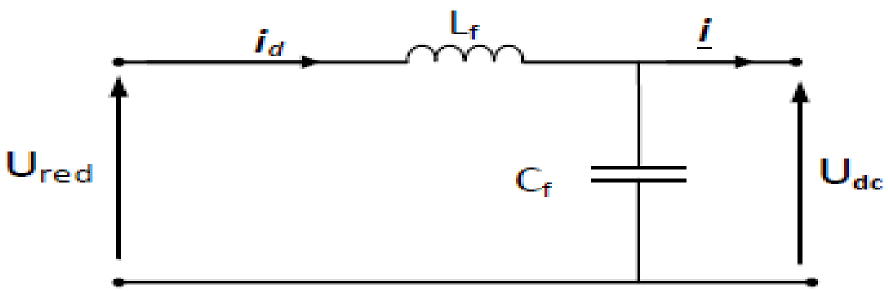



***Figure II.17: Representation of a low-pass filter[10]***

The filter model is defined by the following system of equations;

$$U_d = L_f \frac{d_i d(t)}{dt} + U(t) \qquad (II.31)$$

$$\frac{U(t)}{dt} = \left( \frac{1}{c_f} (id(t) - i(t)) \right) \qquad (II.32)$$

The previous two equations, we give the transfer function F(s) of the filter in the form:

$$f(s) = \frac{U(s)}{U_d(s)} = \frac{1}{1 + \left(\sqrt{L_f c_f s}\right)} \qquad (II.33)$$

The $C_f$ capacitance serves to guarantee the voltage source's character at the inverter's input, supply reactive energy for the device, and absorb any negative current that the load returns. The inductor $L_f$ job is to even out the current id. The cut-off frequency of the filter is of the second order[9].

$$F_c = \frac{1}{\sqrt{L_f c_f}} \qquad (II.34)$$

**b. The voltage inverter**

Following the machine model presentation, we will go over the entire drive system, which includes a three-phase voltage inverter connected to the synchronous machine. So the (figure II.18) illustrates the schematic diagram of this converter-SynRM association [18]:

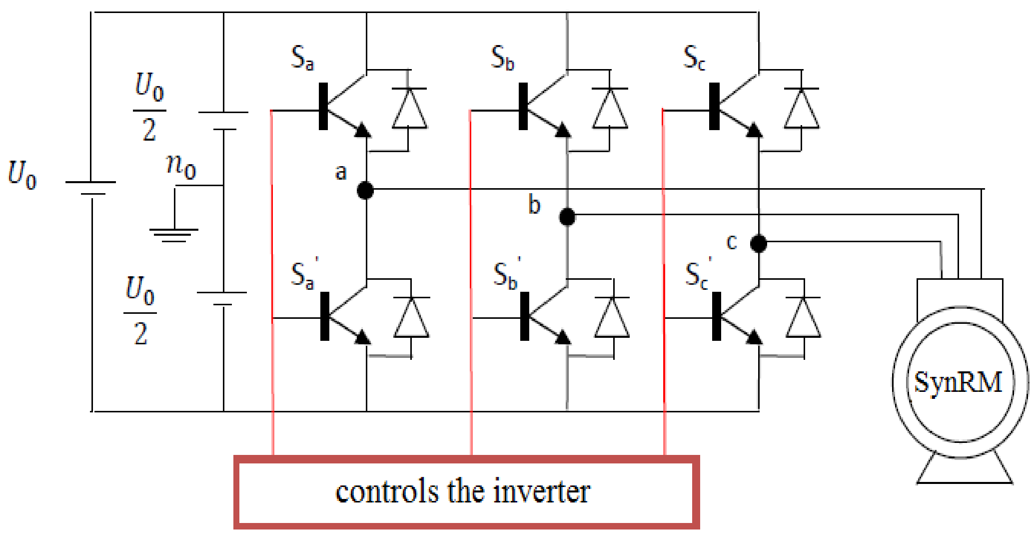



***Figure II.18: Diagram of the SynRM – voltage inverter association[18]***

**II.4.3. SynRM Mathematical Model**

The SynRM version and the induction motor IM are rather comparable, as was previously indicated. The rotor losses from the IM equations are ignored, which makes a difference. The following equations explain the model of a SynRM.

The voltage equations of the SynRM in rotor reference frame are represented as:

$$v_d = R_s i_d - \omega_e L_q i_q + L_d \frac{di_d}{dt} \tag{II.35}$$

$$v_q = R_s i_q - \omega_e L_d i_d + L_q \frac{di_q}{dt} \tag{II.36}$$

where $v_d$ and $v_q$ are the direct and quadrature axes terminal voltages, $i_d$ and $i_q$ the direct and quadrature axes terminal currents.

The electromagnetic torque is stated as:

$$T_e = \frac{3}{2} p\left(L_d - L_q\right) i_d i_q \tag{II.37}$$

The motor dynamic equation is expressed as:

$$T_e = J \frac{d\omega_m}{dt} + f\omega_m + T_L - T_k \tag{II.38}$$

where $T_L$ is the load torque, $J$ the inertia moment of the system rotating parts, $\omega_m$ is the motor mechanical speed, $f$ the viscous friction coefficient, $T_k$ the constant friction load and $p$ the number of pole pairs [12].

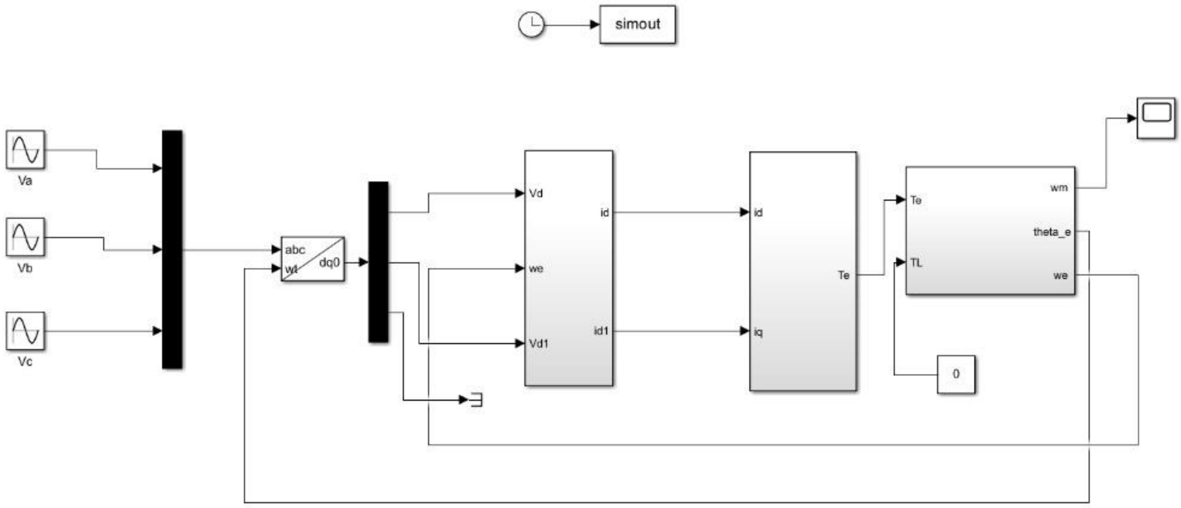



***Figure II.19: SynRM simulation diagram***

## II.5. DC-DC converter modelling

The three basic switching power supply topologies in common use are the buck, boost and buck-boost. These topologies are non-isolated, i.e., the input and output voltages share a common ground. There are, however, isolated derivations of these non-isolated topologies. The power supply topology refers to how the switches, output inductor, and output capacitor are connected.

A DC-DC converter can operate in continuous or discontinuous inductor current mode. Continuous inductor current mode is characterized by current flowing con- tinuously in the inductor during the entire switching cycle in steady-state operation. Discontinuous inductor current mode is characterized by the inductor current being zero for a portion of the switching cycle. It starts at zero, reaches a peak value, and returns to zero during each switching cycle. It is very desirable for a converter to stay in one mode only over its expected operating conditions because the power stage frequency response changes significantly between the two different modes of operation. [19]

The simplified schematics of the basic topologies, buck, boost and buck-boost converter are shown in Figs. II.14 to II.16. In addition to input and output capacitors, the power stage consists of a power metal-oxide semiconductor field-effect transistor (MOSFET), a diode, and an inductor.

The DC-DC converter assumes two states per switching cycle. The ON State is when Q is close and the OFF State is when Q is open. The gate of the switch is driven by a Pulse Modulation Signal (PWM) signal. The duration of the ON state is d $T_s$, where d is the duty cycle of PWM signal and $T_s$ is the switching period.

There are different types of DC-DC converters:

- The step-up (BOOST) in which $V_s>V_e$.
- The step-down (BUCK) in which $V_s<V_e$.

There is also the BUCK-BOOST, which is the mixture between the two precedents:

This work will deals with "Buck".

### II.5.1. Buck converter

Fig. II.20 shows a simplified electric schematic of a basic buck converter. When the switch is on, the power supply is connected to the inductor and the diode is reverse polarized. A current flows in the inductor L, which results in accumulating energy in the inductor. When the transistor turns off, the energy stored in the inductor is output through the diode D. DC-DC buck converter operates as a step down system that will step down the high input voltage to the low output voltage which the magnitude of output voltage is always lower than the input voltage. The objective of this circuit is to produce a purely DC output by adding the LC low pass filter to the basic circuit of this converter. This DC-DC buck converter can be connected to low voltage DC load or battery bank from a high PV array voltage.

The dynamics of the converter in one switching period is represented by the following system[19]:

$$\begin{cases} C_1 \dfrac{dv_{in}(t)}{dt} = i_{in}(t) - di_L(t) \\ C_2 \dfrac{dv_{out}(t)}{dt} = i_L(t) - i_{out}(t) \\ L \dfrac{di_L(t)}{dt} = dv_{in}(t) - dv_{out}(t) - R_i i_L(t) \end{cases} \quad \text{(II.39)}$$

where $i_{in}(t)$, $i_{out}(t)$ and $i_L(t)$ are the input, the output and the inductor current, respectively. $v_{in}(t)$, $v_{out}(t)$ and $v_L(t)$ are the input, the output and the inductor voltgae, respectively.

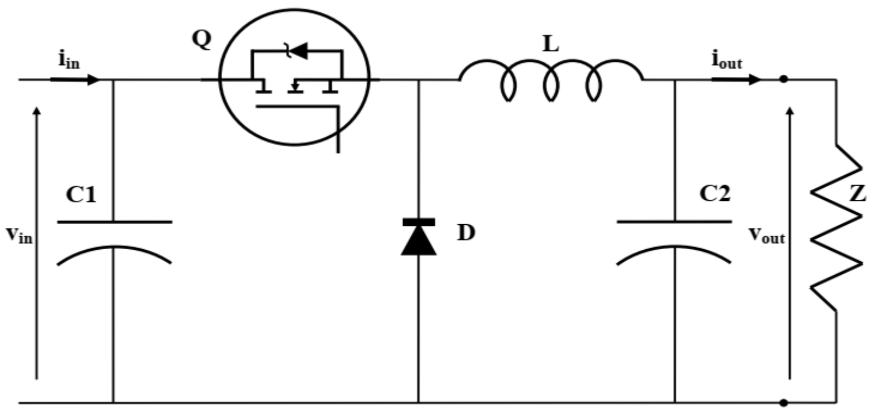



***Figure II.20: Electrical circuit of a buck converter. [19]***

### II.5.2. Boost converter

Another basic switched-mode converter is the boost converter shown in Fig. II.21. This converter converts an input voltage to a higher output voltage. It is also named the step-up converter. The transistor works as a switch which is turned on and off by a pulse-width modulated control voltage. During the on-time of the transistor, the voltage across L is equal to Vin and the inductor current increases linearly. When the transistor is turned off, the inductor current flows through the diode and charges the output capacitor. The function of the boost converter can also be described in terms of energy balance: During the on-phase of the transistor, energy is loaded into the inductor. This energy is then transferred to the output capacitor during the blocking phase of the transistor. The output voltage is always larger than the input voltage. [20]

Even if the transistor is not switched on and off the output capacitor charges via the diode until $V_{out} = V_{in}$. When the transistor is switched the output voltage will increase to higher levels than the input voltage.

The dynamics of the converter in one switching period is represented by the following system[19]:

$$\begin{cases} C_1 \dfrac{dv_{in}(t)}{dt} = i_{in}(t) - i_L(t) \\ C_2 \dfrac{dv_{out}(t)}{dt} = (1-d)i_L(t) - i_{out}(t) \\ L \dfrac{di_L(t)}{dt} = v_{in}(t) - (1-d)v_{out}(t) - R_L i_L(t) \end{cases} \tag{II.40}$$

where $i_{in}(t)$, $i_{out}(t)$ and $i_L(t)$ are the input, the output and the inductor current, respectively. $v_{in}(t)$, $v_{out}(t)$ and $v_L(t)$ are the input, the output and the inductor voltgae, respectively.

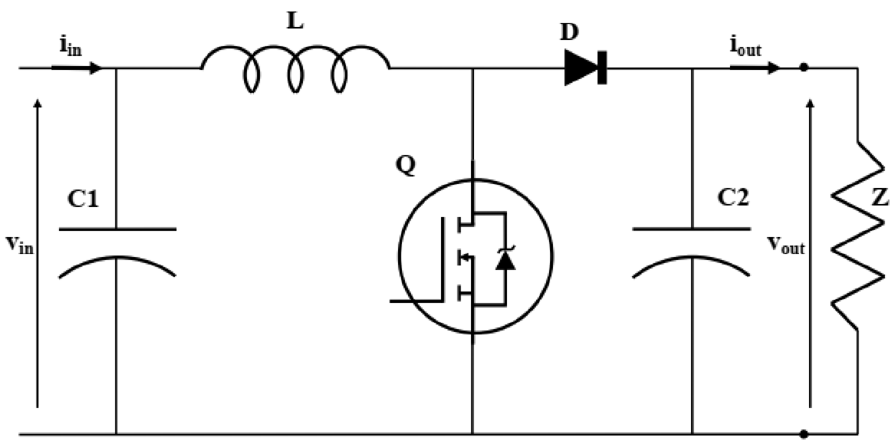



***Figure II.21: Electrical circuit of a boost converter. [19]***

### II.5.3. Buck-boost converter

Fig. II.22 shows a simplified electric schematic of a basic inverting buck-boost converter. During the closing time d $T_s$ of the transistor, the source voltage $V_{in}$ is applied across the inductor L, which results in accumulating energy in the inductor. During the opening period $(1-d)T_s$, the diode D is forward-biased and the voltage of the inductance is applied to the load Z. The current flows anticlockwise through the diode D. Thus, the output voltage will be negative.

The dynamics of the converter in one switching period is represented by the following system[20]:

$$\begin{cases} C_1 \dfrac{dv_{in}(t)}{dt} = i_{in}(t) - d i_L(t) \\ C_2 \dfrac{dv_{out}(t)}{dt} = -(1-d) i_L(t) - i_{out}(t) \\ L \dfrac{di_L(t)}{dt} = d v_{in}(t) + (1-d) v_{out}(t) - R_L i_L(t) \end{cases} \quad \text{(II.41)}$$

where $i_{in}(t)$, $i_{out}(t)$ and $i_L(t)$ are the input, the output and the inductor current, respectively. $v_{in}(t)$, $v_{out}(t)$ and $v_L(t)$ are the input, the output and the inductor voltgae, respectively.

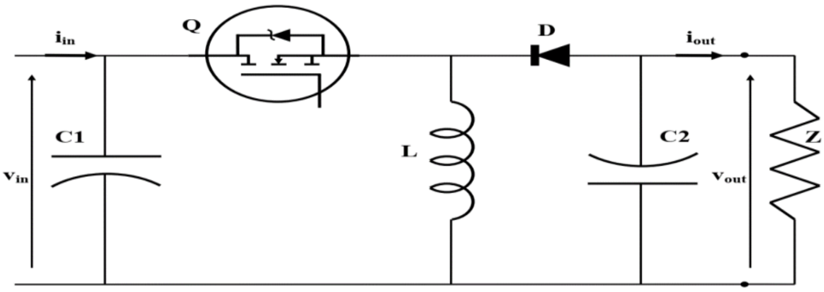



***Figure II.22: Electrical circuit of a buck-boost converter. [20]***

### II.5.4. Design of the buck-boost DC-DC converter

First we design our buck-boost DC-DC converter using MATLAB-SIMULINK.

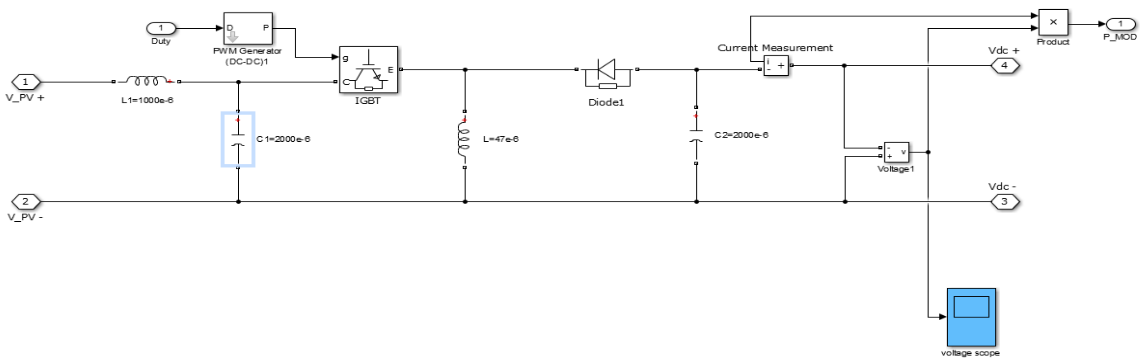



***Figure II.23: SIMULINK model for Buck-boost DC-DC converter.***

## II.6. 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].

$$\dot{X} = A.X + B.U \tag{II.42}$$

With;

$$\dot{X} = A\begin{bmatrix} di_{ds} \\ di_{qs} \\ d\phi_{dr} \\ d\phi_{qr} \end{bmatrix} \tag{II.43}$$

and,

$$X = \begin{bmatrix} di_{ds} \\ di_{qs} \\ d\phi_{dr} \\ d\phi_{qr} \end{bmatrix} \quad and \quad B = \begin{bmatrix} \frac{1}{\delta L_s} & 0 \\ 0 & \frac{1}{\delta L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{II.44}$$

and the control variable matrix U:

$$U = \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} \tag{II.45}$$

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

$$\begin{cases} C_e = \frac{3PM}{2L_r}\Big((\phi_{dr} - i_{qs}) - (\phi_{qr} i_{ds})\Big) \\ \frac{d\Omega_r}{dt} = \frac{1}{j}\Big(C_e - C_r - (K_f \Omega_r)\Big) \end{cases} \tag{II.46}$$

Where;

$$T_r = \frac{L_r}{R_r} \tag{II.47}$$

$$\delta = 1 - \frac{M^2}{L_s L_r} \tag{II.48}$$

$$K_s = \frac{M}{\delta L_s L_r} \tag{II.49}$$

$$\lambda = \frac{R_s}{\delta L_s L_r} + \frac{R_r M^2}{\delta L_s L_r^2} \tag{II.50}$$

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.

$$f(H, Q, P) = 0 \tag{II.51}$$

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:

$$\Delta H_1 = \lambda \frac{V^2}{2.g} \cdot \frac{L}{D} \tag{II.52}$$

$$\Delta H_2 = \varepsilon \frac{V^2}{2.g} = \varepsilon \frac{8Q^2}{\pi^2 D^2 g} \tag{II.53}$$

With;

λ: Coefficient of linear pressure drop;

D: Internal diameter of the pipe [m];

V: Average velocity of the fluid [m/s];

g: Acceleration of gravity [m/s$^2$];

L: Length of the pipe [m];

ε: Coefficient of local pressure drop

Q: Volume flow [$m^3$/h].

Furthermore, a pump is defined by its total head (H), volumetric flow (Q), and power, hydraulic power (HP), given by the relations [3]:

$$H(t) = H_m.\left(\frac{N(t)}{N_m}\right)^2 \tag{II.54}$$

$$Q(t) = Q_m.\left(\frac{N(t)}{N_m}\right) \tag{II.55}$$

$$H_p = \rho * g * Q * H \tag{II.56}$$

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

Hm: Maximum head [m];

N(t): Instantaneous speed [rpm];

Nm: Maximum speed [rpm];

Q(t): Instantaneous 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 $Q_m$** | 0.001 *m3/s* |
| **maximum height $H_m$** | 35 *m* |
| **Nominal speed $N_m$** | 2800 *tr/min* |
| **density of the liquid $\rho$** | 1000 *kg/m3* |
| **acceleration of gravity $g$** | 10 *m/s²* |

***Table II.2: AsM and pump parameters***

## II.7. Conclusion

In this chapter we presented the study and modeling of a voltage inverter controlled by PWM, the choice of this technique allowed us to optimize the operation of the SynRM by eliminating the maximum of low rank harmonics. In addition to modelling of the pumping System to the centrifugal pump.

# Chapter III

## Field Oriented Control and MPPT

## III.1. Introduction

In general, the cost of electricity from the solar array system is more expensivecompared to electricity from the utility grid [13], [14]. For that reason, it is necessary to study carefully the efficiency of the entire solar system to design an efficient system to cover the load demands with lower cost. In the previous chapters, we have seen that the PV array converts solar energy to electric energy. In its V-P characteristic curve, there is a maximum point commonly called the maximum power point (MPP), at which the module operates with maximum efficiency and produces the maximum power output $P_{max}$. In order to obtain an operating point close to this MPP, a controlled DC/DC converter is usually employed to interface the energy flow from the solar module to the load. The main task of MPP seeking and DC/DC converter operation is provided by a control unit (MPPT Controller), where one of the known MPP tracking algorithms is usually implemented. This continuously checks the output (current and voltage) of the PV module.

## III.2. Maximum power point tracking (MPPT)

As was previously noted, the production of photovoltaic systems is greatly impacted by the weather. Because of this, maintaining maximum power generation and achieving high efficiency system performance may be accomplished with maximum power point tracking.

In order to transmit as much power as feasible from the system source to the system load, the MPPTs, which are essentially DC-DC converters, use MPPT algorithms to match the system load impedance with the system source impedance. [16]

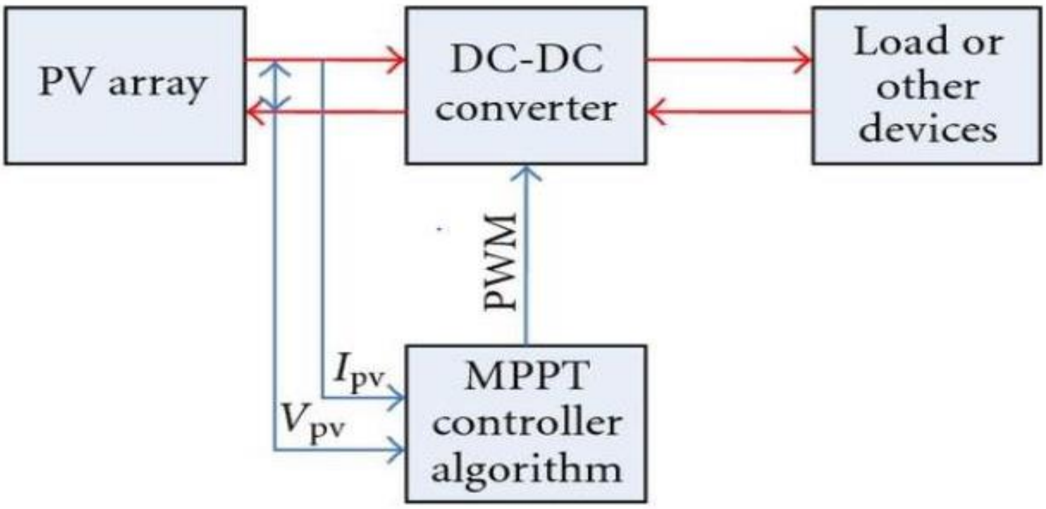



***Figure III.1: MPPT system diagram [17]***

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.

**III.2.1. DC to DC converter**

Power electrical circuits known as DC-DC converters change the voltage level of a DC voltage. In renewable energy systems, a variety of DC to DC converter types are often employed, including boost converters. Figure III.2 illustrates the components of the boost converter: power switch, diode, inductor, capacitors, and load.

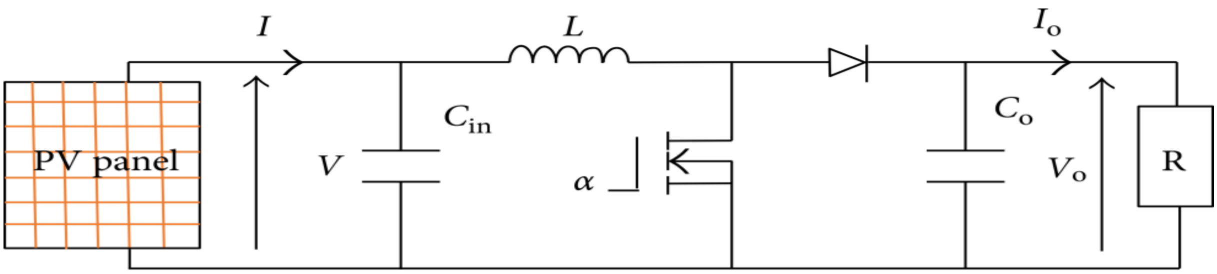



***Figure III.2: Boost Converter in an MPPT based PV System [18]***

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:

$$R = \frac{V_{MPP}}{I_{MPP}} \quad \text{(III.5)}$$

### III.2.2. The P&O algorithm

The diagram in Figure 3 shows the circuit of a boost converter. Here, during the first time interval (αT), the transistor (S) closes and the current in the inductor gradually increases, storing energy until the end of the first period. The transistor is then open for (T-αT) and the inductance (L) across the current sink (IL) produces a voltage that is added to the source voltage (Vi) applied to the load (R) via the diode (D) [17].

To get the maximum power from the solar panel, a maximum power point tracker (MPPT) is used to control the variation of the cell's current-voltage characteristic I(V). MPPT control is therefore an important part of most PV systems [18]-[20]. In this work, a Perturb and Observe (P&O) control is used as the most widely used technique. This is due to its simplicity with few measured parameters. MPPT control based on P&O technology operates according to the following flowchart [21] [22].

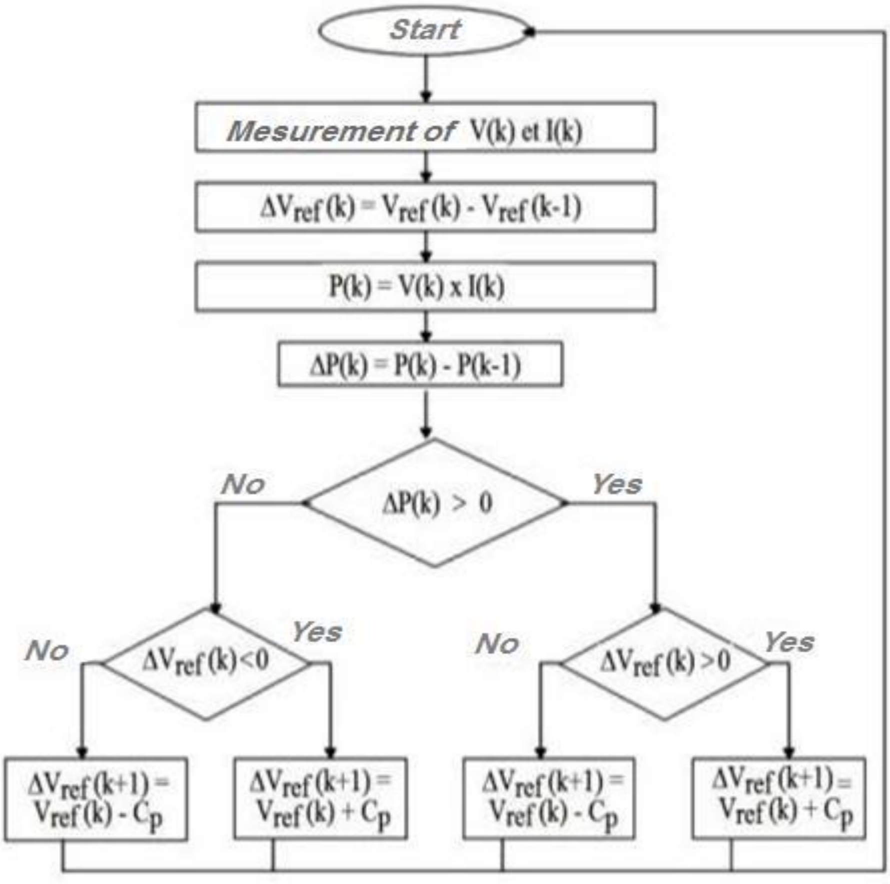



***Figure III.3: Flowchart of the Perturb & Observe MPPT algorithm. [15]***

### III.2.3. Classification of MPPT commands

We can broadly classify MPPT commands according to the type of electronic implementation: analog, digital or mixed. However, it is more interesting to classify them according to the type of research they perform and according to the input parameters of the MPPT command.

#### III.2.3.1. Indirect MPPT

This type of MPPT commands use the existing link between the measured variables ($I_{sc}$ or $V_{oc}$), which can be easily determined, and the approximate position of the MPP.

#### III.2.3.2. Direct MPPT

This type of MPPT control determines the optimum operating point (MPP) from the currents, voltages or powers measured in the system. It can therefore react to unpredictable changes in the operation of the GPV. [22]

### III.2.4. Model of the DC-DC converter with MPPT

DC-DC converter, as described previously, it is used to convert the dc voltage coming from the PV to a different voltage level. It is comprised of dc input voltage coming from PV, boost inductor L, boost capacitor C, controlled switch IGBT/diode, diode D and a capacitor C. The equivalent circuit with the appropriate parameters is shown on the figure below:

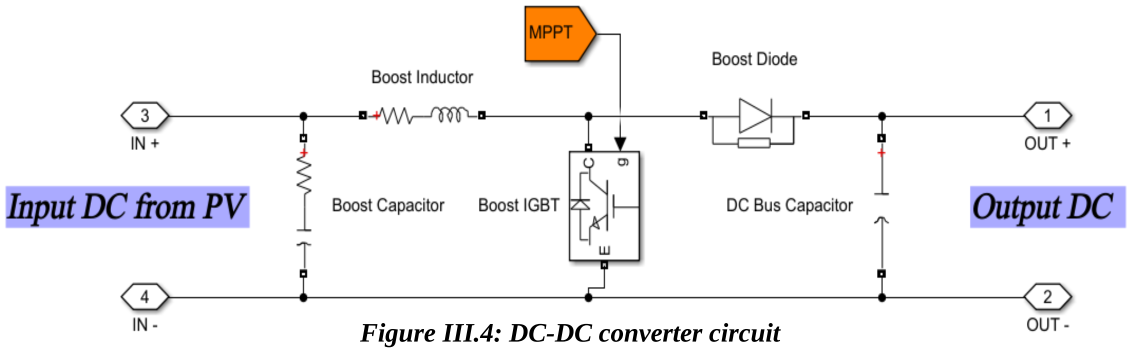



***Figure III.4: DC-DC converter circuit***

DC link capacitor, also called bus link or DC bus, it is used primarily to balance the instantaneous power variations between the input circuit and the output circuit. In a power inverter, a DC link capacitor is placed in parallel with the input to minimize the effects of voltage variations as the load changes. The DC link capacitor also provides a lowimpedance path for ripple currents generated by power switching circuits.

To enhance the performance of the PV module and track its MPP, P&O algorithm was used to control the DC-DC converter. This was accomplished as a MATLAB function written in such a way that follows the algorithm described in the previous section. The IGBT/diode switch is governed by the PWM control signal which is generated by the MPPT controller. The

MPPT controller analyzes $V_{pv}$ and $I_{pv}$; then, it adjusts the duty cycle accordingly so that it can extract maximum power from the PV array. The MPPT controller is shown below:

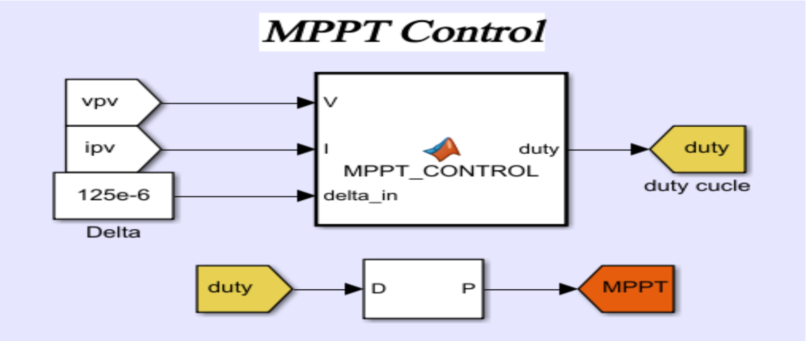



***Figure III.5: MPPT controller***

## III.3. Field Oriented Control of SynRM

The field oriented control has proven that AC motors can be controlled as a separately excited DC motor, thus increasing the efficiency of AC drives. Vector control is suitable for both synchronous and asynchronous motor drives [19].

As shown in Fig. III.6, where the indirect FOC is employed, the torque and flux are indirectly controlled by means of $i_d$, $i_q$ currents control, thus no flux or torque estimation is required. Firstly, $i_q$ reference value is obtained from the speed PI controller, then it is compared to the measured value, and the PI cascade controller acts to eliminate the error $e_{iq}$ . $i_d$ current is controlled as well, and its reference is fixed to a constant value. PI is used within the control loop. id reference value can be generated in other control modes, such as Maximum Torque Per Ampere (MTPA) and/or Flux Weakening (FW) according to the flux reference at the actual operating speed, where optimal drive control is required for a wide speed region.

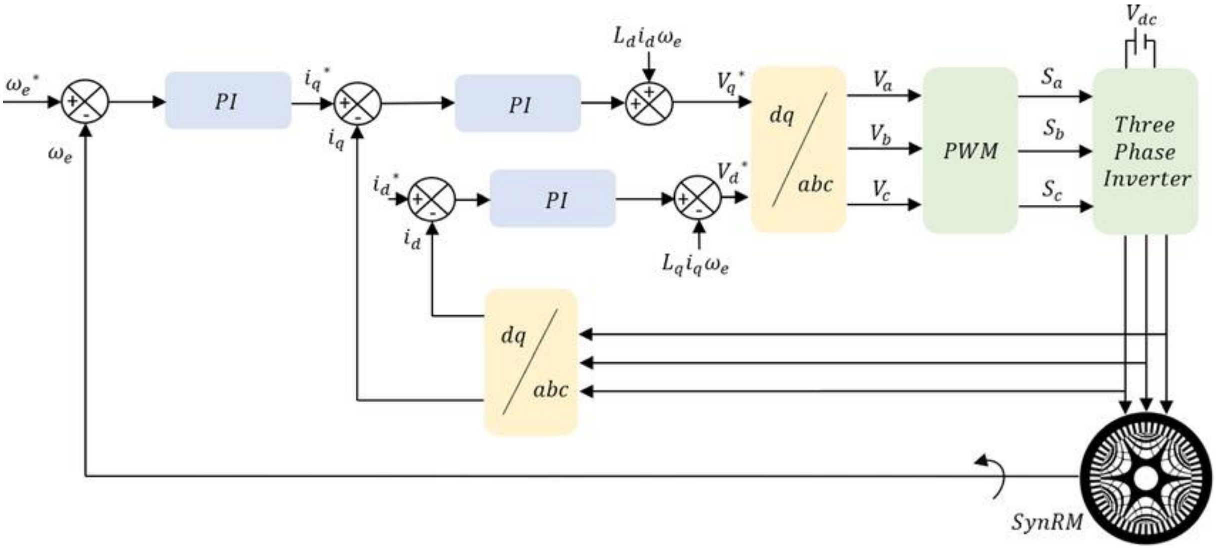



***Figure III.6: Overall field oriented control schematic of Syn-RM.***

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

$$V_d^* = i_d^* R_s - w_e i_q^* L_q \tag{III.6}$$

$$V_q^* = i_q^* R_s - w_e i_d^* L_d \tag{III.7}$$

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, as shown in Fig. III.6.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = M_p^{-1} \begin{bmatrix} V_d^* \\ V_q^* \end{bmatrix} \tag{III.8}$$

$$M_p^{-1} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e & 1 \\ \cos\left(\theta_e - \frac{2\pi}{3}\right) & -\sin\left(\theta_e - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_e + \frac{2\pi}{3}\right) & -\sin\left(\theta_e + \frac{2\pi}{3}\right) & 1 \end{bmatrix} (iii) \tag{III.9}$$

### III.3.1 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:

$$R_s I_d + L_d \frac{dI_d}{\mathrm{dt}} = V_{sd} - wL_d I_q \tag{III.10}$$

$$R_s I_q + L_q \frac{dI_q}{\mathrm{dt}} = V_{sq} - wL_q I_d \tag{III.11}$$

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.3.1.1. Decoupling by compensation

The principle of this decoupling amounts to defining two new control variables $V_{d1}$ and $V_{q1}$ figure (III. 6)

$$V_{sd1} = V_{sd} + e_q \tag{III.12}$$

$$V_{sq1} = V_{sq} + e_d \quad \text{(III.13)}$$

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].

$$e_d = wL_dI_q \quad \text{(III.14)}$$

$$e_q = wL_qI_d \quad \text{(III.15)}$$

$$V_{sd} = V_{sd1} - e_q \quad \text{(III.16)}$$

$$V_{sq} = V_{sq1} - e_d \quad \text{(III.17)}$$

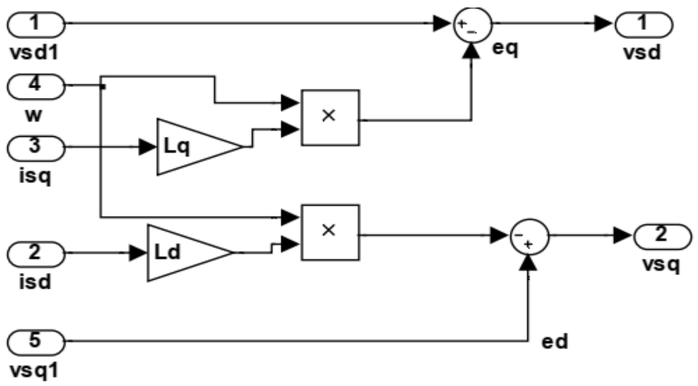


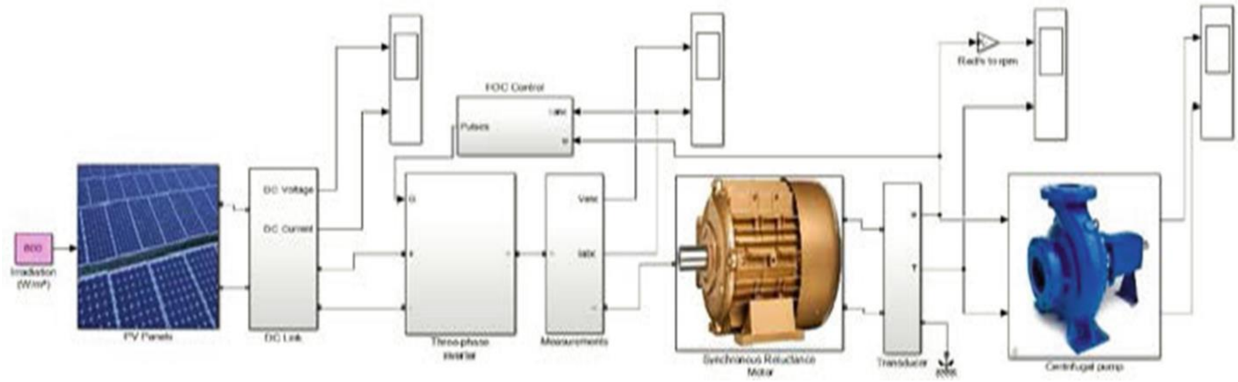

***Figure III. 7: Compensation block scheme***

## III.4. Simulation results

### III.4.1. System Simulation

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

Six panels are joined in series to form the PV array, which was modelled using solar cell blocks. Since Simscape does not include a block for synchronous reluctance motors, a new machine block was created by writing Equations (II.22), (II.23), (II.24), and (II.25). A specially designed block for the centrifugal pump was also created using Eqs. (II.41), (II.42), and (II.43). The system configuration is shown overall in Figure III.8.


FOC Control
Pulses
DC Voltage
DC Current
PV Panels
DC Link
Three-phase inverter
Measurements
Synchronous Reluctance Motor
Transducer
Centrifugal pump
Rad/s to rpm

# General Conclusion

# GENERAL CONCLUSION

An When considering alternative energy sources, installing and maintaining a solar-powered water collecting system is very simple and affordable. For isolated locations with little or no access to energy, this technology offers an alluring option. When compared to conventional energy sources, this technology has the advantages of a smaller carbon footprint, a longer service life, and cheaper operating expenses.

A mathematical model and simulation of a directly coupled water pumping system employing a PV fed synchronous reluctance motor is presented in this paper. The direct coupling is used to simplify the system control and minimize the cost. The SynRM is a cost effective choice as well. Simulation results shows the simplicity and effectiveness of the proposed system.

In order to enhance solar energy harvesting and use the simulated system in real time, more research is being done on managing the MPPT of the PV panels.

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