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Control of the Four Switch Z-source Three Phase Inverter Integrated in a Photovoltaic system

Presented by

Widad SADKI and Wassila FEROUHAT

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Commande d'un onduleur Z-source à quatre interrupteur intégré dans un système Photovoltaïque

Présenté par

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Dedicates

“The Pessimist sees difficulty in every opportunity. The Optimist sees opportunity in every difficulty” Winston Churchill

My humble effort is dedicated to:

My Mother,

The memory of my beloved mother, A strong and gentle soul who taught me to trust in Allah, believe in hard work and that so much could be done with little, "May God have mercy upon your soul"

To The dearest person,

My Father,

I appreciate everything that you have done for me.

*A special dedicate to my sister **Siham**, for helping me to finished this work, and make me an advice, “may god bless you with all his blessing and care”*

*To My dear sisters and my second mother **Imane**, who sacrificed herself for our happiness and our success, “may god bless you”.*

*To my dear brothers **Mohammed** and **Taha Yacine**, I wish a good continuation for their studies.*

*To My college and my best friend **Widad,***

*I also dedicate this dissertation to my friends and all my family who have supported me throughout this process. I will always appreciate all they have done, especially: **Chahrazed**, I wish all the best for you dear*

Wassila

Dedicates

"Everything's possible if you've got enough never" J.K.Rowling

Specially dedicated to...

My humble effort I dedicate to my loving:

Mother & father

Whose affection, love, support, encouragement and prays of day and night make me able to get such success honor.

My sister and brother, and my family;

My colleague in this work, ***Wassila****;*

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Widad

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In th Name of Allah, the Most Merciful, the Most Compassionate, all praise be to Allah, the Lord of the worlds; and prayers and peace be upon Mohamed His servant messenger.

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Wassila & Widad

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List of abbreviations

Acronym	**Meaning**
PV	Photovoltaic
ZSI	Z-Source Inverter
DC	Direct Current
AC	Alternating Current
OTEC	Ocean Thermal Energy Conversion
Si	Silicon
CdS	cadmium sulfide
CdTe	Cadmium Telluride
a-si	Amorphous silicon
CIS	Current Source Inverter
CIGS	Copper Indium Gallium Selenide
VSI	Voltage Source Inverter
CSI	Current Source Inverter
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion
HP-ZSI	High performance Z-Source Inverter
MPPT	Maximum Power Point Tracking
P&O	Perturb And Observe
CE	Change of error
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
RPWM	Random Pulse Width Modulation
FSTPI	Four Switch Three Phase Inverter
THD	Total Harmonic Distortion
SHE	Selective Harmonic Elimination
DSP	Digital Signal Processor

List of symbols

Symbol	**Signification**	**Unit**
E	Energy of photon	(J)
h	Planck's Constant	(Js)
v	Frequency of light	(Hz)
V_{PV}	Output Voltage Of a PV Module	(V)
I_{ph}	Module Photo-Current (Current Source)	(A)
I_d	Diode Current	(A)
I_{rs}	Module Reverse Saturation Current	(A)
R_s	Series Resistance	(Ω)
R_p	Parallel Resistances	(Ω)
I_0	Saturation Current of diode	(A)
N_s	The Number Of Cells Connected In Series	/
N_p	The Number Of Cells Connected In Parallel	/
G	The PV Module Illumination	(W/m^2)
K	Boltzman Constant	(J/K)
A	Ideality Factor	/
T	The Module Operating Temperature	(K)
T_{ref}	The Reference Temperature	(K)
e	Electron charge	(C)
E_g	The Band Gap For Silicon	(eV)
V_{oc}	Open circuit current	(V)
Vin	Input Voltage	(V)
D	The Converter Duty Cycle	/
V_{out}	Output Voltage	(V)
ΔI_L	Current ripple	(A)
ΔV_0	Voltage ripple	(V)
ΔIL	Inductor ripple current	/
f_s	Switching frequency	(Hz)
L	Inductor	(H)
ΔV_c	Capacitor ripple voltage	(V)

C	Capacitor	(F)
C_{min}	Minimum value of the filter capacitance	(F)
CRF	Current ripple factor	/
VRF	Voltage ripple factor	/
V_{out}	Voltage output	(V)
P	Puissance	(W)
V_a,V_b and V_c	Line To Neutral Voltage	(V)
V_{dc}	DC Source Voltage Of Three Phase Inverter	(V)
C_1 and C_2	Two Capacitors Of Z-Source Inverter	(H)
$L_1$and L_2	Two Inductors Of Z-Source Inverter	(F)
q_1, q_2 and q_3	The Ups Switch States	/
M	The Modulation Index	/
T_s	Total Switching Time Period	(sec)
T_0	shoot-through period	(sec)
D_0	The Shoot Through Duty Ratio	/
β	Boosting Factor	/
V_{AC}	the output AC voltage	(V)
$V_{c\ max}$	the maximum voltage across the capacitor	(V)
$D_{0\ max}$	The maximum shoot-through duty ratio.	/
ω	The Radian Frequency	(rad/sec)
V_{an}, V_{bn} and V_{cn}	The output phase voltage	(V)
S_1, S_3 and S_5	Switching variable	/

General Introduction

Producing electricity is one of the main priorities for countries to develop and maintain their independence, exploitation of renewable energy in total electricity generation is eagerly welcomed by all nations. Renewable energy stations are growing at the fastest rate due to increasing global public awareness, all of the hazardous consequences coming from fossil fuels can eliminate by using renewable energy sources. Among these sources, solar energy is one of the most important renewable energy origin and the fastest-growing among them all.

Since solar energy source is available in plenty, its utilization is felt quite promising to accomplish the future energy requirements. Harnessing solar energy for electric power generation is an area of research interest and at present, the emphasis is being given to the cost-effective utilization of these energy sources for quality and reliable power supply. Solar power is environment friendly, noiseless, has a longer life with little maintenance, highly mobile, and portable because of its lightweight [1].

The integration of these renewable energies into the grid poses technical problems, knowing these energies are intermittent: The nature variable of these sources requires adaptation stages that allow the optimal use adapted with the different applications and ensure a transfer quality of the energy produced. So the static converters and their control have become unavoidable in current electrical energy conversion devices.

The Z-source inverter has overcome the problem associated with the conventional voltage source inverter for implementing DC-AC, AC-DC, AC-AC, and DC-DC power conversion. It employs a unique impedance network (circuit) to couple the converter main circuit to the power source, thus providing unique features that cannot be obtainable in a conventional voltage source inverter.

The four-switch three-phase inverter(FSTPI) reduces harmonics, electromagnetic interference noise, and low common-mode noise, it can be used to feed the adjustable induction motor drive system and it has better performance and results as compared to the conventional VSI this new approach has been implemented to fuel cell systems for boosting and inverting the DC voltage into AC voltage. FSTPI is also implementable to a grid-connected PV system, which is transformerless and has a low cost.

This work is dedicated to studying the performance and the efficiency of the new topology that was inspired by combining both Z-source inverter and FSTPI.

This thesis is organized as follow:

- ❖ The first chapter summarized the background study and the current status of renewable energies, mainly focusing on photovoltaic solar energy, we also provided some General Information on Z-source converters and their topologies.

- ❖ The second chapter is divided into two parts, first part focuses on providing info regarding photovoltaic panels, their mathematical model, second part, covers the converter dc/dc and the MPPT control techniques. In addition, the chapter discusses the characteristic of the SOLKAR 36 W PV module using MATLAB/Simulink.

- ❖ The third chapter provides a deep study of the Z-source inverter and its advantages; we also explain the working principle of the FSTPI, its control strategies, and design it using MATLAB/Simulink.

- ❖ The fourth chapter presents the final results and analysis of the global model of the PV array and the FSTP Z-source Inverter connected to the grid using SVPWM.

- ❖ Finally, the general conclusion sum up the consequence of this project for control of the FSTP Z-source inverter applied to a photovoltaic system and the grid.

CHAPTER I:

Current Status

I.1 Introduction:

The increasing concern for the environment and resources has motivated the world towards rationalizing the use of conventional energy sources and exploring the non-conventional energy sources to meet the ever-increasing energy demand. A number of renewable energy sources like solar, hydro, wind, bio, geothermal, etc, are in trend for electric power generation.

Since solar energy source is available in plenty, its utilization is felt quiet promising to accomplish the future energy requirements. Harnessing solar energy for electric power generation is an area of research interest and at present, the emphasis is being given to the cost-effective utilization of these energy sources for quality and reliable power supply.

Now-a-days, PV energy has attracted interest as a next generation energy source capable of solving the Problems of global warming and energy exhaustion caused by increasing energy consumption.

In this chapter we shall introduce the different kinds of renewable energy and mainly focusing on the photovoltaic solar energy, which will represent the input to our Z-source inverter. We will also study the different types of inverters and their applications.

I.2 Renewable energy:

I.2.1 Definition:

Renewable resources are energies with unlimited resources and continually replenished, include solar energy, wind, falling water, the heat of the earth (geothermal), plant materials (biomass), waves, ocean currents, temperature differences in the oceans and the energy of the tides. Renewable energy technologies produce power, heat or mechanical energy by converting those resources either to electricity or to motive power [2].

I.2.2 The different types of renewable energy:

I.2.2.1 Solar energy:

Sunlight is one of our planet’s most abundant and freely available energy resources [3]. It is usually produced using photovoltaic cells that capture sunlight and turn it into electricity [...]. Solar power has now become affordable enough to be used for domestic purposes including garden lighting, although it is also used on a larger scale to power entire neighborhoods [4].

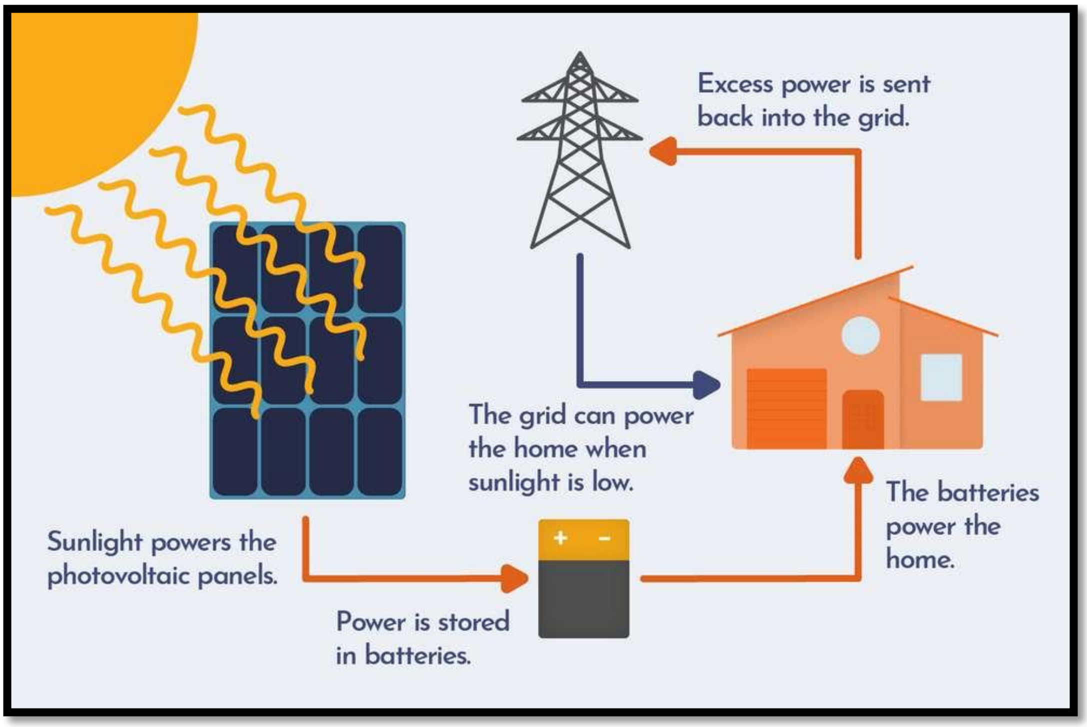


Figure I.1: Solar energy resources [5].

I.2.2.2 Wind energy:

Wind is a plentiful source of clean energy, particularly suited to offshore and higher altitude sites, wind energy uses the power of the flow of air around the world to push turbine's blades, causing them to rotate and turn the turbine connected to them. That changes the kinetic energy to rotational energy, by moving a shaft which is connected to a generator, and thereby producing electrical energy through electromagnetism [6].

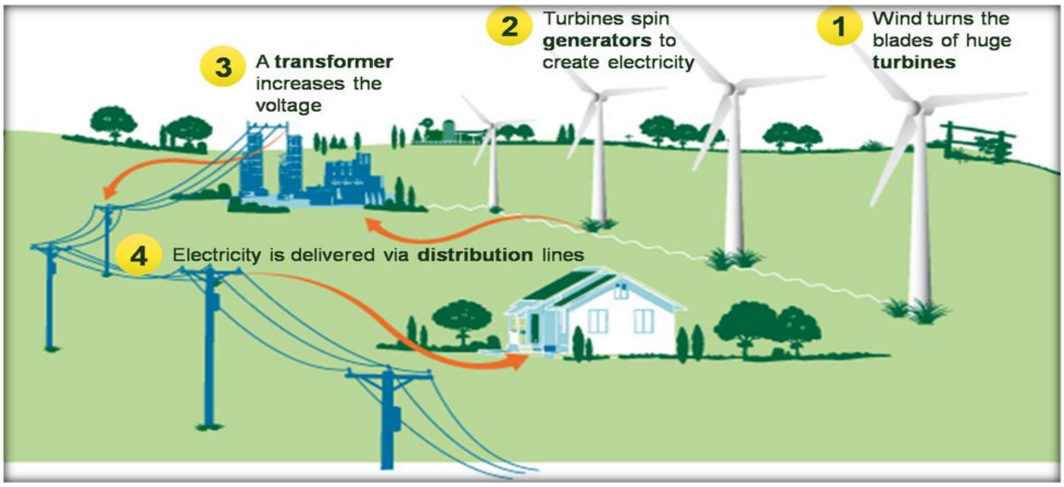


Figure I.2: Wind energy resources [7].

1.2.2.3 Hydropower:

Also known as hydroelectric power, this type of green energy uses the flow of water in rivers, streams, or by building a dam or barrier, a large reservoir can be used to create a controlled flow of water that will drive a turbine, generating electricity. Hydropower can even work on a small scale using the flow of water through pipes in the home or can come from evaporation, rainfall or the tides in the oceans [4].

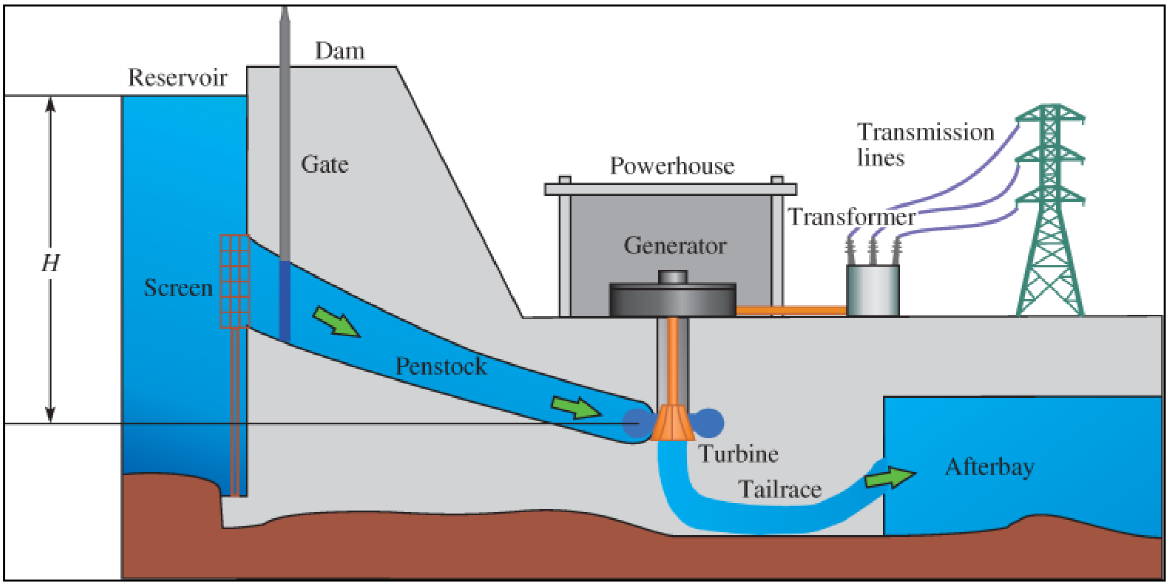


Figure I.3: Hydropower resources [8].

I.2.2.4. Geothermal Energy:

Geothermal energy refers to the energy derived from the heat contained in the earth's crust and in the surface layers of the earth, geothermal energy can be used to heat homes directly or to generate electricity. We distinguish usually two forms of geothermal energy with surface geothermal energy and deep geothermal energy [9].

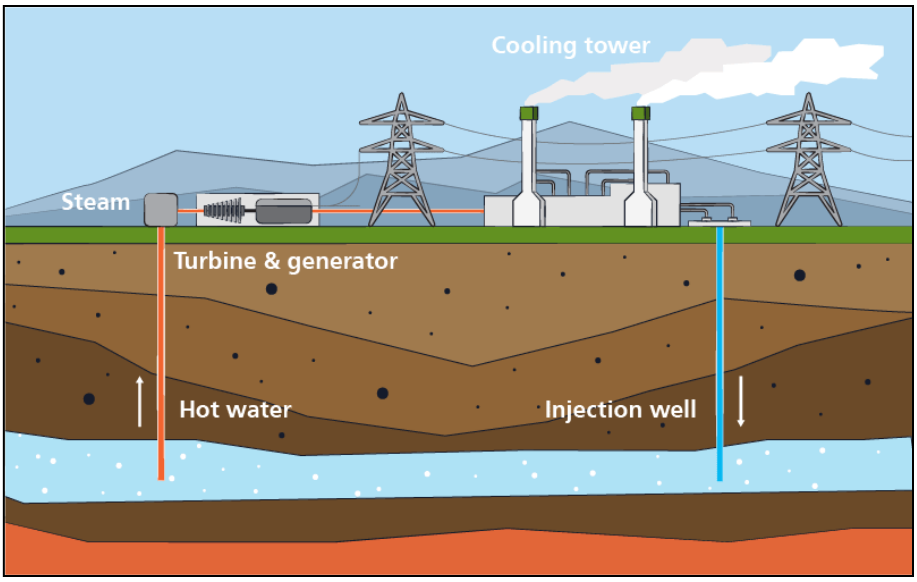


Figure I.4: Geothermal energy resources [10].

I.2.2.5. Marine energy:

Marine energies depend on the natural resources of sea and ocean waters. They make it possible to produce electricity thanks to the natural energy flows of currents and tides, and to marine matter, exploited in different types of installations Water largely covers our planet, mainly through the seas and the oceans. It is therefore an important source of energy, still little exploited today [9].

The three most well-known generating technologies for deriving electrical power from the ocean are:

- Tidal Energy
- Wave Energy
- Ocean Thermal Energy Conversion (OTEC)

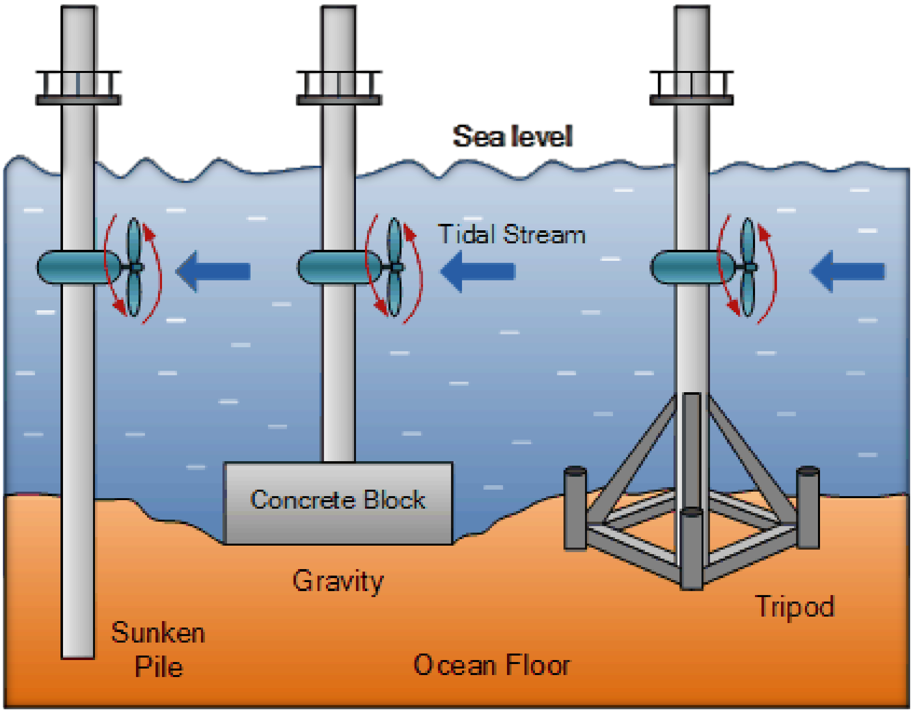


Figure I.5: marine energy resources [11].

I.2.2.6. Bioenergy:

This is the conversion of solid fuel made from plant materials into electricity. Although fundamentally, biomass involves burning organic materials to produce electricity, and nowadays this is a much cleaner, more energy-efficient process. By converting agricultural, industrial and domestic waste into solid, liquid and gas fuel, biomass generates power at a much lower economic and environmental cost [3].

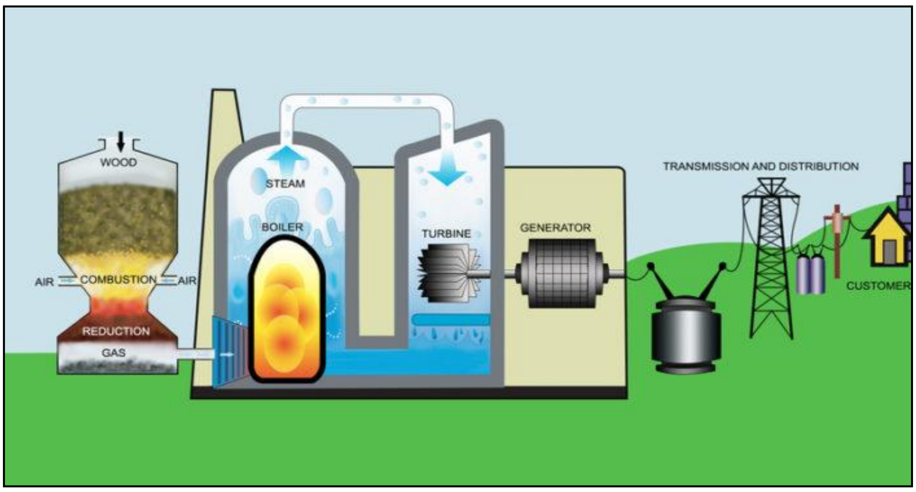


Figure I.6: Bioenergy energy resources [12].

I.3 Photovoltaic solar energy:

I.3.1. Introduction:

Photovoltaic solar energy is a clean, renewable source of energy that uses solar radiation to produce electricity. It is based on the so-called photoelectric effect, by which certain materials are able to absorb photons (light particles) and release electrons, generating an electric current. [13].

A solar cell is an electronic component that generates an electric current when exposed to the flax, (this effect is called the photovoltaic effect) The current obtained is a direct current and the voltage obtained is of the order of 0.5 V. photovoltaic cells are made of silicon-based semiconductors (Si), cadmium sulfide (CdS) or cadmium telluride (CdTe).

Photovoltaic modules or panels can be a safe, reliable, maintenance-free and environmentally friendly source of energy for a long time. Most modules on the market today have a warranty of more than 20 years and will continue to maintain good performance thereafter.

Millions of systems have been installed around the world, powers different ranges ranging from a fraction of a watt to several megawatts. For many applications, solar electric systems are not only profitable, but they can also be the cheapest option. [6]

I.3.2. Historical:

Photos = light.

Voltaic = electricity.

- The photovoltaic effect was discovered by the French physicist Antoine Becquerel in 1839.
- The first selenium solar cell was built in 1883 by the American Charles Fritts with a yield of 1%.
- Albert Einstein explained this effect in 1904 and received the Noble Prize in 1921.

- Bell laboratories (Charpin, Pearson and Price) presented the first silicon cell on April 25, 1954 with a yield of 4%.
- First photovoltaic use in an American artificial satellite Vanguard 1 in 1958 with an efficiency of 9% and a power of 0.1W.
- First land application in a lighthouse in Japan in 1963 with a power of 242W.
- First photovoltaic house, solar one, built at the University of Delaware in the USA in 1973.
- First installation connected to the electricity grid in Europe (TISO in Switzerland) [14].

I.3.3. Solar radiation:

Solar radiation is the radiation, or energy we get from the sun. It is also known as short-wave radiation. Solar radiation comes in many forms, such as visible light, radio waves, heat (infrared), x-rays, and ultraviolet rays. Measurements for solar radiation are higher on clear, sunny day and usually low on cloudy days. When the sun is down, or there are heavy clouds blocking the sun, solar radiation is measured at zero [15].

I.3.3.1 Radiation components:

The solar radiation that reaches the earth is divided into three main components:

- **Direct radiation:**

This is solar energy that directly reaches the earth's surface from the sun. It is defined as direct solar energy per unit area of a plane perpendicular to a direct solar beam.

- **Diffuse radiation:**

This is solar energy that reaches the earth's surface from all directions of the sky via diffusion and reflection by way of an atmospheric component. It is defined as the diffused solar energy arriving per unit area on a horizontal plane.

- **Global radiation:**

This is the total solar energy that reaches the earth's surface from all directions of the sky. It is defined as the total solar energy arriving per unit area on a horizontal plane.

- **Reflected radiation:**

This is solar energy that reaches the earth's surface and is then reflected upward. It is defined as the total upward solar energy arriving per unit area on a horizontal plane.

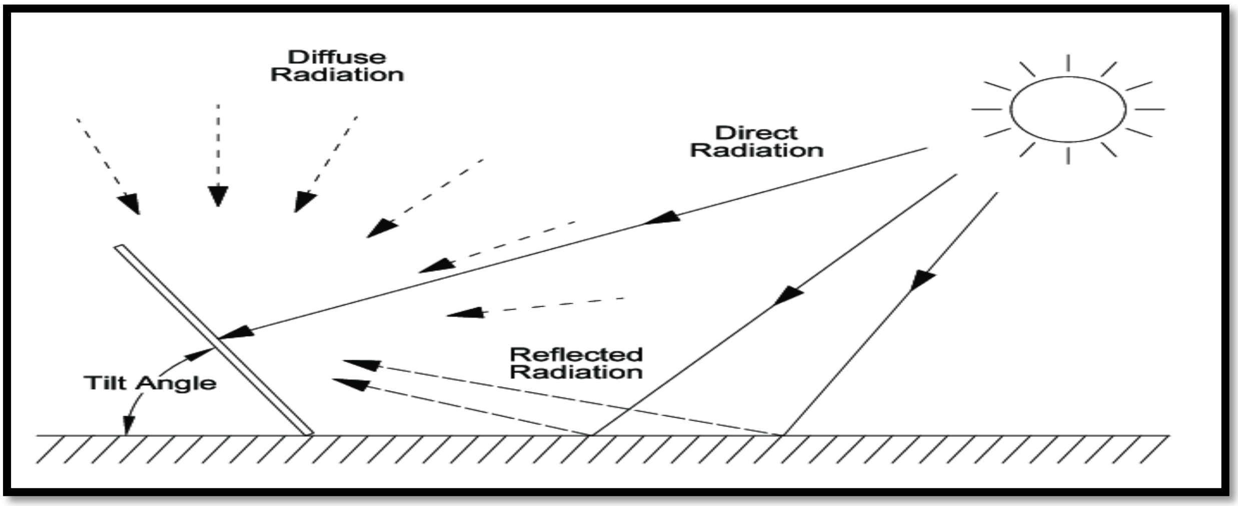


Figure I.8: Solar radiation types [15].

I.3.4. Principal of photoelectrique conversion:

The photovoltaic effect a played in solar cells allows the light energy of the sun's rays to be directly converted into electricity through the production and transportation of positive and negative electric charges in semiconductor under the effect of light. This material has two parts, one with an excess of electrons and the other with an electron deficit, called n-type doped (by Bor) and p-type doped (by phosphore), respectively. When the first is brought into contact with the second, the electrons in excess in the material n diffuse in the material p. The initially n-doped zone becomes positively charged, and the initially p-doped zone negatively charged.

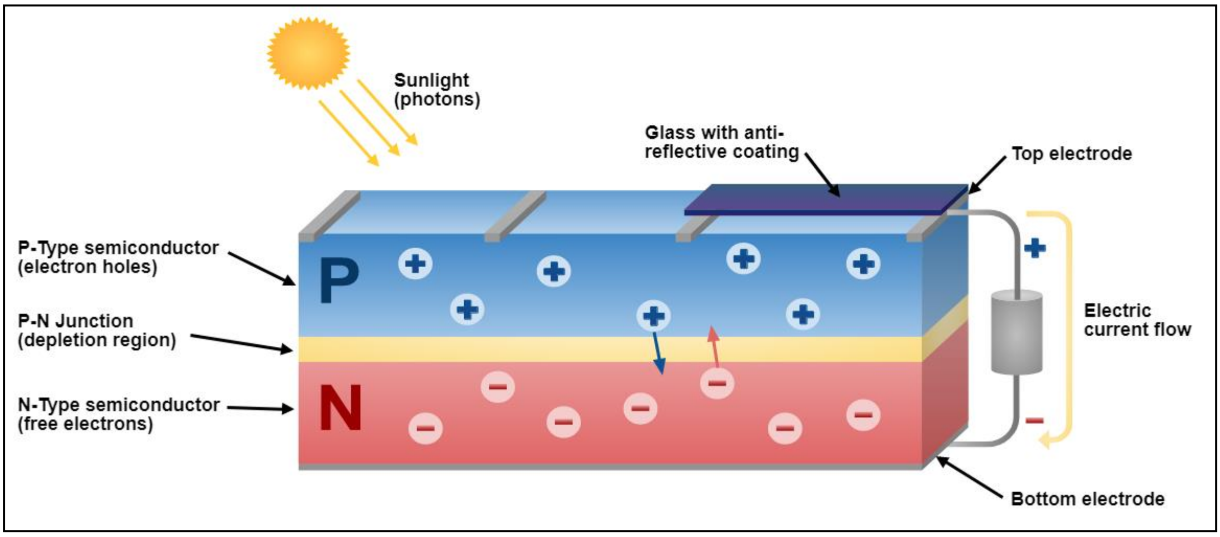


Figure I.9: Principale of photoelectrique conversion

I.3.5 Photovoltaic cell:

A photovoltaic (PV) cell is an energy harvesting technology that converts solar energy into useful electricity through a process called the photovoltaic effect. There are several different types of PV cells which all use semiconductors to interact with incoming photons from the Sun in order to generate an electric current [17]. It is a form of photoelectric cell, defined as a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light. Solar cells are the building blocks of photovoltaic modules, otherwise known as solar panels [18].

Figure I.10: Photovoltaic cell

The operation of a photovoltaic (PV) cell requires three basic attributes:

- The absorption of light, generating either electron-hole pairs or excitons.
- The separation of charge carriers of opposite types.
- The separate extraction of those carriers to an external circuit [19].

I.3.5.1 Photovoltaic cell technologies:

The different existing PV cell technologies are:

- **1st technology based on crystalline silicon:**

The first generation cells are based on a single P-N junction which uses generally silicon in crystalline form as a semiconductor material. The method of production based on silicon wafers is very energy-intensive and therefore very expensive. It also requires a high level of pure silicon. This technology uses monocrystalline and poly crystalline silicon base cells [20].

- **2nd generation thin-film technology:**

This model of a photovoltaic cell is made of silicon or other materials. Thin-film cells are what some call second-generation cells because they historically follow on from relatively thick crystalline silicon cells. There are several types of thin film cells, namely [21]:

- Amorphous silicon (a-si).
- Cadmium tellurium (CdTe).
- Copper / Indium / Selenium or Copper / Indium / Gallium / Selenium (CIS or CIGS)

- **3rd generation technology: multi-junction concentration**

They are made up of organic molecules combining flexibility and lightness. These technologies are still in the research and development stage. There are three types of cells [20]:

- Multilayer cell.
- Organic cell.
- Concentration cell

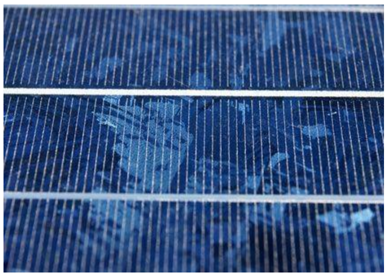
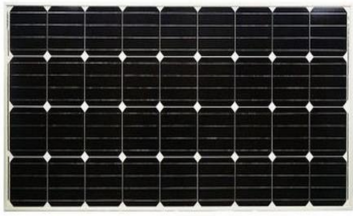
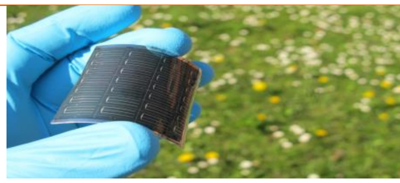
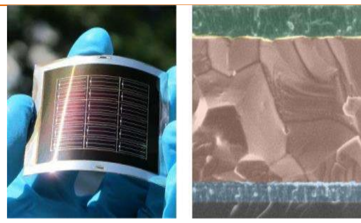
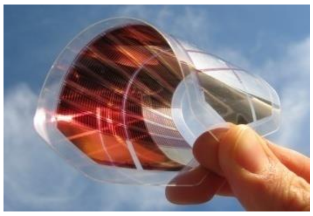
Cell type	yield	advantages	disadvantages	drawing
Silicon polycrystalline	11-15%	Good yield for module	High manufacturing cost, loss of material during manufacturing	
Silicon monocrystalline	13-17%	Good yield for a cell	High manufacturing cost, loss of material during manufacturing	
Amorphous silicon	5-6%	Easy to make	Poor performance	
CdTe	7-11%	Absorbs 90% of incident photons	Cadmium Very polluting	
CIGS	20%	Adjustable gap energy 99% of absorbed photons	Lack of raw material	
Organic cells	5%	Low cost of flexible manufacturing	Yield still too low	

Table I.1: type of PV

I.3.6 Photovoltaic systems:

I.3.6.1 Stand-alone systems [22]:

Depends only on a single source of energy, as in our case Stand-alone photovoltaic system which is under solar energy only. It is frequently used in isolated places, for example in cabins where their connection to the distribution network is very far. Solar energy is only available during the day, and in order to adapt production to demand, this system requires storage elements, therefore accumulators.

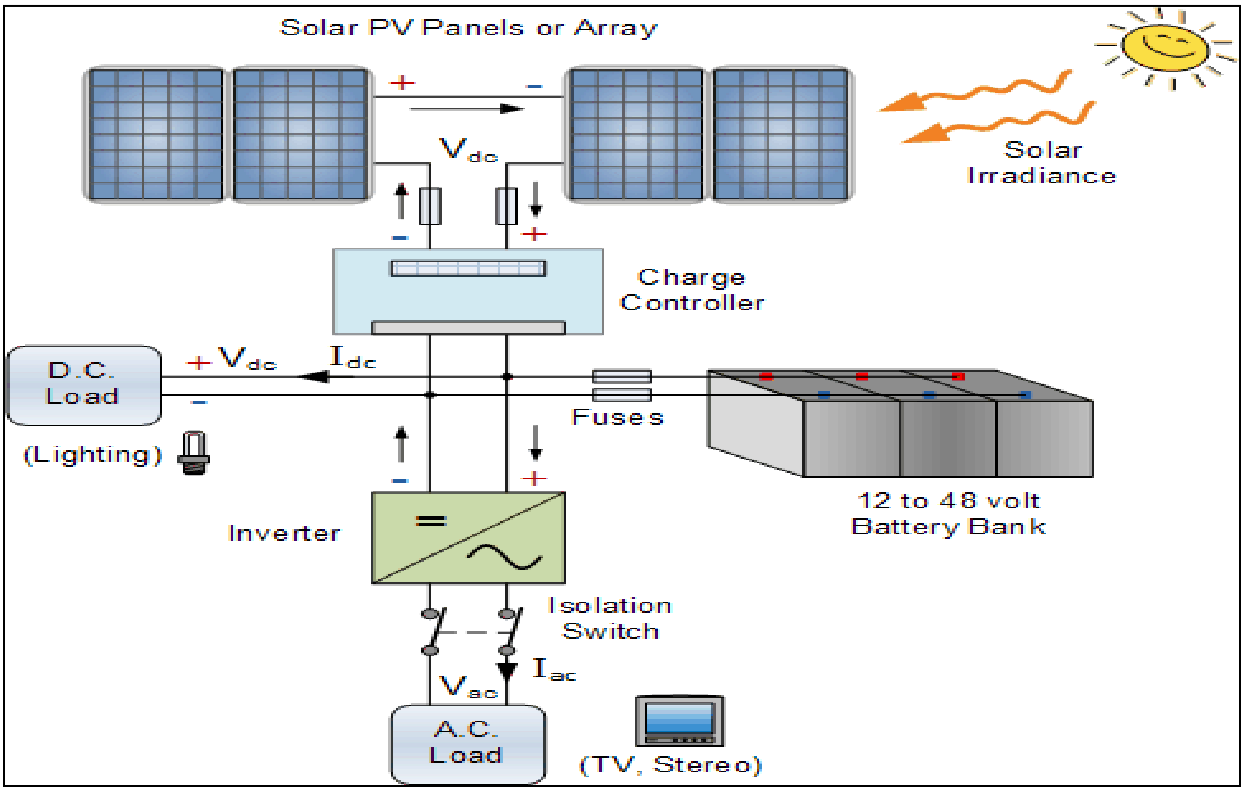


Figure I.11: Stand-alone systems

I.3.6.2 Grid-connected systems [23]:

In this case of a system, we are talking more about energy storage, so it is totally injected into the electrical network, which means no energy storage, and so absence of accumulator batteries which reduces the cost of installation, thus reducing the complexity of the operation, and this is why in terms of investment and operation is the most advantageous. Such a system is installed on a site connected to the network, generally on homes or businesses that want to use a form of renewable energy and benefit from good sunlight.

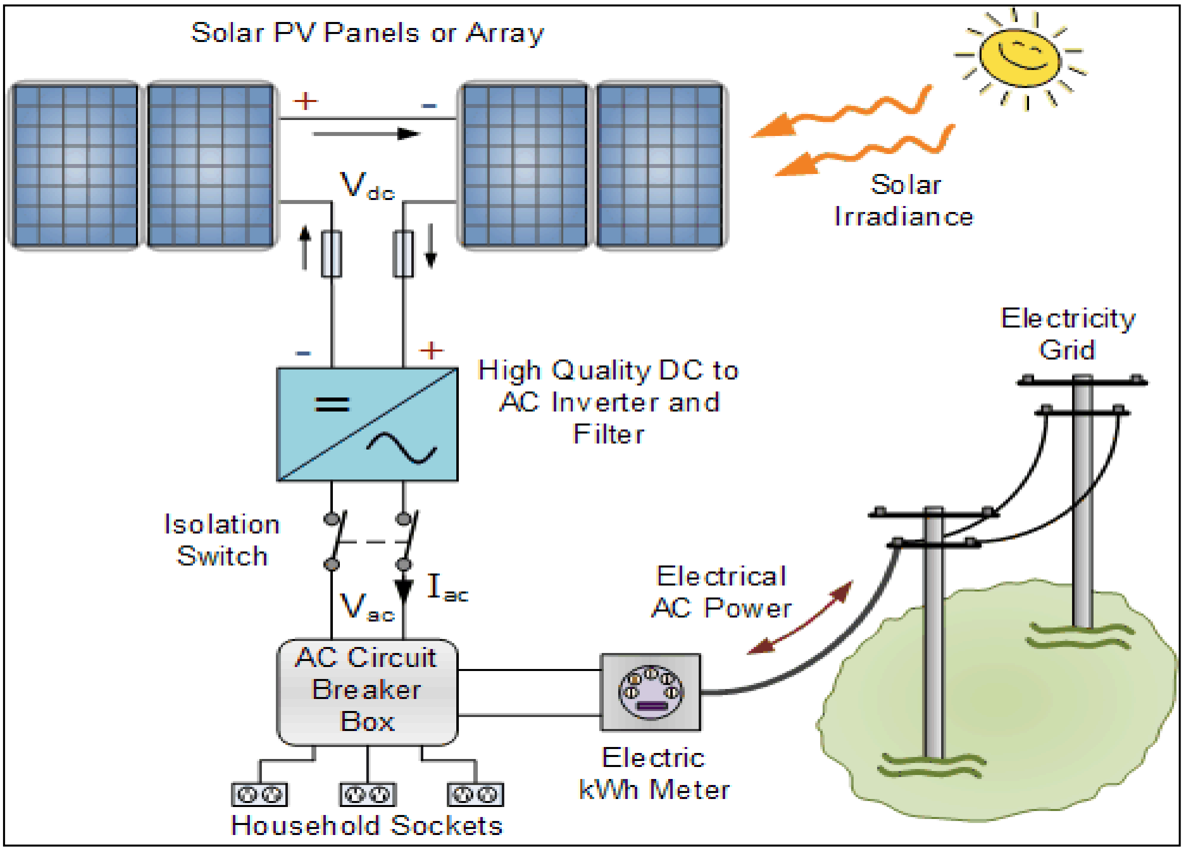


Figure I.12: Grid-connected systems

I.3.6.3 Hybrid Systems [23]:

As the name suggests, it is a combination of at least two different types of energy, one of which is photovoltaic. It contains energy storage accumulator batteries. This other source can be a group generator or a wind turbine. When it comes to cloudy periods or the batteries are low, the generator will take care of the task. If these periods are windy, it is the wind turbine that takes over and charges these accumulators. Such a system may be suitable for a residential or commercial building not connected to the network, most systems.

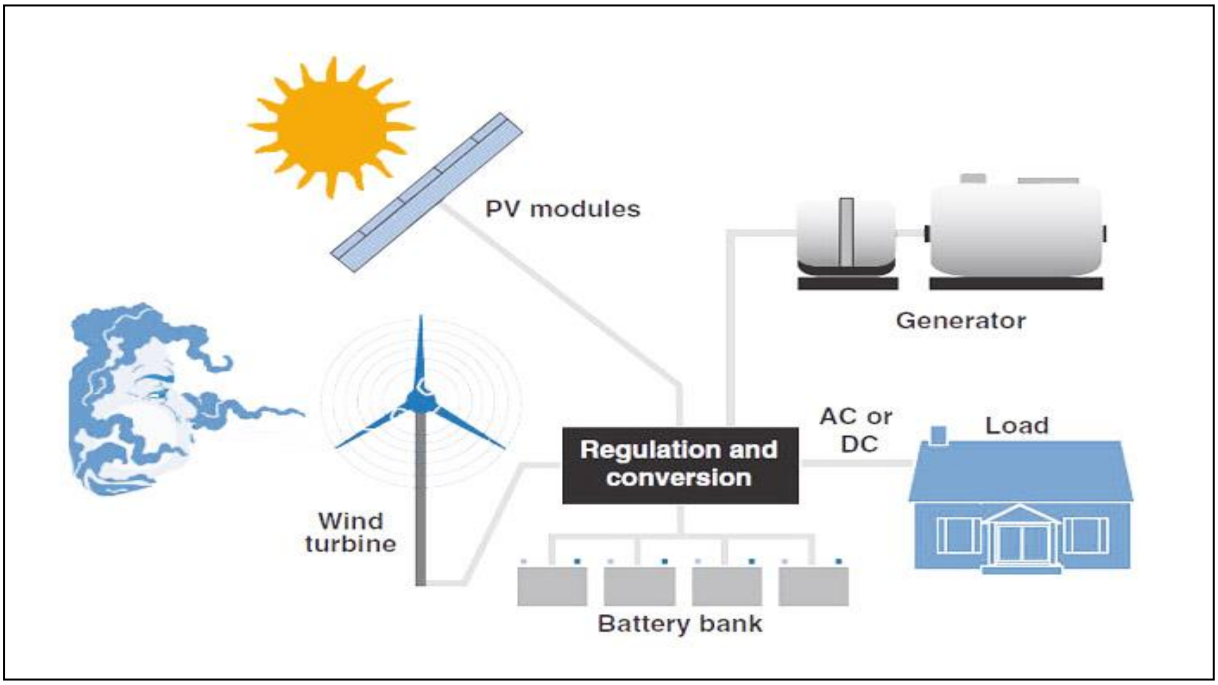


Figure I.13: Hybrid Systems

I.3.7 Advantages and Disadvantages of Photovoltaic Energy [24]:

Advantage	Disadvantages
Renewable, inexhaustible and not toxic.	Energy is a function of sunlight.
They are extremely reliable	The pollution that is generated during the manufacture of the panels photovoltaic
The lifespan of photovoltaic panels is very long (25years)	The production cost is very high
Solar energy is available everywhere	Low conversion efficiency

Table I.2: advantage and disadvantage of PV energy

I.4 General Information on Z-source converters:

I.4.1 Introduction:

The voltage of the photovoltaic generator varies with temperature and radiation, the voltage supplied by the battery drops sharply with the current, while the voltage of the wind generator varies with the speed of the wind. However, the traditional voltage inverter coupled to the grid cannot operate correctly in the presence of low DC voltages and often requires the use of an additional dc-dc converter, generally of the boost type. In this situation two separate commands are essential. One to increase the DC voltage and the other to order the inverter.

Recently, z-source converter has been presented as a competitive alternative to overcome the limitation of the traditional voltage inverter.

I.4.2 Converter:

The task of a power converter is to process and control the flow of electrical energy by supplying voltages and currents in a form that is optimally suited for user loads.

Energy conversions were initially achieved using electromechanical converters (which were mainly rotating machines). Today, with the development and the massive production of power semiconductors, static power converters are used in numerous application domains and especially in particle accelerators. Their weight and volume are smaller and their static and dynamic performances are better.

A static converter is composed of a set of electrical components building a meshed network that acts as a linking, adapting, or transforming stage between two sources, generally between a generator and a load (figure I.14) [25].

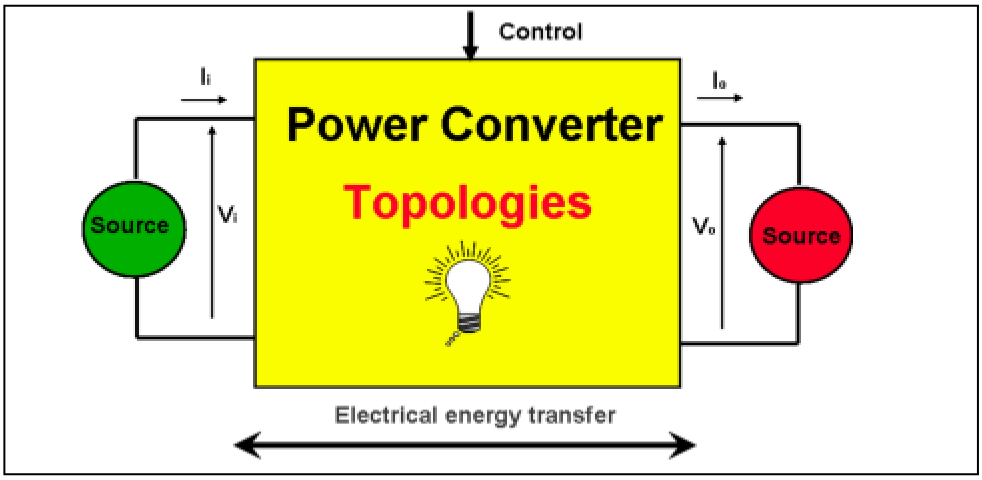


Figure I.14: Definition of a power converter

There are several types of converters based on the wave form of source input and output and these falls into four categories namely [26]:

- The AC to DC converter known as the rectifier.

- The AC to AC converter known as the changer or transformer of cycloconverter.
- The DC to AC converter known as the inverter.
- The DC to DC converter known as the chopper (buck, boost or buck-boost).

I.4.3 Different Types of Inverters [27]:

Inverters are classified into many different categories based on the applied input source, connection wise, output voltage wise etc. In this part, we will see some of the categories.

I.4.3.1 Input Source Wise Classification:

The inverter can be defined as the device which converts DC input supply into AC output where input may be a voltage source or current source. Inverters are mainly classified into two main categories.

- **Voltage Source Inverter (VSI):**

The inverter is known as voltage source inverter when the input of the inverter is a constant DC voltage source. The input to the voltage source inverter has a stiff DC voltage source […] VSI are assumed to be supplied with ideal voltage sources (very low impedance sources). The AC output voltage is completely determined by the states of switching devices in the inverter and the applied DC source.

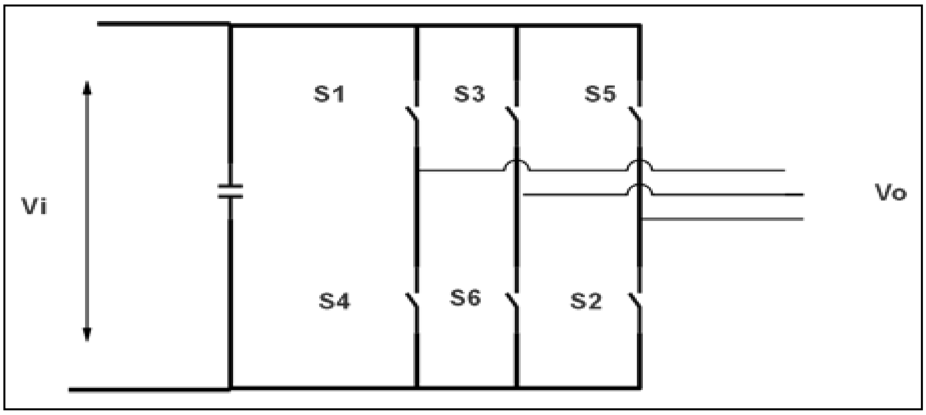


Figure I.15: Voltage Source Inverter

- **Current Source Inverter (CSI):**

The inverter is known as current source inverter when the input of the inverter is a constant DC current source .This type of inverters is used in the medium voltage industrial application, where high-quality current waveforms are compulsory. But CSIs are not popular.

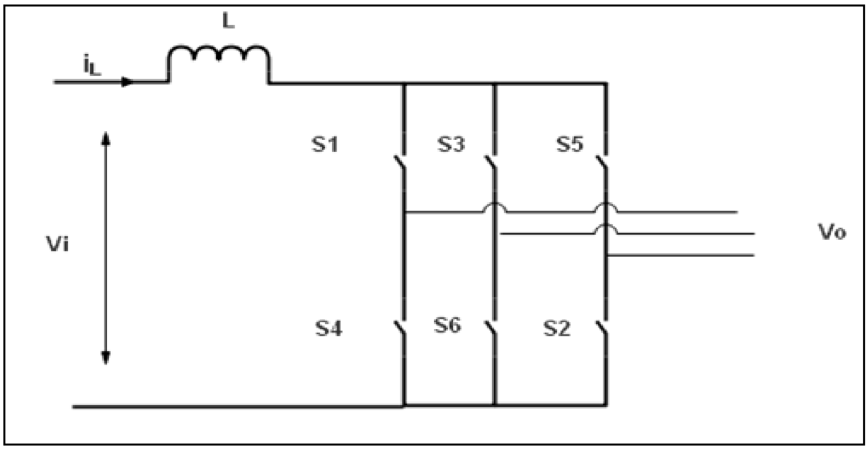


Figure I.16: Current Source Inverter

I.4.3.2 Output Phase Wise Classification:

According to the output voltage and current phases, inverters are divided into two main categories. Single-phase inverters and three-phase inverters. These categories are briefly discussed here.

- **Single Phase Inverters:**

A single-phase inverter converts DC input into Single phase output. The output voltage/current of single-phase inverter has exactly one phase which has a nominal frequency of 50HZ or 60Hz a nominal voltage.

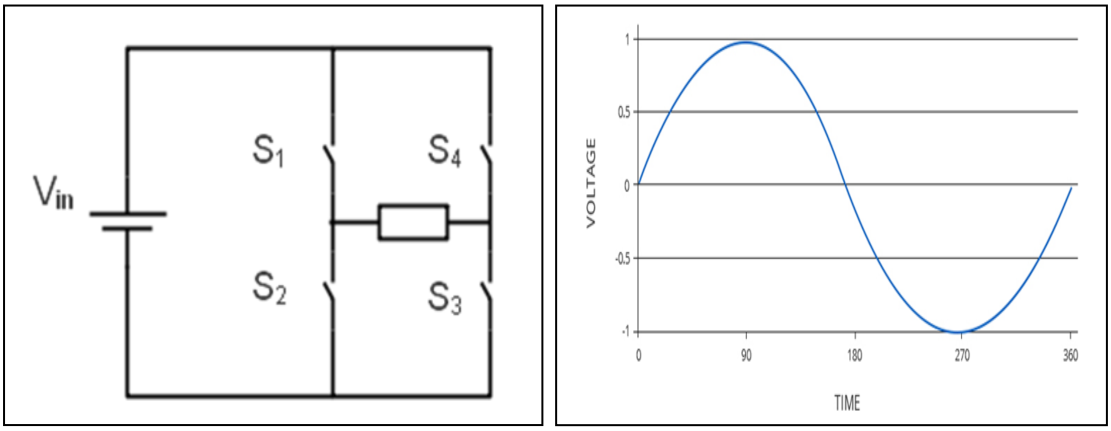


Figure I.17: Single phase power and it's output

- **Three Phase Inverters:**

Three-phase inverters convert DC into three-phase power. Three-phase power provides three alternating currents which are uniformly separated in phase angle. Amplitudes and frequencies of all three waves generated at the output are same with slight variations due to load while each wave has a 120o phase shift from each other.

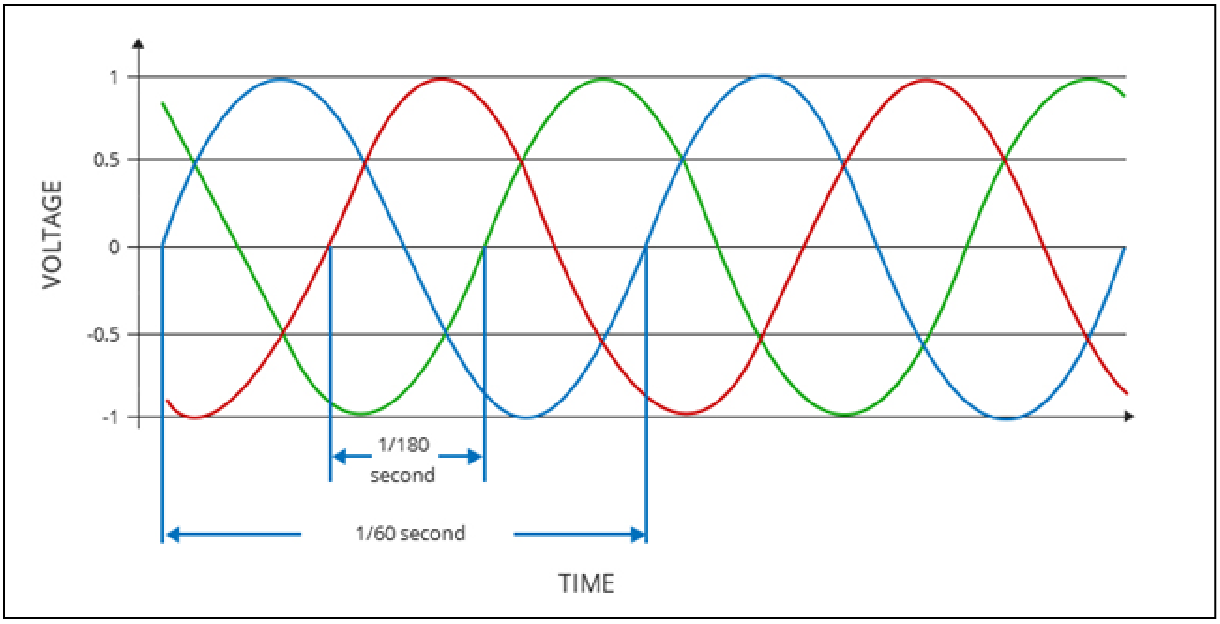


Figure I.18: Three phase power and its output

Note:

Single-phase inverters are used for low loads. There are more losses in single-phase as well as the efficiency of single-phase is low with respect to three-phase inverter. Therefore, 3 phase inverters are preferred for high loads.

Basically, a single 3-phase inverter is 3 single-phase inverters, where phases of each inverter are 120 degrees apart and each single-phase inverter is connected to one of the three load terminals.

I.4.4 Z-source Inverter:

DC / AC converters of the impedance source inverter type appeared in the scientific literature in the 2000s through the work of Professor Fang Zheng Peng published in the congress article published in 2002. At the origin of these converters appears the Z-source inverter shown in Figure. I.18 [28].

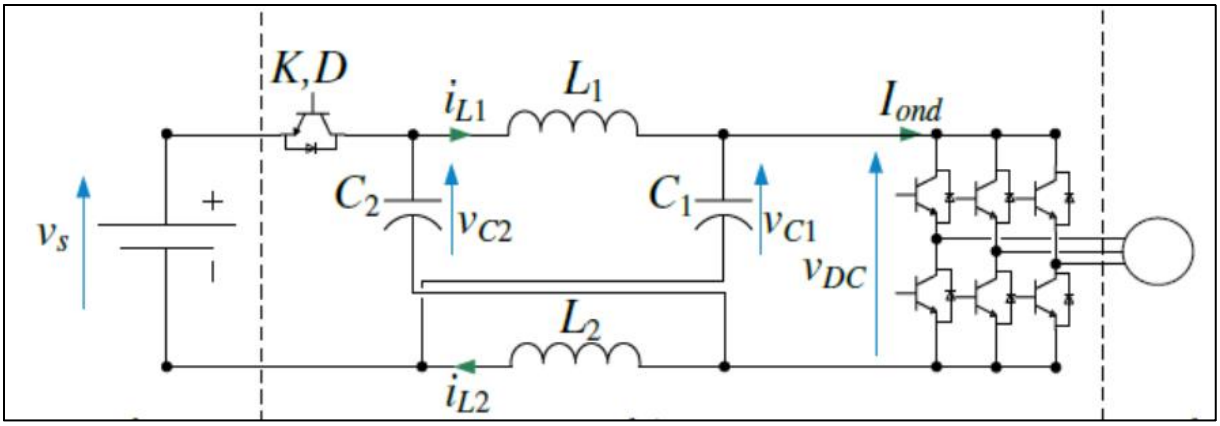


Figure I.19: Z-source inverter

Z-source inverters use an impedance network to couple the inverter to the DC voltage source. This impedance network consists of a cross hybrid L C structure; It allows the inverter to amplify the output voltage through a specific command, which makes it equivalent to cascading a step-up chopper with a conventional inverter. Z-source terminology (Source of Impedance) being linked to the replacement of the conventional DC bus of the inverter by a crossed hybrid LC DC stage. Its interest is to be able to obtain a higher AC output voltage than with a conventional inverter, a "natural boost" effect. This modification is linked to the possibility of introducing short-circuit phases of the inverter arms, superimposed on the conventional control of the PWM inverter. The continuous input source must not be reversible and the control of the inverter is slightly modified [29].

I.4.4.1 Z-source inverter topologies [30]:

ZSI has proved itself over two stage converters, as a single stage converter with the ability of buck-boost and inversion from dc-ac with minimum number of active components , ZSI general topology shown in Figure I.19 mainly consists of dc supply (voltage source or current source), impedance network (active or passive) and inverter bridge (single phase, three phase or multi-phase).

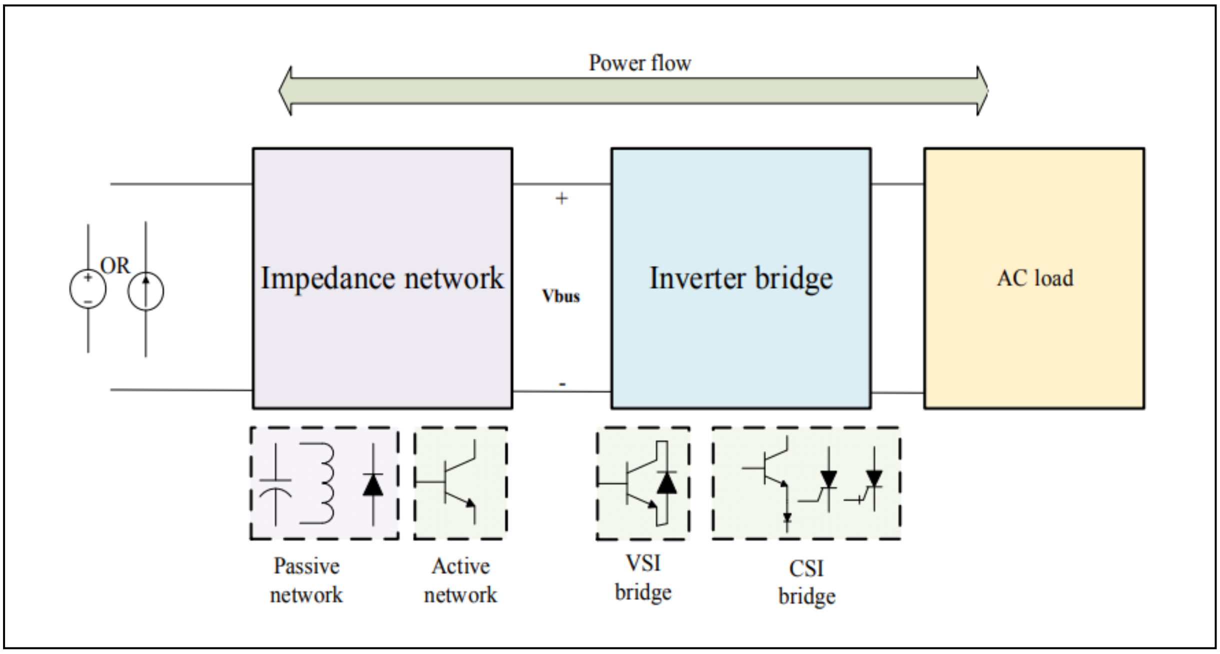


Figure I.20: ZSI general topology

Navigating through ZSIs' literature, researchers have given their focus to improve ZSI via improving its control technique or improving its own topology to obtain a reasonable voltage gain with limited voltage stresses, limited THD and reduced size impedance network with a satisfied efficiency. In other hand, many modified topologies of ZSI were proposed for reducing impedance network size or extending voltage boost ability with limited voltage stresses. Those modifications mainly concern with the impedance network arrangement and elements, inserting more linear or non-linear elements to the network.

We will introduce some of these topologies:

a- High performance ZSI (HP-ZSI):

High performance ZSI (HP-ZSI) improves the operation of the traditional Z source inverter by adding extra capacitor and bidirectional switch S1 as shown in figure (4.b). (HP-ZSI) can operate with wide range of load variation with low Z-network inductor.

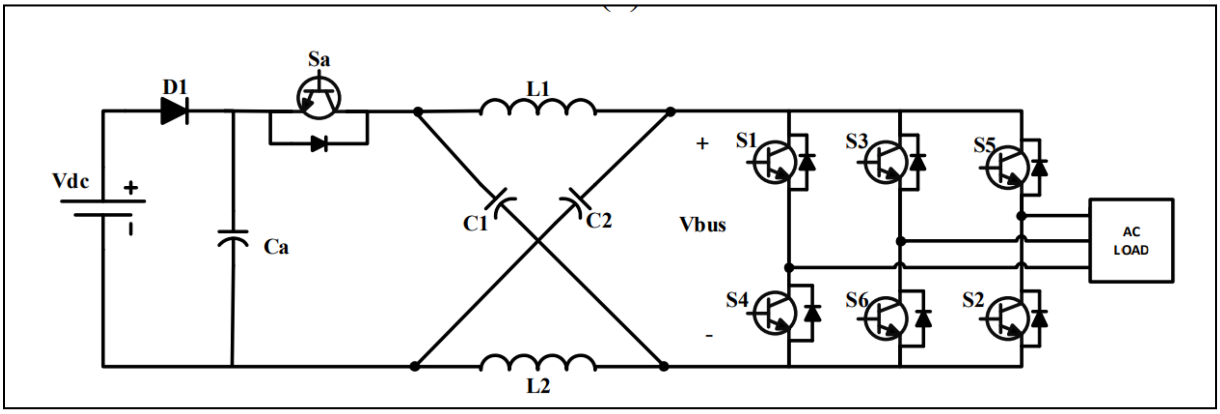


Figure I.21: High performance ZSI (HP-ZSI)

b- Quasi-ZSI (QZSI):

Quasi-ZSI (QZSI) was a revolutionary improvement to the ZSI basic topology, as it keeps the same number of Z-network components without adding any extra active or passive components.

QZSI achieves common earthling point between the dc-supply and the inverter bridge, which enhances the current and voltage profiles of the dc link lowering the power ratings for the Z-network capacitors and inductors.

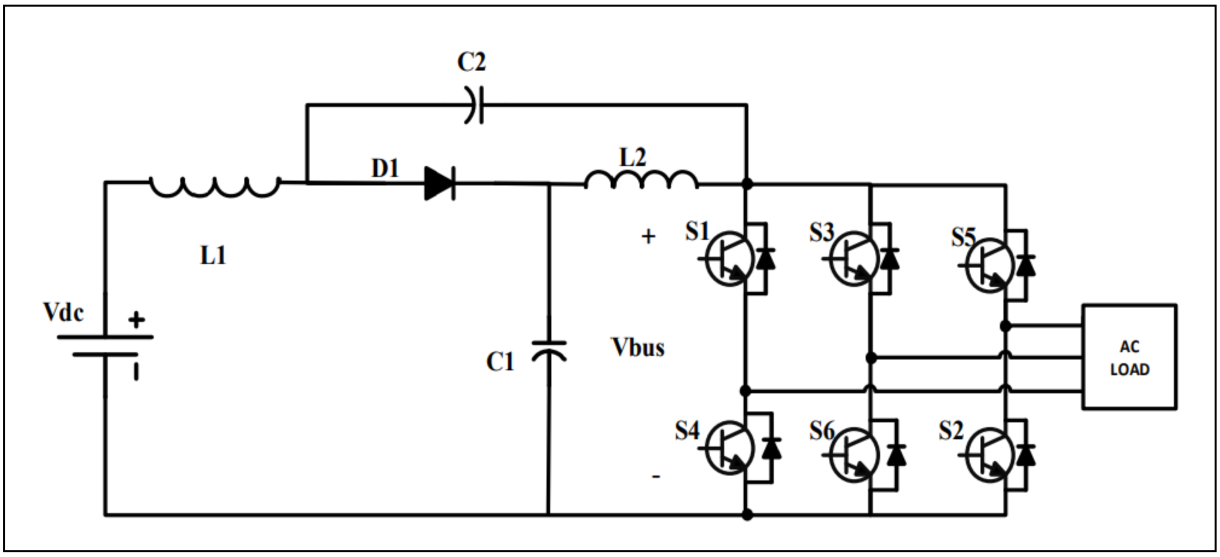


Figure I.22: Quasi-ZSI (QZSI)

c- Four Switch Z-source inverter [24]:

This new topology, besides the self-boost property, has low switch count and it can operate as a buck-boost inverter. In contrast to standard four-switch three-phase inverter which operates at half dc input voltage the proposed four-switch z-source inverter, by self boosting, brings the output voltage at same (or higher) value as in six switch standard three-phase inverter.

We will focus later on studying this topology later on.

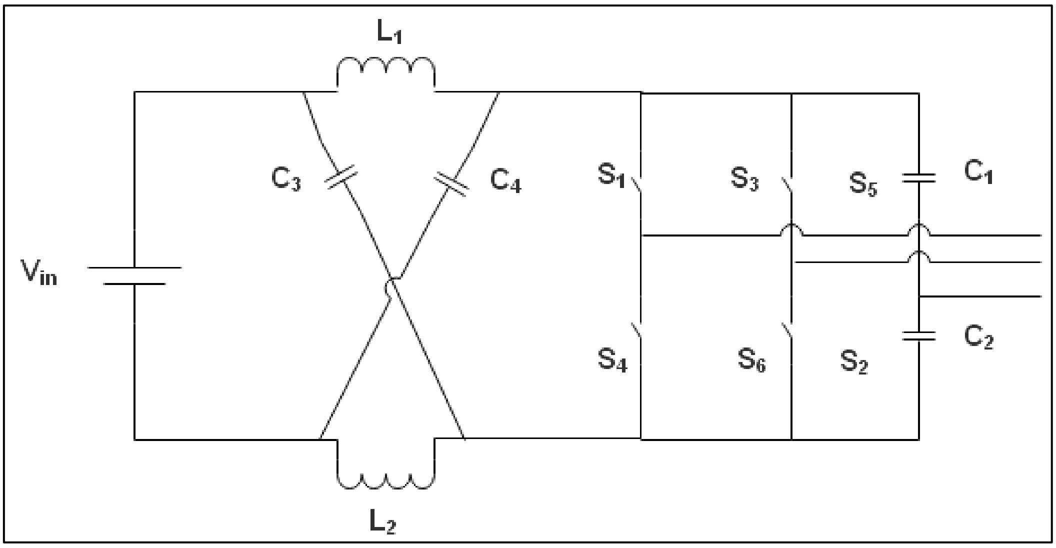


Figure I.23: Four Switch Z-source inverter

I.4.4.2 Industrial Applications of Z-Source Inverter [31]:

- Energy Storage Application
- Fuel Cell
- Grid Applications
- Uninterruptible Power Supply Application
- Photovoltaic Cell
- Vehicular Applications
- Offshore Wind Energy
- Adjustable Speed Drives

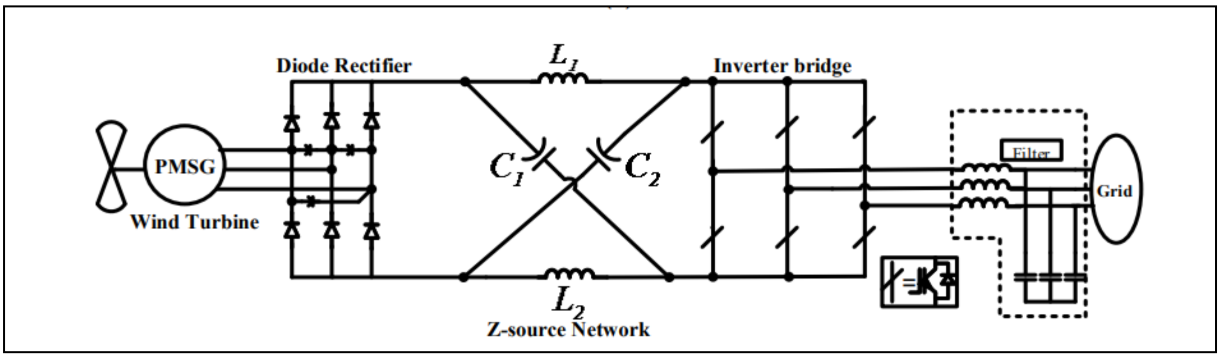


Figure I.24: ZSI for Wind energy

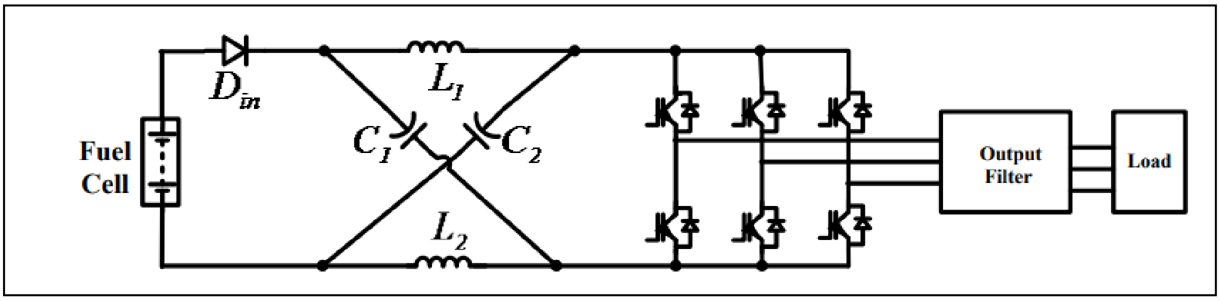


Figure I.25: Fuel cell network.

I.5 Conclusion:

In this chapter we presented the current state of the photovoltaic systems and the z-source inverter. We started with the definition of renewable energies and their different forms; we got deep in photovoltaic energy and the various types of photovoltaic systems used in harvesting this fortune. In addition, we introduced general information on the z-source inverter, with mentioning its different types according to the classification and also presenting some of the promising topologies.

CHAPTER II:

Modeling of PV Panels and MPPT Control

II.1 Introduction:

As a kind of novel clean energy, solar energy has been widely concerned and studied all over the world. Affected by light irradiation and temperature, the output characteristic of the PV module has non-linear features. The output voltage and power will greatly change with the variations of the external environment.

The simulation model of the PV module, which is based on Simulink software, the mathematical model, and the equivalent circuit of the PV module, is built in this paper. This PV module model can be used to show the output characteristics of the PV module under different irradiation and temperatures. Moreover, this model can be extended to various parameters of PV modules and used to study parallel and serial characteristics of PV modules. The output characteristic of the PV module, which is affected greatly by light irradiation and ambient temperature, has obvious non-linear features. Therefore, a Maximum Power Point Tracker (MPPT) is needed.

MPPT is put forward to obtain electric energy and improve PV system efficiency as much as possible. Besides, as the external environment where the solar cell panels are set up is unpredictable, the inconvenience will be brought to the experiment and study of the PV power system [32].

This chapter is divided into two parts; the first section is a modeling of PV Panels. The SOLAR make 36 W PV module is taken as the reference module and the PV equations are modeled with Simulink blocks. The next sections present the MPPT controller with the P&O algorithm, using a boost converter to track the MPP of the PV module; at the end, the simulation results are discussed.

II.2. PART 1: Modeling Of Photovoltaic Panels

II.2.1 Basic Functioning Of the Solar Cell:

The working principle of solar cells is based on thephotovoltaic effect, i.e. the generation of a potential difference at the junction of two different materials in response to electromagnetic radiation. The photovoltaiceffect is closely related to the photoelectric effect, whereelectrons are emitted from a material that has absorbedlight with a frequency above a material-dependent threshold frequency. In 1905, Albert Einstein understood that this effect can be explained by assuming that light consists of well-defined energy quanta, calledphotons. The energy of such a photon is given by:

$$E = h * v \tag{II.1}$$

Where h is Planck's constant and v is the frequency ofthe light. For his explanation of the photoelectric effect, Einstein received the Nobel Prize in Physics in 1921 [33].

The photovoltaic effect can be divided into three basicprocesses:

a) Generation of charge carriers due to the absorption of photons in the materials that form a junction.
b) Subsequent separation of the photo-generated charge carriers in the junction.
c) Collection of the photo-generated charge carriers at the terminals of the junction.

II.2.2 Photovoltaic Modules Interconnection:

A PV module is a larger device in which manysolar cells are connected, as illustrated in Fig.II.1 (b). The names PV module and solar module are often used interchangeably. A solar panel, as illustrated in Fig. II.1 (c) consists of several PV modules that are electrically connected and mounted on a supporting structure. Finally, a PV array consists of several solar panels. An example of such an array is shown in Fig II.1 (d). This array consists of two strings of two solar panels each, where string means that these panels are connected in series.

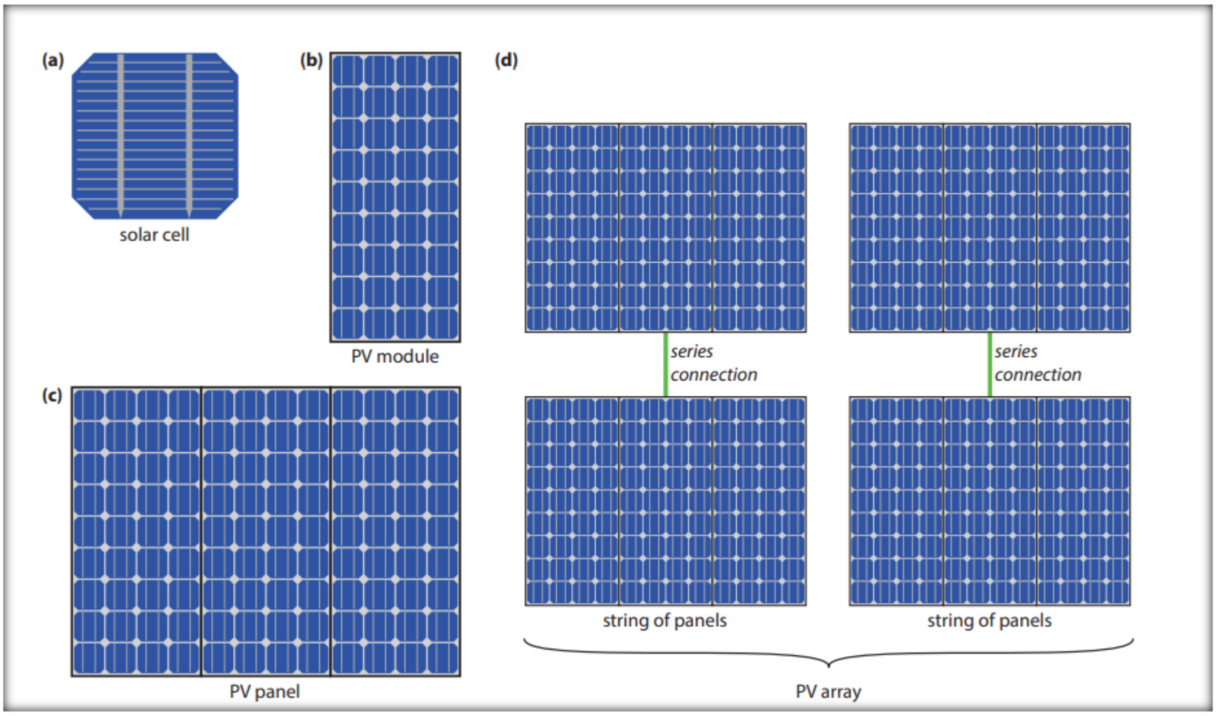


Figure II.1: Photovoltaic Modules Interconnection

II.2.2.1Connection of Modules in Series:

Shown in Figure.II.2, in a series connection the voltages add up. For example, if the open-circuit voltage of one cell is equal to 0.6 V, a string of three cells will deliver an open circuit voltage of 1.8 V.

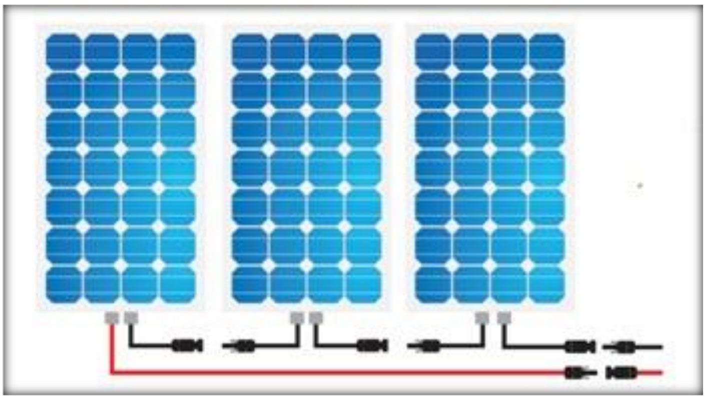


Figure II.2: Illustrating a series connection of three solar cells

II.2.2.2 Connection of Modules in Parallel Combination:

We can connect solar cells in parallel as illustrated in Fig II.3, which shows three solar cells connected in parallel. If cells are connected in parallel, the voltage is the same overall solar cells, while the currents of the solar cells add up.

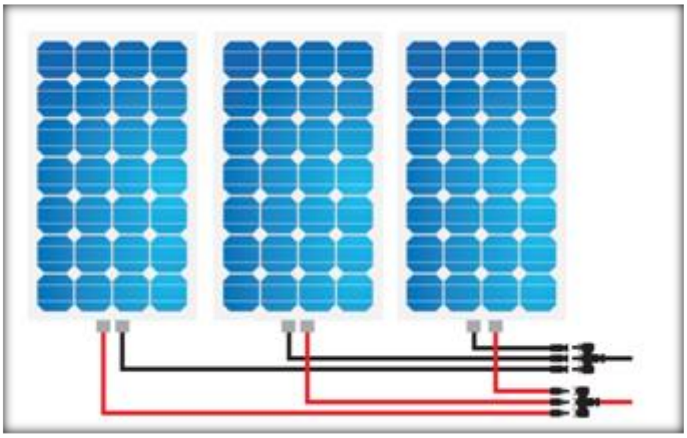


Figure II.3: Illustrating a parallel connection of three solar cells.

For series-connected cells, the current does not add up but is determined by the photocurrent in each solar cell. Hence, the total current in a string of solar cells is equal to the current generated by one single solar cell. If we connect e.g. three cells in parallel, the current becomes three times as large, while the voltage is the same as for a single cell, as illustrated in Figure II.4.

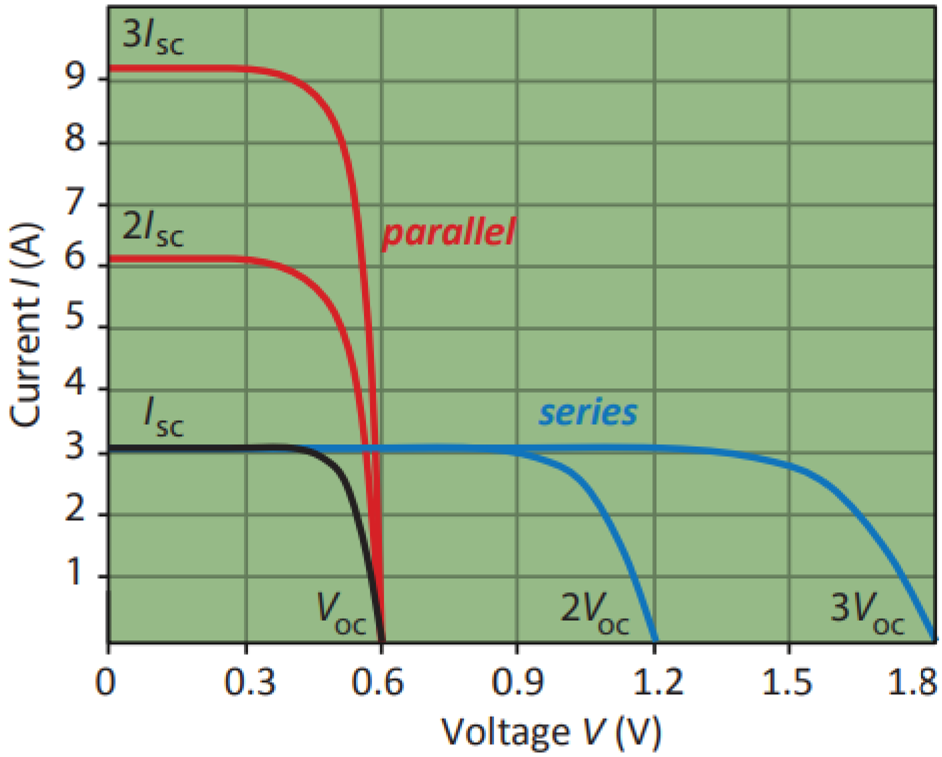


Figure II.4: curves of solar cells connected in series and parallel.

II.2.2.3 Connection of Modules in Series and Parallel (Mixed Combination):

Solar PV panels are connected in series and in parallel to meet both current and voltage requirements.

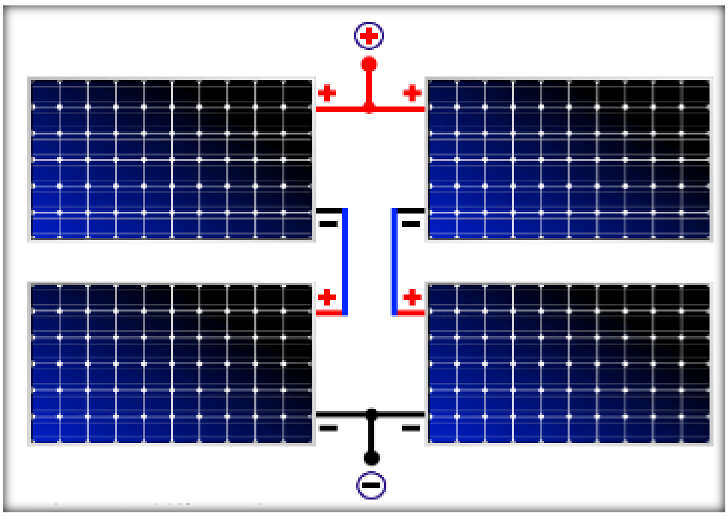


Figure II.5: Connection of Modules in Series and Parallel.

II.2.3 Mathematical model for a PV module:

The Photovoltaic (PV) cell itself is made up of many P-N junctions, which can convert light energy into electricity. The basic characteristics of PV cells are similar to the diode. The equivalent circuit of the general PV model, which consists of a photocurrent, a diode, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow [34], is shown in Figure II.6.

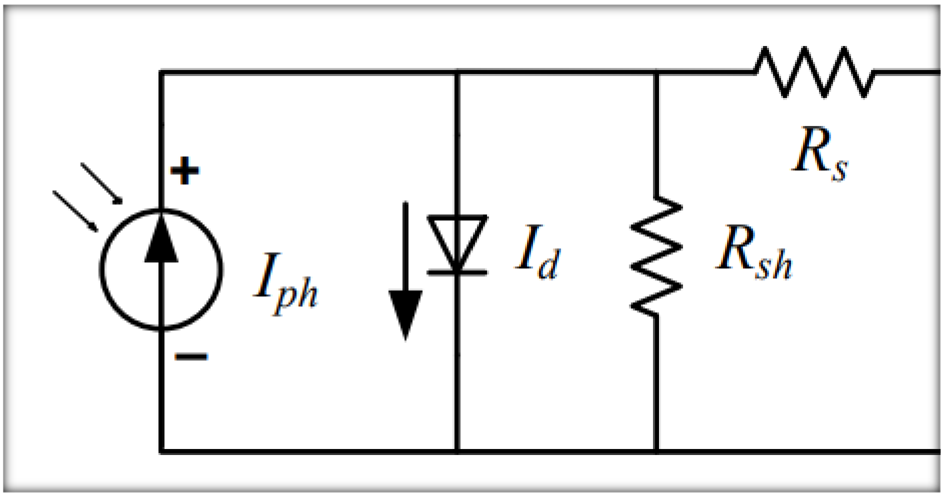


Figure II.6:PV module equivalent circuit

Irradiation level, The PV cell output voltage can be expressed as:

$$V = \frac{AkT}{e} ln \frac{I_p h + I_0 - I}{I_0} - R_s I \qquad \text{(II.2)}$$

Where:

e : Electronic charge (1.602× 10 C).

k : Boltzmann constant (1.38× 10J/0 K).

I : Cell output current, in A.

I_{ph} : Photocurrent depends on temperature and solar irradiance (5 A).

I_0 : Reverse Saturation Current of diode (0.0002 A)

R_s :Series resistance of cell (0.001).

T : Reference cell operating temperature (200 C).

The mathematical model of PV array for a single diode circuit can be represented by the following equation:

- **Photo Current (I_{ph}):**

I_{ph} depends on the solar irradiation and cell's operating temperature according to the below equation:

$$I_{ph} = \left[I_{sc} + K_1\left(T_c + T_{ref}\right)\right] * H \tag{II.3}$$

Where

I_{sc} is short-circuit current of the PV module, $K_1$is the temperature coefficient of short-circuit, T is cell temperature (K) and T_{ref} is reference temperature (K).

- **Reverse Saturation Current (I_{rs}):**

The reverse saturation current of a PV system can be determined by the given equation:

$$I_{rs} = \frac{I_{cs}}{exp\frac{eV_{oc}}{N_s kAt} - 1} \tag{II.4}$$

Where:

V_{oc} is the open-circuit voltage, e is electron's charge and A is the diode ideality factor

- **Diode Saturation Current (I_0):**

The Saturation current of the PV system varies with the cell temperature can be determined by given equation.

$$I_0 = I_{rs} * (\frac{T}{T_r})^3 * \exp\left[\left(\frac{e * E_{go}}{A * k}\right) * (\left(\frac{1}{T_r}\right) - \left(\frac{1}{T}\right))\right] \tag{II.5}$$

Where:

$E_{g0}$is the silicon gap energy of a semiconductor

- **Output current (I):**

The equation for output current of the PV system of single diode model presented in Figure 1 is given by:

$$I_{pv} = N_p * I_{ph} - N_p * I_0 \left[\exp\left(\frac{q * (V_{pv} + I_{pv}R_s)}{N_s * A * k * T}\right) - 1\right] \quad (II.6)$$

Where:

$N_S$cells in series and N_P cells in parallel, I_{ph} Photovoltaic current source, I_{pv} cell current, and V_{pv} cell voltage

II.2.4 Simulation Model:

II.2.4.1 SIMULINK model PV cell:

A model of PV module with moderate complexity that includes the temperature independence of the photocurrentsource, the saturation current of the diode, and series resistance is considered based on the Shockley diode equation.

Being illuminated with radiation of sunlight, PV cell converts part of the photovoltaic potential directly into electricity with both I-V and P-V output characteristics[35].

Based on the mathematical equations discussed previously and the detailed model of a photovoltaic module of 36 cells in series.

II.2.4.2 Reference Model:

SOLKAR makes 36 W PV module is taken as the reference module for simulation and the name-plate details are given in Table II.1 [35].

Rated Power	37.08 W
Voltage at Maximum Power (V_{mp})	16.56 V
Current at Maximum Power (I_{mp})	2.25 A
Open circuit current (V_{oc})	21.24 V
Short circuit current (I_{SCr})	2.25 A
Total number of cells in series (N_s)	36
Total number of cells in parallel (N_p)	1

Table II.1: Electrical characteristics of the SOLKAR 36 W PV module

Note: The electrical specifications are under test conditions of irradiance of 1kW/m2, a spectrum of 1.5 air masses, and a cell temperature of 25 o C.

The modeling and the power control with the different simulations were done by MATLAB / SIMULINK.

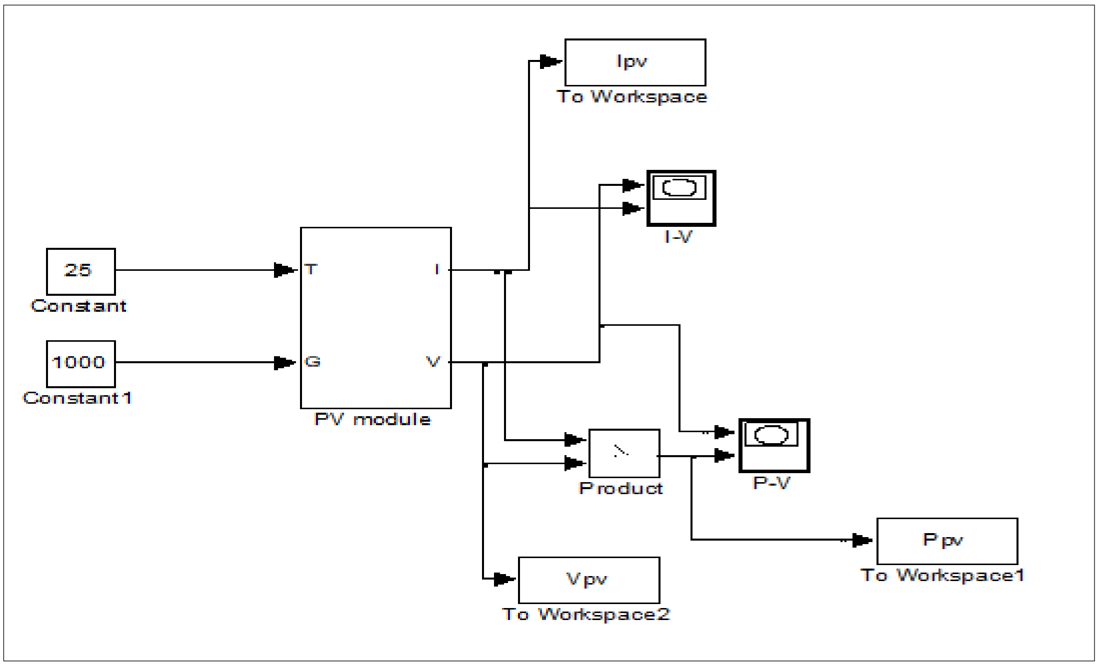


Figure II.7: External view of PV module in SIMULINK window

The I_{pv} (V) and P_{pv} (V) characteristics of PV generator under standard conditions (E = 1000 W / m ^ 2 and T = 25 ° C) are presented as follows:

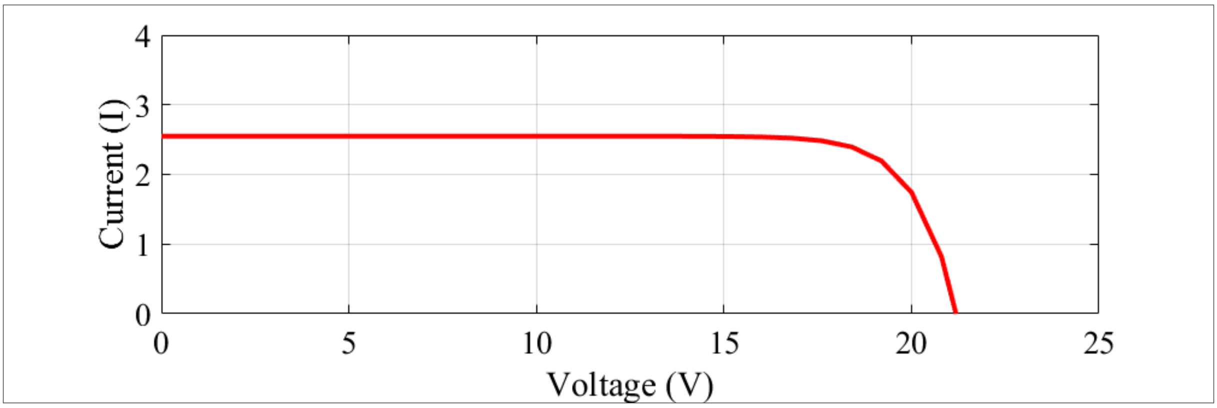


Figure II.8: I-V characteristics of a solar cell.

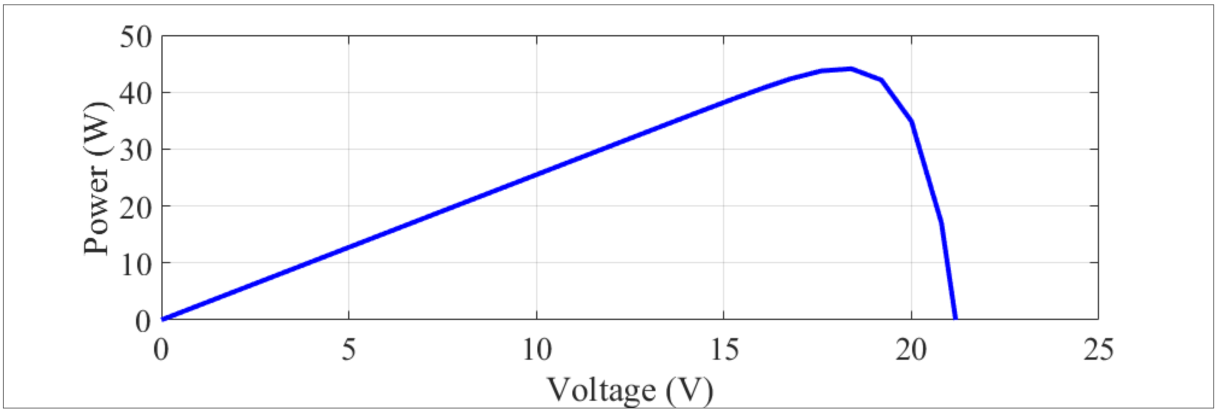


Figure II.9: P-V characteristics of a solar cell.

II.2.4.3 Effect of Variation of Solar Irradiation:

I-V and P-V characteristics under varying irradiation with constant temperature (T=25c°) are obtained in Figures (II.10) and (II.11):

The I-V output characteristics of the PV module withvarying irradiation at a constant temperature of 25°C are shown in figure (II.10).

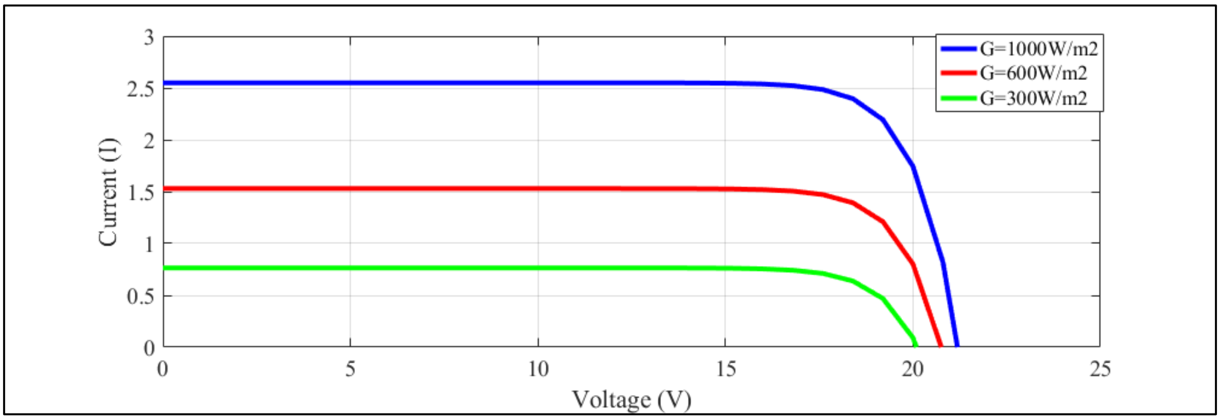


Figure II.10: Output – I-V characteristics with varying irradiation.

The P-V output characteristics of the PV module with varying irradiation at a constant temperature of 25°C are shown in figure (II.11).

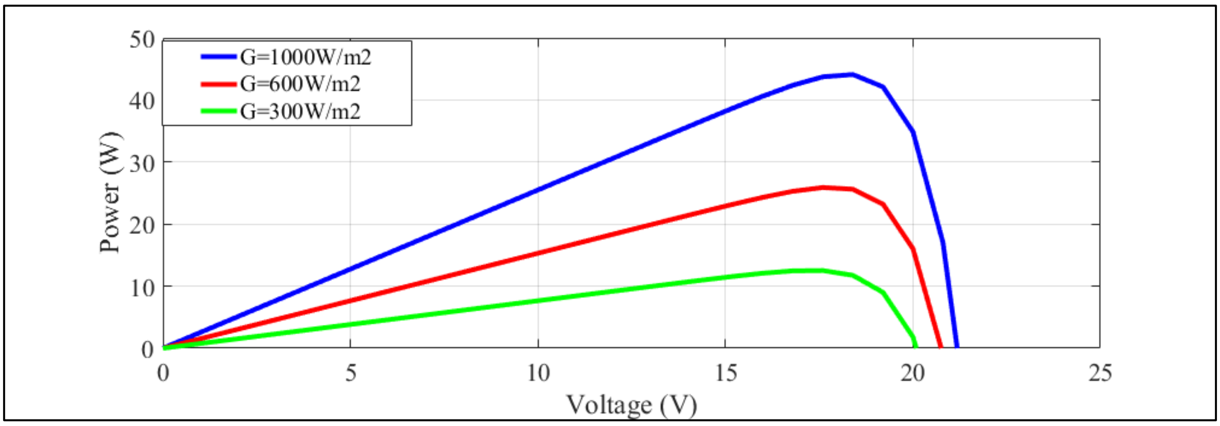


Figure II.11: Output – P-V characteristics with varying irradiation.

Analysis of the results:

As shown in the figures, we see that irradiation has a strong effect on the performance of PV cells in which as the irradiation increases, the current and voltage outputs also increase. Thus, the power output of the PV module increases with an increase in irradiation when the temperature remains constant at 25° C.

II.2.4.4 Effect of Variation of Temperature:

I-V and P-V characteristics under varying temperature with constant Irradiation are obtained in Figures (II.12) and (II.13):

The I-V output characteristics of the PV module with the varying temperature at constant irradiation of 1000W/m2 are shown in figure (II.12).

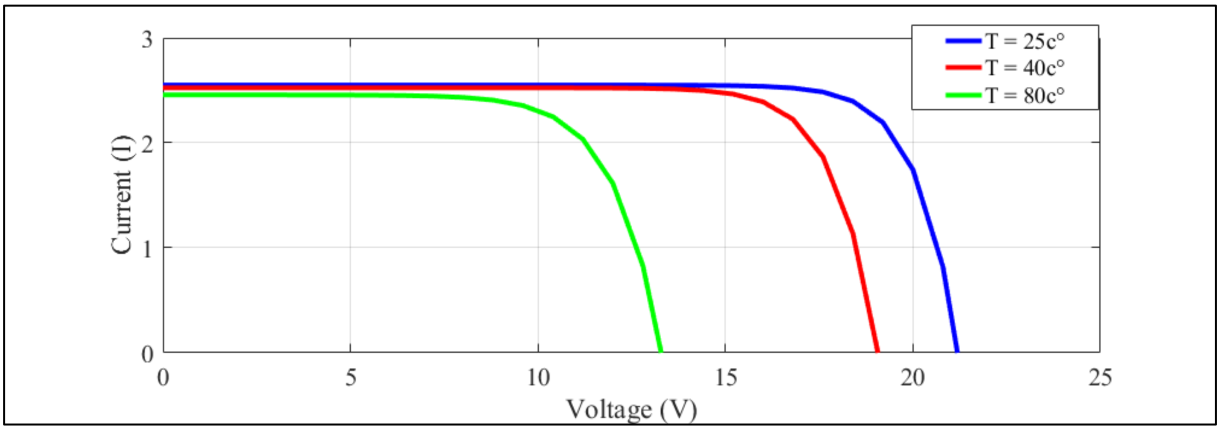


Figure II.12: Output – I-V characteristics with varying temperature.

The P-V output characteristics of the PV module with the varying temperature at constant irradiation of 1000W/m2 are shown in figure (II.13).

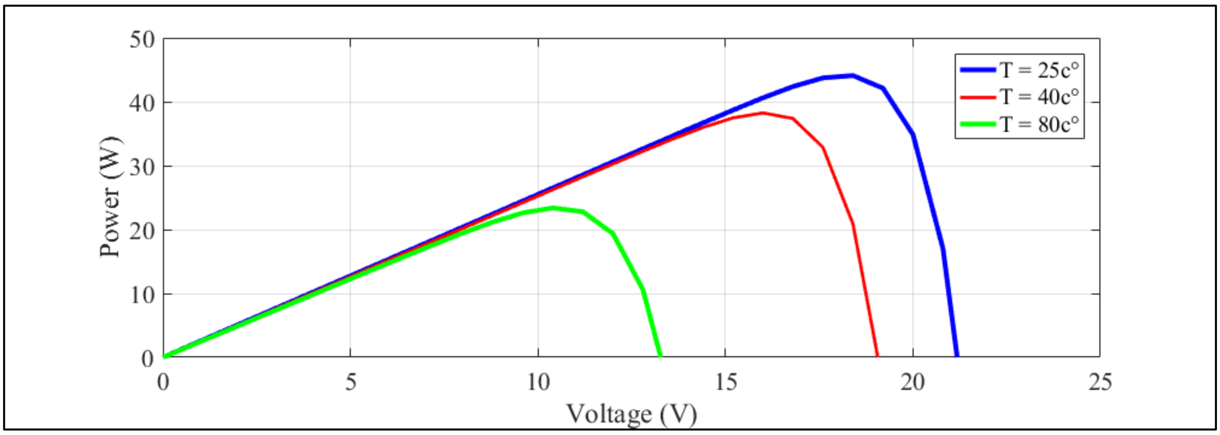


Figure II.13: Output P-V characteristics with varying temperature.

Analysis of the results:

With the same pattern, we notice a changein PV output caused by the temperature rising, in which the current output slightly decreasing but, the voltage output decreases drastically. This has a huge effect on the power output when the irradiation remains constant at 1000W/m².

II.3. Part B: The MPPT Control Technique:

For the module to provide its maximum available power, it is necessary to permanently adapt the load with the photovoltaic generator. This adaptation can be achieved by inserting a DC-DC converter (chopper) controlled by a "Maximum Power Point Tracking" (MPPT) mechanism.

So in this part, we will start with a brief introduction to the DC/DC converters, and then we will dive deep into the MPPT control.

II.3.1 DC-DC converter:

DC-DC converters are power electronic circuits that convert a dc voltage to a different voltage level. There are several types of DC-DC converters. Among these, we present the principle of the three types of switching converters (boost, buck, and buck-boost), that are frequently used in photovoltaic systems to generate the desired sets and currents as well as for the adaptation of solar panels with the various loads [36].

II.3.1.1 Boost converter (step-up converter):

It's a booster converter, also known under the name of the parallel chopper; its basic principle diagram is that of figure (2.12). It's typical application is to convert its input voltage to a higher output voltage.

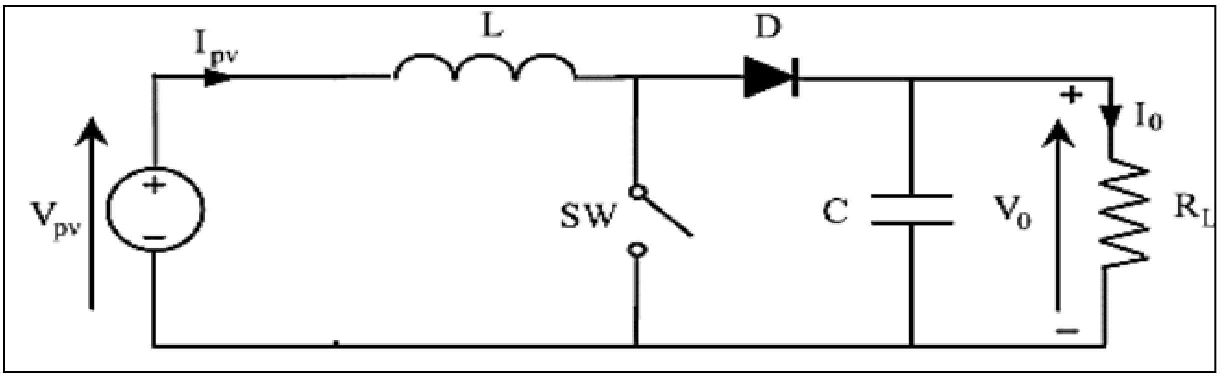


Figure II.14: Circuit diagram of a Boost converter

The configurations of the boost converter circuit during switching ON and OFF intervals are shown in Figures II.14 and II.15 respectively.

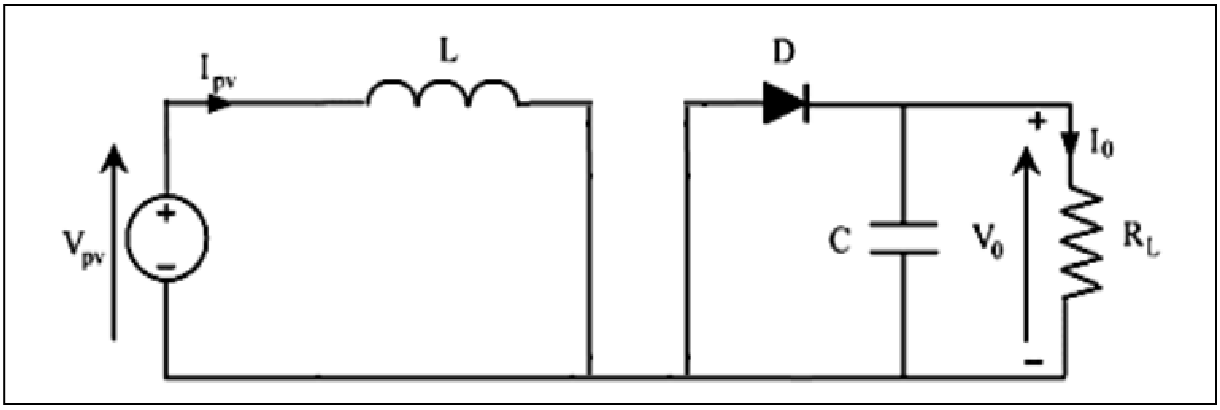


Figure II.15: ON state of the switch

When the switch isON, the inductor is directly connected to the input voltage source. In this case, the inductor current rises to charge it and the inductor is storing energy while the diode is reversely biased disconnecting the load (RL) and output capacitor (C) from the source voltage. During this interval, the pre-charged capacitor assures constant voltage across the load terminals [37]

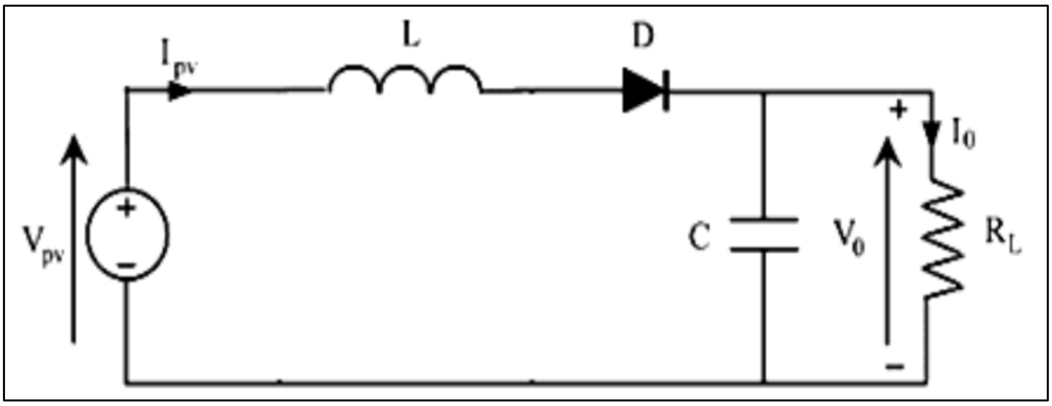


Figure II.16: OFF state of the switch

When the switch is OFF, the diode is forward biased and both the source and the charged inductor are connected to the load. The inductor releases the energy stored in it. This energy is transferred to the load in the form of voltage that adds to the source voltage. Hence, the converter has boosts the input voltage [37].

The voltage and current of the load in the case of continuous conduction are given by:

$$\begin{cases} V_0 = \frac{1}{1-D} V_{in} \\ I_0 = (1-D) I_{in} \end{cases} \text{In which} \quad V_{in} = V_{pv} \quad \text{and} \quad I_{in} = I_{pv} \tag{II.7}$$

The current ripple is:

$$\Delta I_L = \frac{V_{pv}}{L\,f} D \tag{II.8}$$

The voltage ripple is:

$$\Delta V_0 = \frac{1}{C\,f} D I_0 \tag{II.9}$$

With:

D: the converter duty cycle.

f: the switching frequency of the converter.

II.3.1.2 Buck converter (step-down converter):

A buck or step-down converter is a DC/DC switch mode power supply that is intended to buck (or lower) the input voltage of an unregulated DC supply to a stabilized lower output voltage. Buck converters are, especially compared to traditional voltage regulators, widely valued for their extremely high efficiencies which can easily exceed 95% [38]. The circuit diagram of this converter is shown in Figure (II.17).

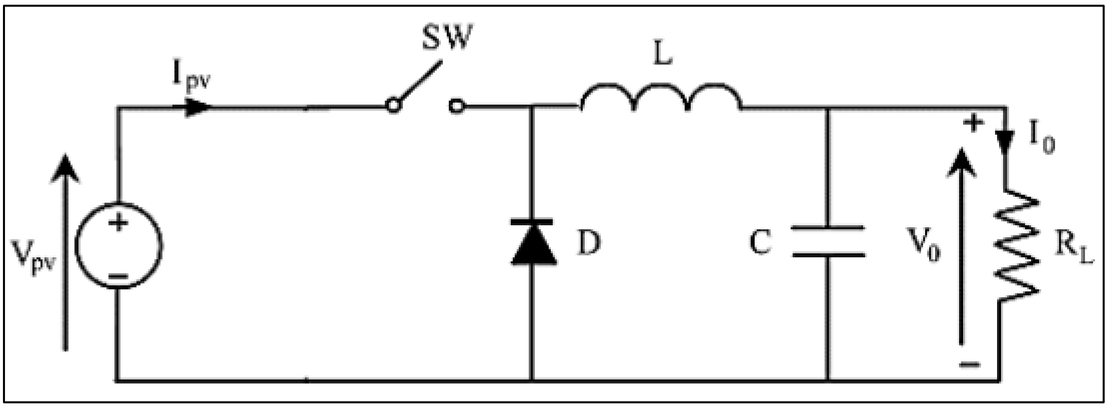


Figure II.17: Circuit diagram of a Buck converter.

II.3.1.3 Buck-Boost converter (step-to-step converter):

A buck-boost boost converter can supply a regulated DC output from a power source delivering a voltage either below or above the regulated output voltage. A buck-boost converter circuit combines elements of both a buck converter and a boost converter [38]. The circuit diagram of this converter is shown in Figure (II.18).

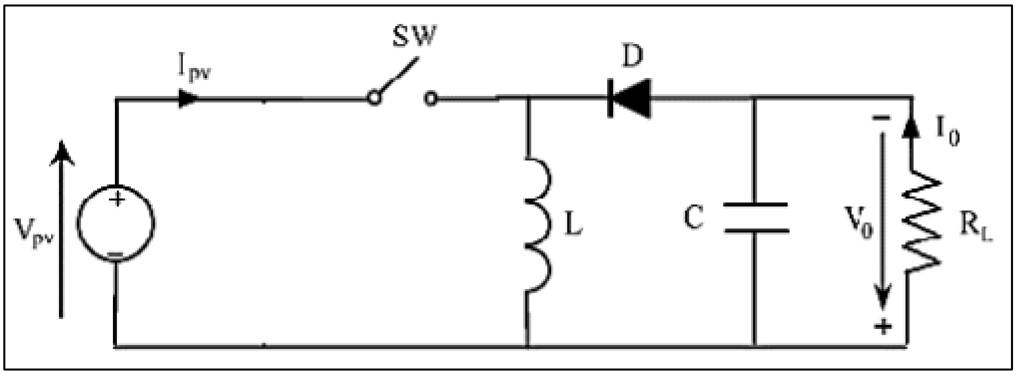


Figure II.18: Circuit diagram of a Buck-Boost converter.

II.3.2. The MPPT Control Technique:

II.3.2.1 Definition:

A typical solar panel converts only 30 to 40 percent of the incident solar irradiation into electrical energy. Maximum power point tracking (MPPT) technique is used to improve the efficiency of the solar panel [39].

By definition, an MPPT control makes it possible to operate a PV generator to continuously produce the maximum of its power. Thus, whatever the weather conditions (temperature and irradiation), and whatever the battery voltage or the load, the converter control places the system at the maximum operating point [40].

II.3.2.2 Converter For the continuation of the maximum power point:

For the maximization of the power of the PV source, by inserting an adaptation quadrupole which is a DC-DC energy converter between the PV source and the load and with the rigorous control of the duty cycle of the latter, This adaptation is carried out by automatically seeking the PPM of the PV panel and continuous monitoring of the maximum power is ensured.

The DC / DC type converter is used in the Control part of the photovoltaic system because it is easy to control by their duty cycles using a PWM signal. Here, in our study we use the Boost chopper as a power interface controlled by the MPPT regulator, in order to adapt the output voltage of the chopper to the voltage required by the load [40].

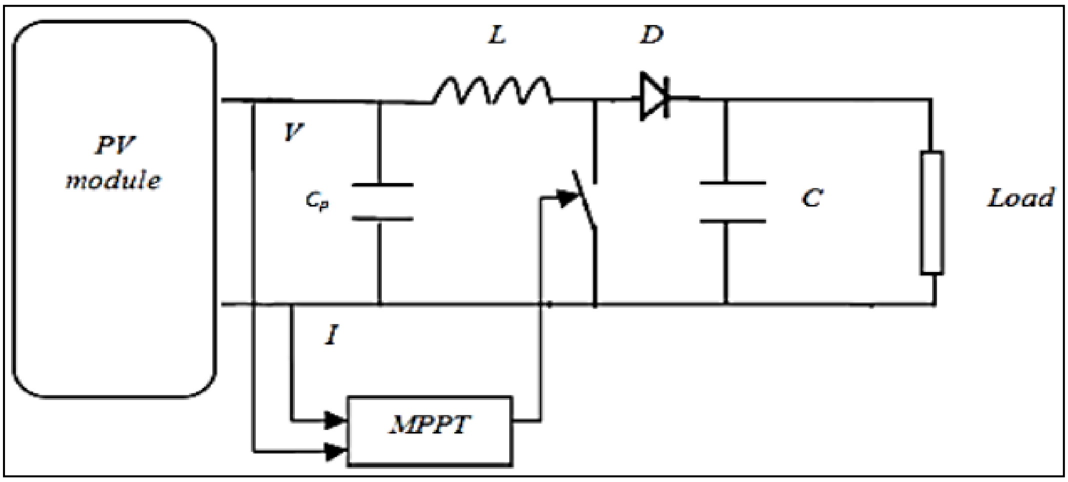


Figure II.19: PV system with DC-DC Boost converter.

II.3.2.3 Operation and Design of a Boost Converter:

Figure II.14 shows the basic circuit configuration of a boost converter, where V_{pv} is the dc input voltage, L is the boost inductor, S_w is the controlled switch, D is a diode, C is a filter capacitor, and R_L is the load resistance. Boost converter works in two states. When the switch S is open, current in the boost inductor increases linearly, and the diode D is off at that time. When the switch S_w is closed, the energy stored in the inductor is released through the diode to the output RC circuit.

The main equation associated with duty cycle and input-output voltage of boost converter is given below as follows:

$$M = \frac{V_0}{V_{PV}} = \frac{1}{1 - D} \tag{II.10}$$

The rest of the necessary equations related to the designing are listed below as follows:

Inductor ripples current (peak to peak):

$$\Delta IL = \frac{V_{PV} * D}{f_S * L} \tag{II.11}$$

Capacitor ripples voltage (peak to peak):

$$\Delta V_c = \frac{I_0 * D}{f_s * C} \tag{II.12}$$

Critical value of inductor necessary for the continuous conducting mode:

$$L_b = \frac{(1 - D^2)D_R}{2f_s} \tag{II.13}$$

Minimum value of the filter capacitance that results in the voltage ripple:

$$C_{min} = \frac{D}{2f_s R} \tag{II.14}$$

Current ripple factor,

$$CRF = \frac{\Delta IL}{IL} \tag{II.15}$$

Voltage ripple factor,

$$VRF = \frac{\Delta V_0}{V_0} \quad \text{(II.16)}$$

The values of the components obtained from the equations are associated with the practical implementation of the converter. Such as, for continuous current operation of circuit, the value of inductor $L > L_b$, and to limit the output voltage ripple the condition $C > C_{min}$ should be satisfied. Besides, ΔIL and ΔVc are related to CRF and VRF. The value of these two terms should not exceed 30% and 5%, respectively. The specifications of the necessary components selected for this work are listed below:

Description	Value
Input voltage (V_{in})	16.6V
the converter duty (D)	0.34
Output voltage (V_{out})	25V
Boost inductor	100Mh
Output filter capacitor	2400 µF
Switching frequency	5 KHz
Input filter capacitor	400 µF

Table II.2: The boost converter specification

II.3.2.4 Principle of finding the maximum power point:

The MPPT control varies the duty cycle of the static converter, using an appropriate electrical signal, to get the most power that the GPV can provide. The MPPT algorithm can be more or less complicated to find the MPP [41].

In general, it is based on the variation of the duty cycle of the Boost converter according to the evolution of the input parameters of the latter (I and V and consequently of the power of the GPV) until being placed on the MPP [42].

II.3.3 Description of Different MPPT techniques:

The characteristic of the solar cell V-I is not linear and varies according to the illumination and the temperature. There is a point on the curve V-P, V-I we call the maximum power point, this point is not known, but it can be calculated.

There are many algorithms and methods used for maximum power point tracking a few are listed below:

1) Perturb and Observe (hill climbing method)
2) Incremental Conductance method
3) Fractional short circuit current
4) Fractional open circuit voltage
5) Neural networks
6) Fuzzy logic

II.3.3.1 Perturb and observe (P&O) method:

The first algorithm that we discuss is the Perturb and Observe (P&O) algorithm, which also is known as "hill climbing" algorithm. In this algorithm, a perturbation is provided to the voltage at that the module is currently driven. This perturbation in voltage will lead to a change in the power output. If an increasing voltage leads to an increasing in power, the operating point is at a lower voltage than the MPP, and hence further voltage perturbation towards higher voltages is required to reach the MPP. In contrast, if an increasing voltage leads to a decreasing power; further perturbation towards lower voltages is required in order to reach the MPP. Hence, the algorithm will converge towards the MPP over several perturbations. This principle is summarized in the following diagram [43].

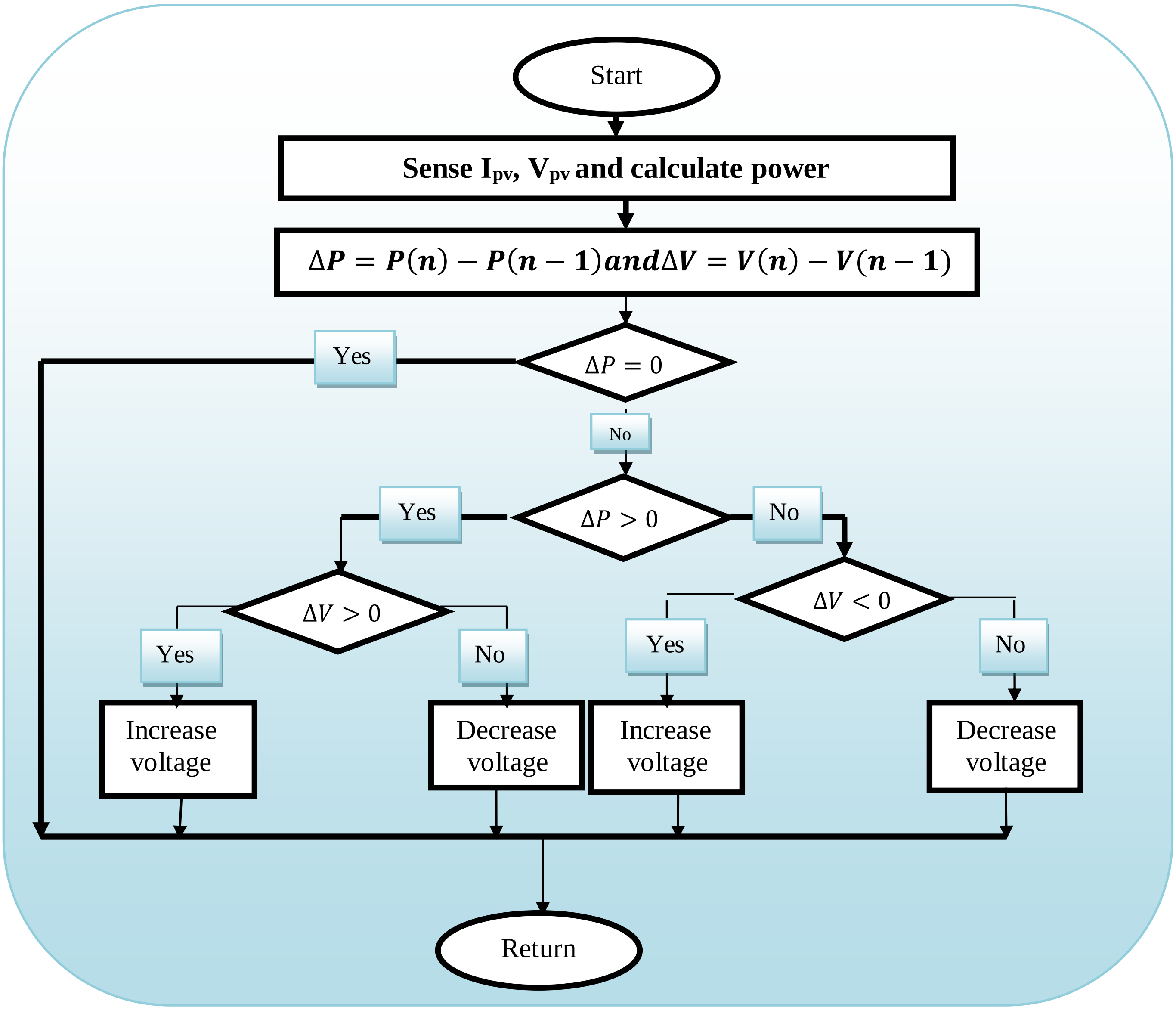


Figure II.20: P&O algorithm.

II.3.3.2 Implementation of Fuzzy Logic Based MPPT Algorithm:

Even though Fuzzy Logic control method MPPT has some difficulties to construct, it has facility to find maximum power point of PV panels. Fuzzy logic MPPT method doesn't need the knowledge about model of the system, Inputs of the fuzzy logic controller are the error of the system which is E and the change of error is CE, and the Following equations clarify E and CE [44].

$$E(k) = \frac{\Delta I}{\Delta V} + \frac{I}{V} = \frac{\Delta P}{\Delta V} = \frac{\Delta P}{\Delta I} \tag{II.17}$$

$$CE(k) = E(k) - E(k-1) \tag{II.18}$$

With: $\Delta I = I(k) - I(k-1)$ (II.19)

$$\Delta V = V(k) - V(k-1) \quad (II.20)$$

$$\Delta P = P(k) - P(k-1) \quad (II.21)$$

II.3.3.3 The fuzzy logic algorithm:

- Calculate error and change of error signal,
- Set up of membership function for fuzzy variables
- setting of fuzzy rules
- Calculation of duty cycle

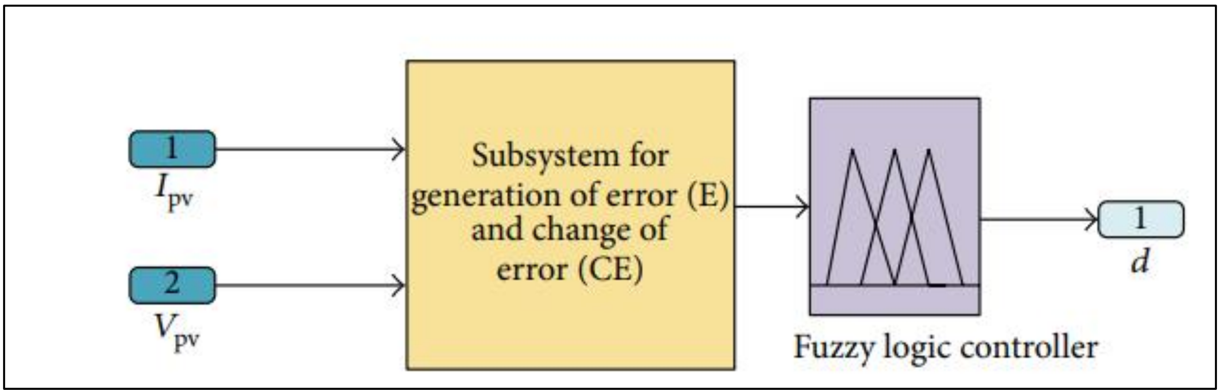


Figure II.21: The external block view of the fuzzy logic algorithm.

a. Setting up of membership function for fuzzy variables:

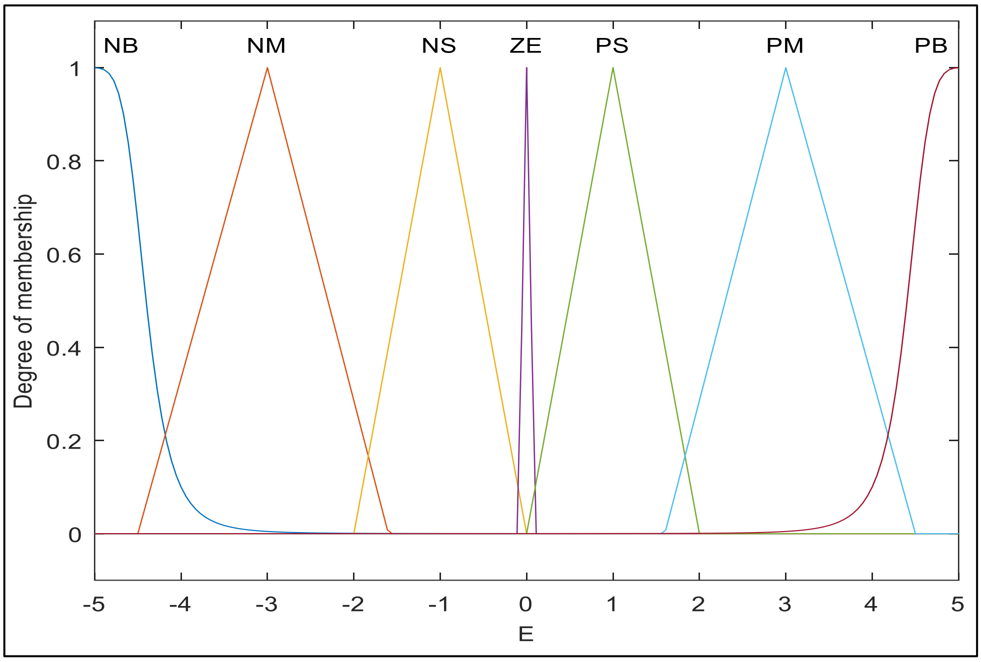


Figure II.22: Graphical view of the membership function for error « E » signal

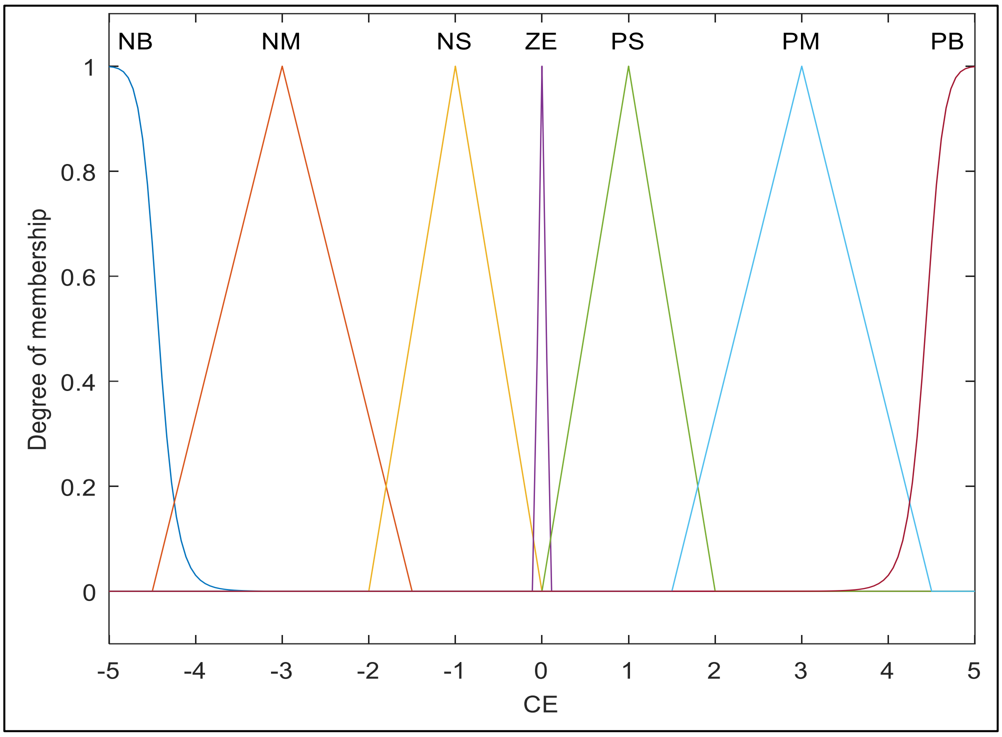


Figure II.23: Graphical view of the membership function for change of error « CE » signal

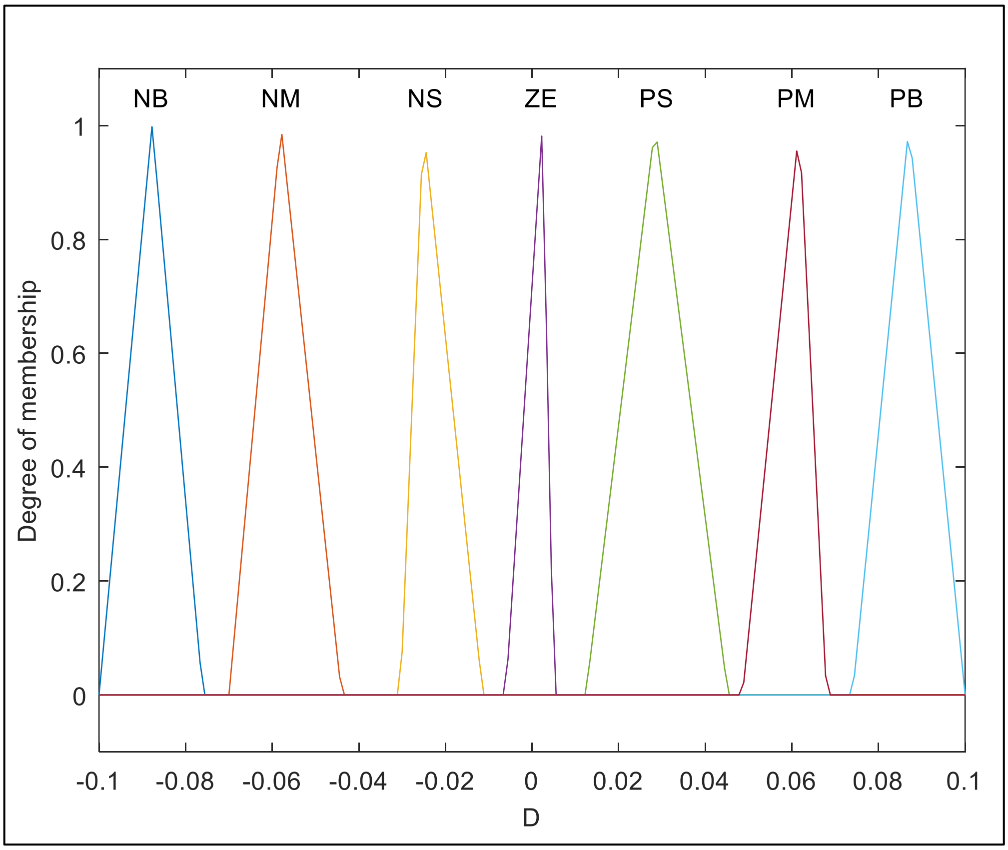


Figure II.24: Graphical view of the membership function for duty cycle

b. Setting of fuzzy rules:

E \ CE	NB	NM	NS	ZE	PS	PM	PN
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PN	ZE	PS	PM	PB	PB	PB	PB

Table II.3: Fuzzy rule base

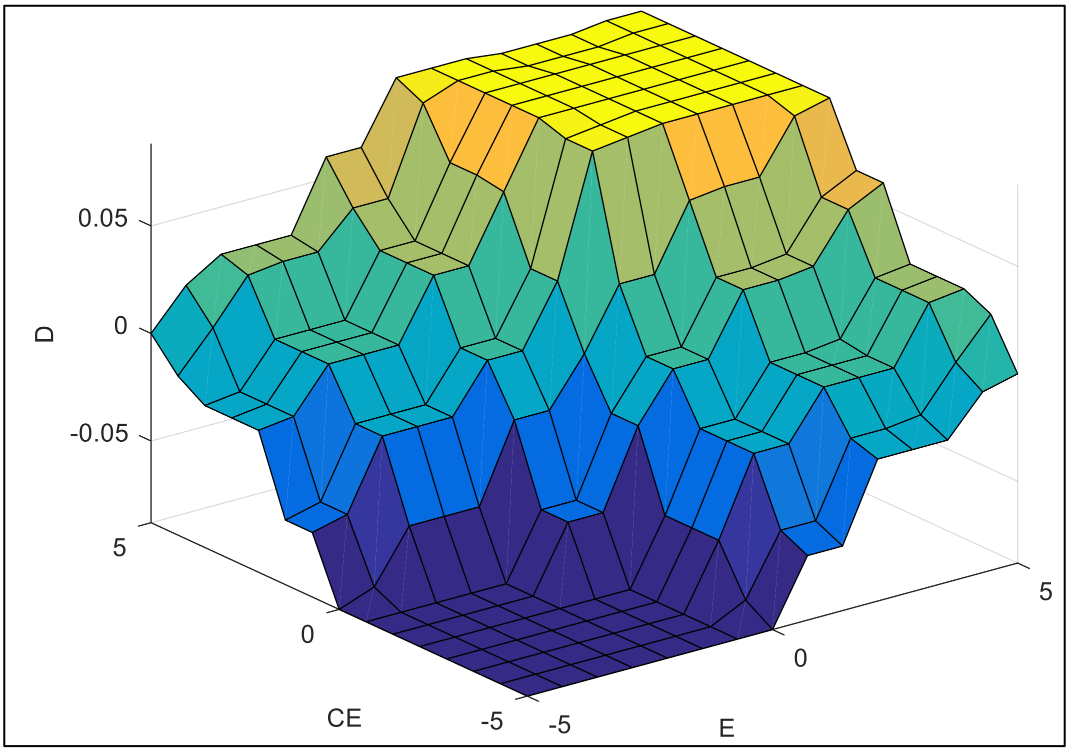


Figure II.25: Surface view of fuzzy input versus output functions

II.3.4 Simulation and Analyze:

II.3.4.1 PV model with P&O MPPT:

- **Simulink Block :**

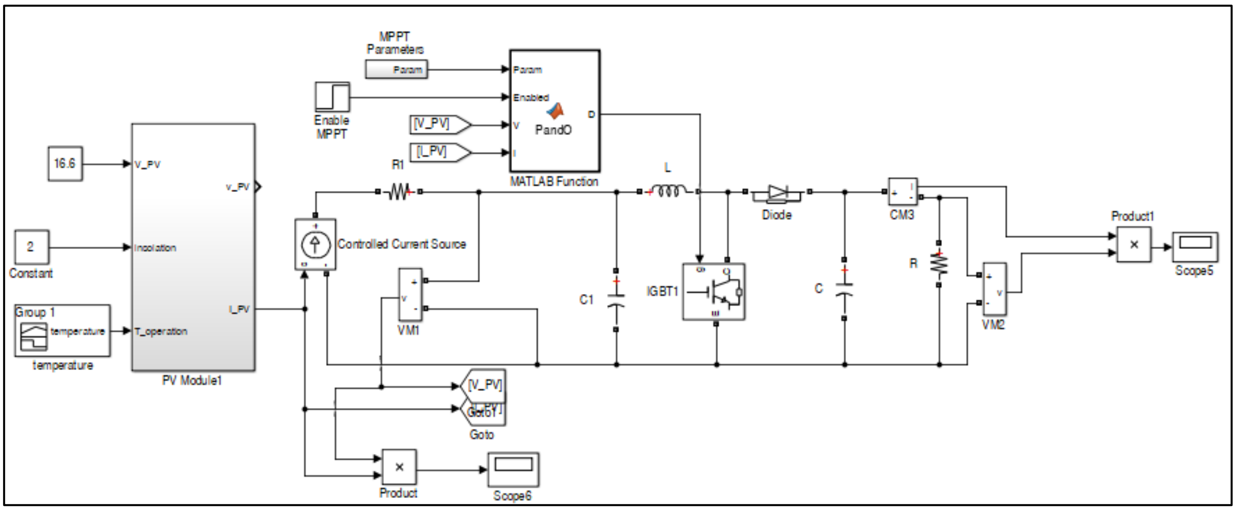


Figure II.26: Simulink Block of PV model with P&O MPPT

- **Simulation Results:**

The results presented to you are made under conditions of T= 25c° from t=0 till t=2s and T=80c°and be yond, with a fixed irradiation of 1000W/m2.

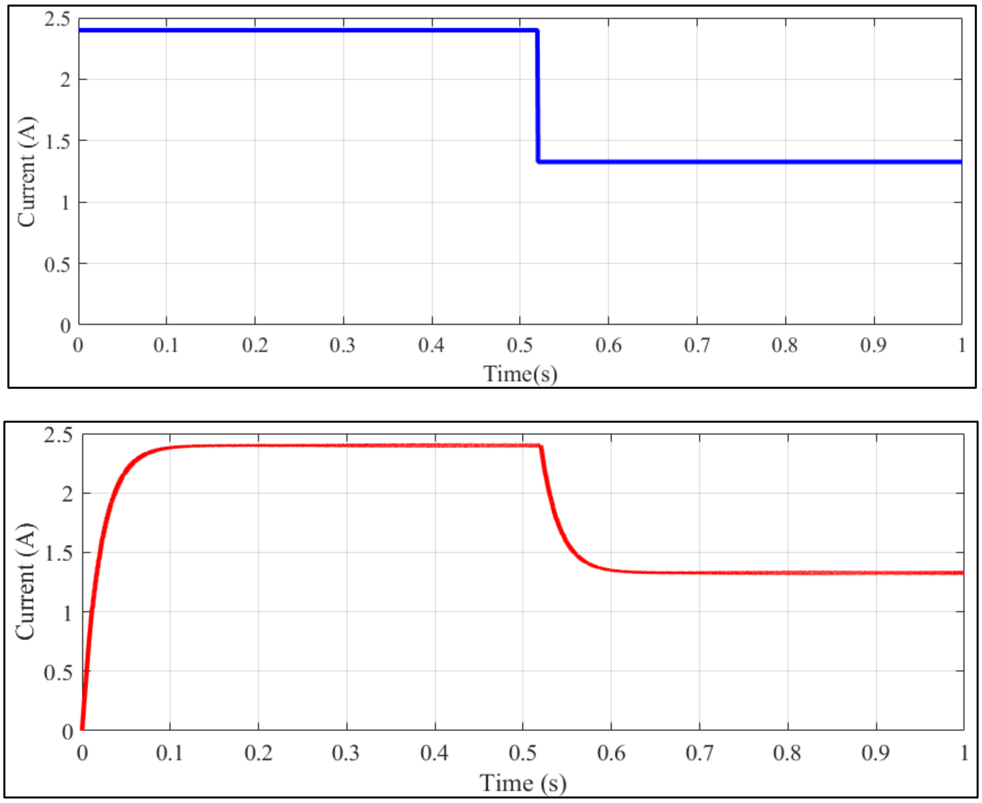


Figure II.27: The output Current from both the PV module and the Boost converter

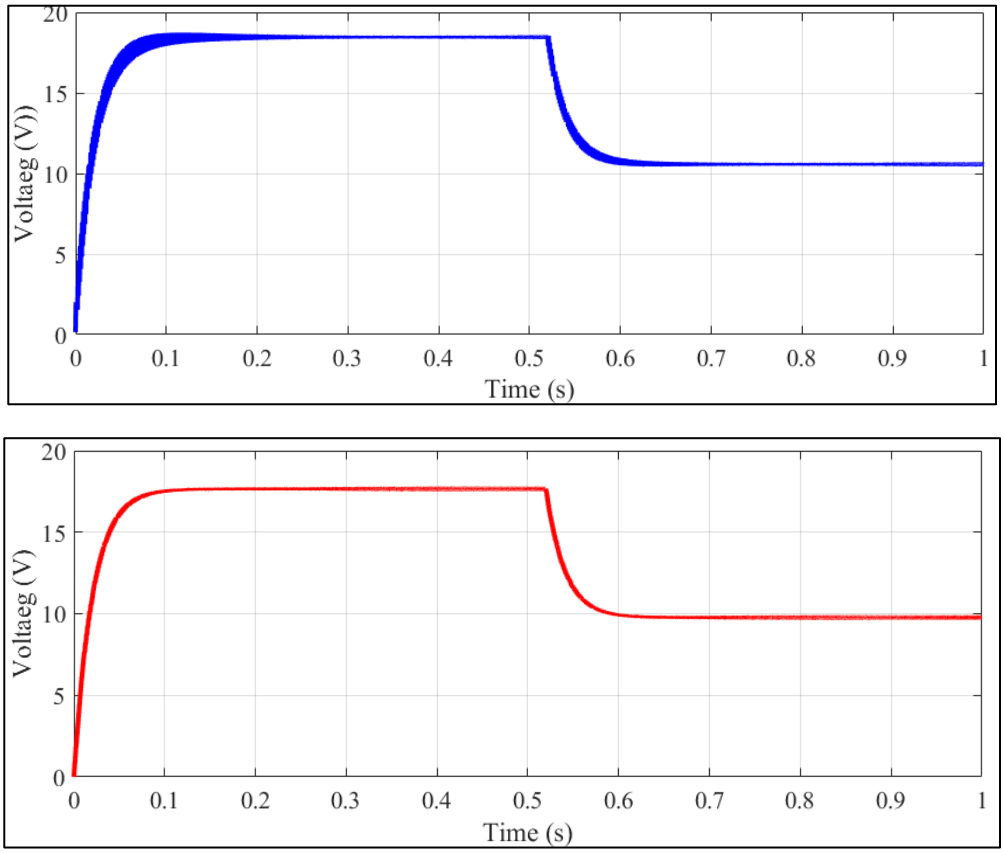


Figure II.28: The output Voltage from both the PV module and the Boost converter

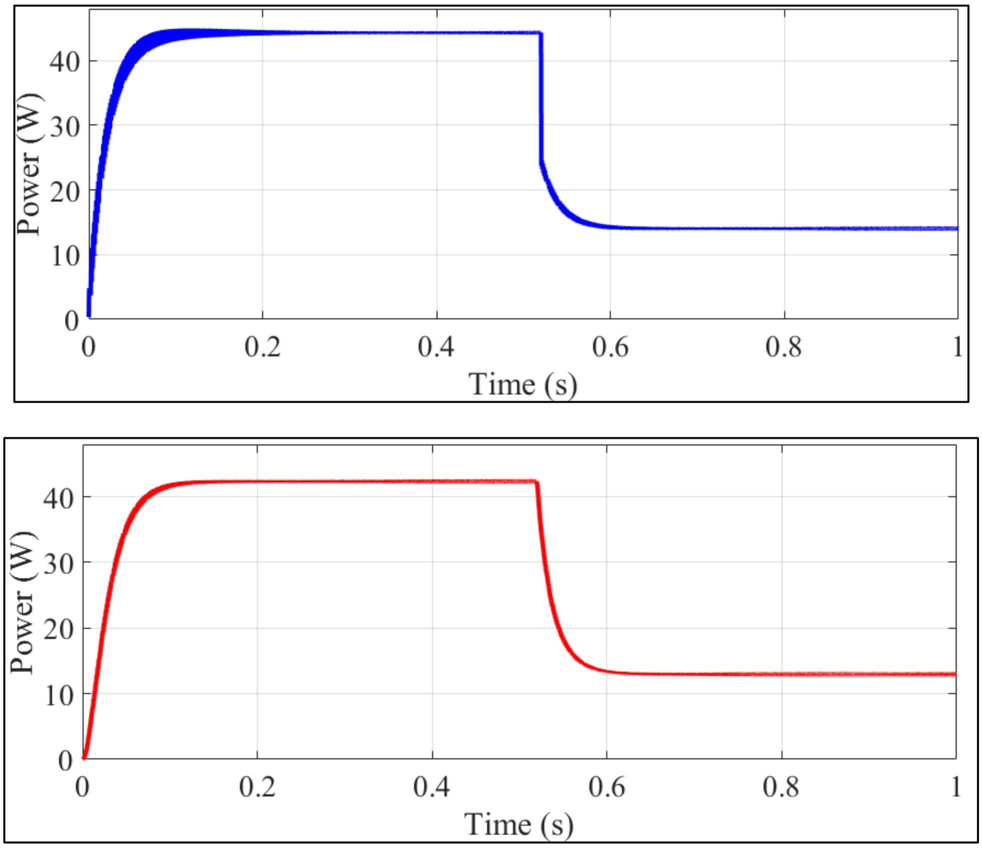


Figure II.29: The output Power from both the PV module and the Boost converter

- **Analyze and discuss:**

  The P&O algorithm succeeded in tracking the MPP, even after the sudden change of temperature, the controller manage to track the new MPP and maintain it. All though we notice there is a small loss of power from the solar panel side to the boost converter output side due to the switching losses and the losses in the inductor and capacitor of the boost converter.

II.3.4.2 PV model with Fuzzy Logic controller:

- **Simulink Block:**

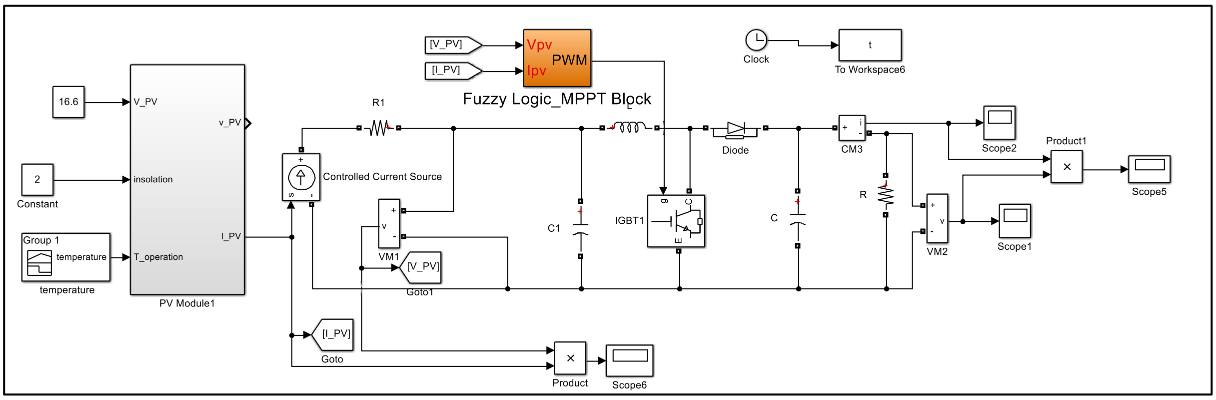


Figure II.30: Simulink Block of PV model with Fuzzy Logic controller

The internal view of Fuzzy Logic controller is shown in annex B.

- **Simulation Results:**

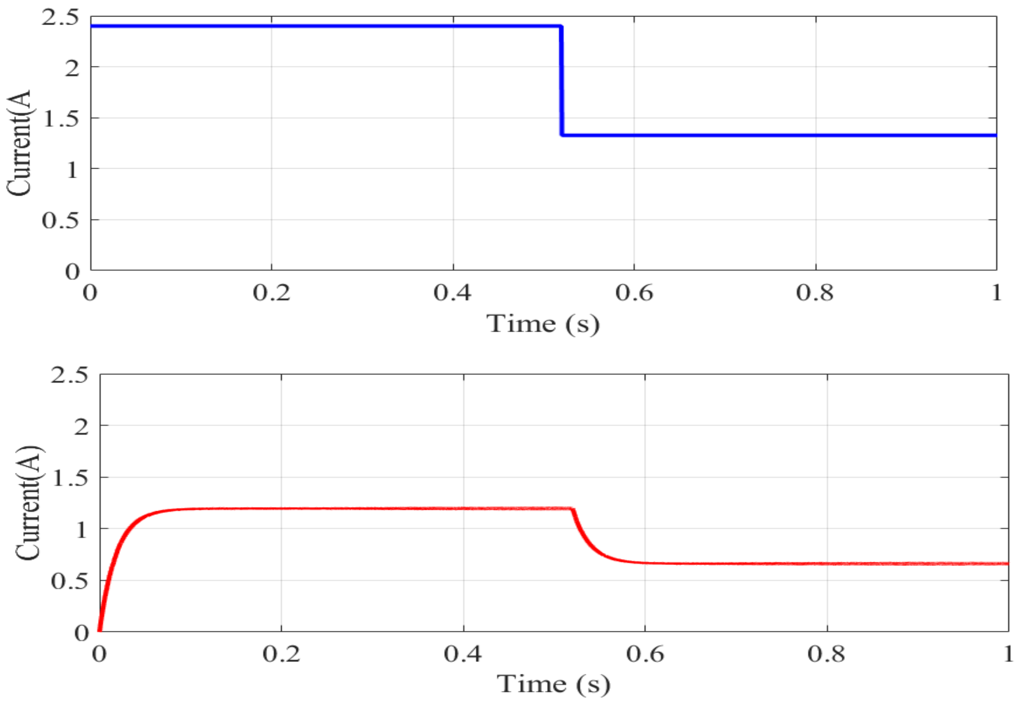


Figure II.31: The output Current from both the PV module and the Boost converter

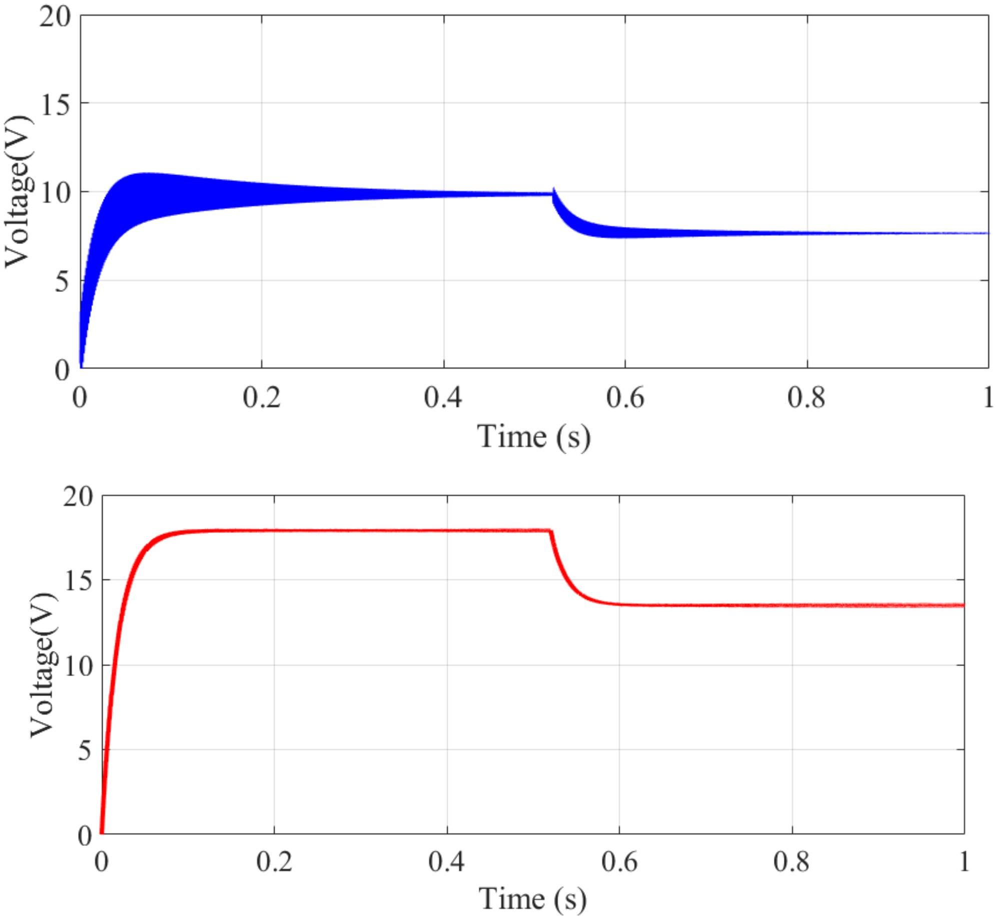


Figure II.32: The output Voltage from both the PV module and the Boost converter

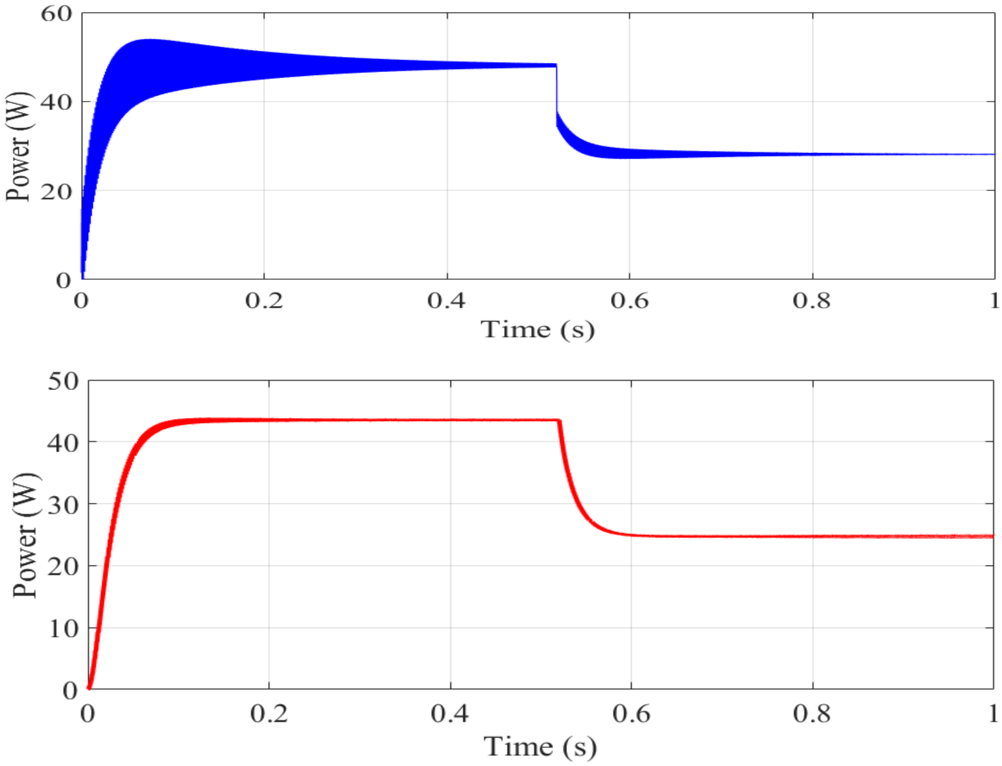


Figure II.33: The output Power from both the PV module and the Boost converter

- **Analyze and discuss:**

  For The fuzzy logic controller we notice some disturbance in the PV voltage and power output which are caused by the fast response of the FLC, these perturbations don't affect the setting time, which was slightly shorter than the P&O time.

II.3.4 Comparison of Fuzzy Logic and P&O MPPT Techniques

Both Fuzzy Logic and P&O MPPT Techniques have their ups & downs, we will list the few that we noticed:

	P&O	Fuzzy Logic
Setting Time	Medium	Fast
Accuracy of MPP	oscillates around the MPP after setting	holds it steady
Before setting	The process of detecting the MPP is smooth	has some problems detecting MPP in thefirst milliseconds that didn't affect the setting time but it will for sure effect the equipment

Table II.4: comparison of Fuzzy Logic and P&O MPPT Technique

II.5 Conclusion:

In this chapter we discussed about the photovoltaic cell function does and how modules interconnection affects their output. We also presented a mathematical module to make the theoretical study of the cell characteristics possible and easy, and for that a simulation was necessary.From the simulation we found that the power delivered by the photovoltaic module depends on several parameters including temperature and Irradiation.

Thus, we have briefly exposed some basic topologies of switching power supplies, which are nothing more than DC-DC converters. We have cited the Boost converter, Buck converter and Boost buck converter. We have also presented the MPPT control of DC / DC converters to find the point where the power of the photovoltaic generator is maximum by the method.

CHAPTER III:

Modeling and Simulation of Z-source Inverter

III.1 Introduction:

DC / AC converters of the impendent source inverter type appeared in the scientific literature in the 2000s through the work of Professor Fang Zheng Peng published in the congress article [21] published in 2002.

The evolution of inverters did not stop at the ordinary Z-source inverter with 6 switches, recently a new topology was proposed, Reduced Switch Z Source Inverter, which contains 4 switches instead of 6 and has a way better performance regarding power quality and the losses.

In this chapter, we will provide the Operating principle and circuit analysis of the Z-source network and its Control strategies. Simulation and results were done with MATLAB/Simulink.

III.2 Inverter:

An inverter (power inverter) is an electrical device that converts DC/AC power or direct current (DC) to AC power or alternating current (AC). The converted alternating current (AC) can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.

A typical DC/AC converter system is shown in **figure (III.1).**

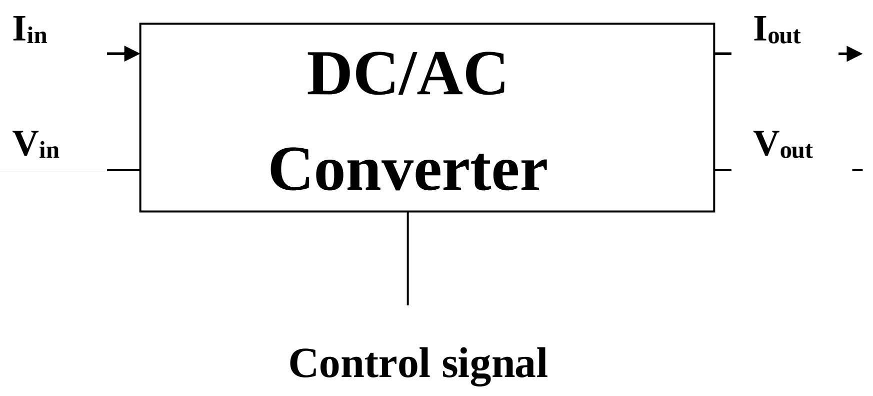


Figure III.1: General block diagram of DC-AC converter.

III.3 Z-Source Inverter (ZSI):

The Z-source inverter is an alternative power conversion topology that can both buck and boost the input voltage using passive components. It uses a unique LC impedance network for coupling the converter main circuit to the power source, which provides a way of boosting the input voltage, a condition that cannot be obtained in the traditional inverters.

It has a valuable feature due to two particular ideas added to the basic Voltage Source converter:

- Turning on at least one leg of switches set, a shoot-through mode, which is forbidden in conventional converters.
- X-shaped impedance network includes two pairs of capacitors and inductances, which maintain energy in the shoot-through state.

Also, a diode is used to prevent the passage of reverse currents.

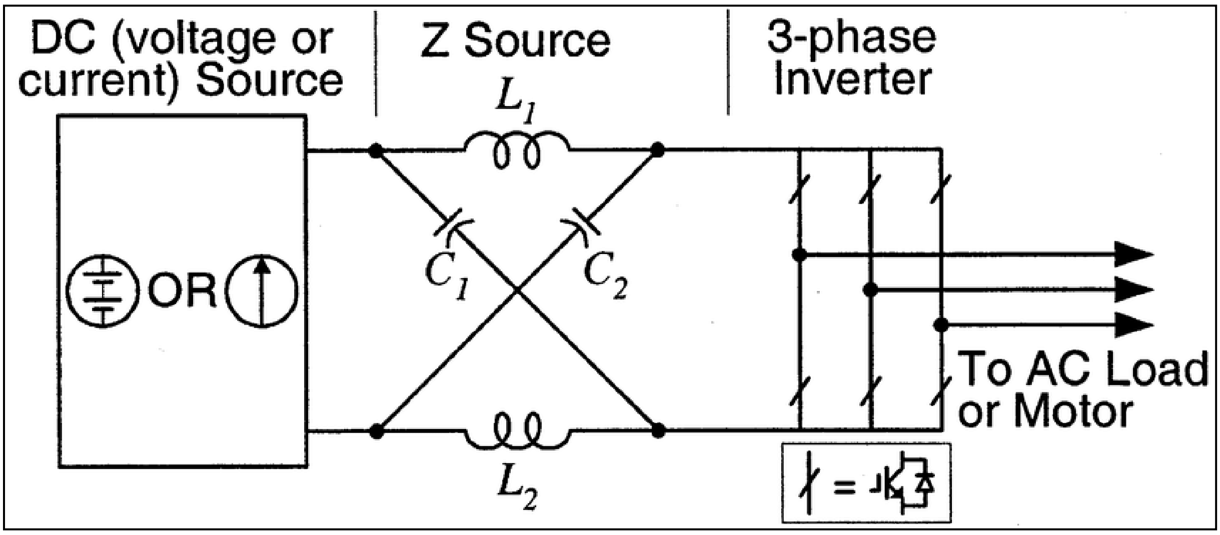


Figure III.2: General structure of the Z-source inverter.

III.4 Comparison between CSI, VSI, and ZSI:

Current Source Inverter	Voltage source inverter	Z-source inverter
The CSI acts as a constant current source or current stiff since a large inductor is used in series with the voltage source	The VSI acts as a constant voltage source or voltage stiff inverter since a large capacitor is used in parallel with the voltage source	The ZSI acts as a constant high impedance voltage source. As capacitor and inductor is used in the DC link
A CSI is capable of withstanding short circuits across any two of its output terminals. Hence momentary short circuit on load.	A VSI is a more dangerous situation as the parallel capacitor feeds more power to the fault.	In ZSI miss-firing of the switches sometimes is also acceptable.
Cannot be used in both buck or boost operation of the inverter at the same time.	Cannot be used in both buck or boost operation of the inverter at the same time.	Can be used in both buck and boost operation of the inverter at the same time.
The main circuits cannot be interchangeable	The main circuit cannot be interchangeable here also	Here the main circuits are Interchangeable.
It is affected by the EMI noise	It is affected by the EMI noise.	It is less affected by the EMI noise.
It has a considerable amount of harmonic distortion.	It has a considerable amount of harmonic distortion.	Harmonics Distortion in low.
Power loss should be high because of the filter.	Power loss is high.	Power loss should be lower.
Observed that power loss decreases efficiency here.8	High power loss decreases efficiency here.	Higher efficiency because of less power loss

Table III.1: Comparisons of CSI, VSI, and Impedance Source Inverter (ZSI) [45].

III.5 Analysis of Z-source network:

The Z-source inverter is used to overcome the problems in the traditional inverters, this Z-source inverter employs a unique impedance network coupled with the inverter main circuit to the power source. This inverter has unique features compared with the traditional sources.

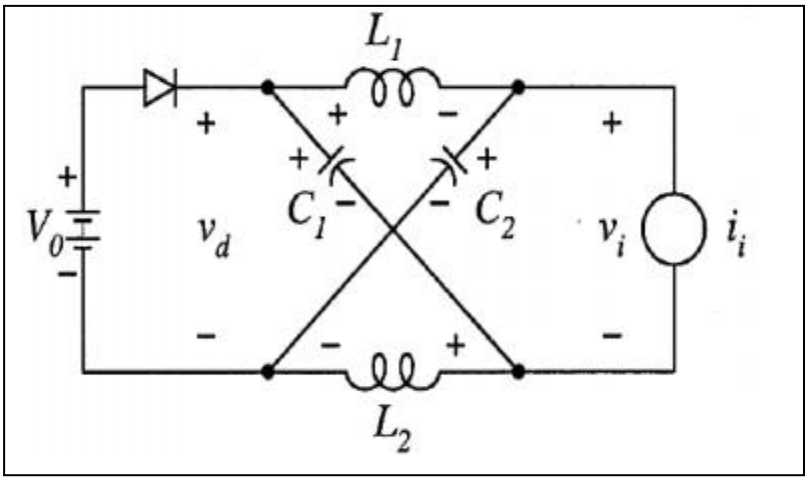


Figure III.3: Equivalent circuit of the Z-source inverter viewed from the dc link.

Assume the inductors (L_1 and L_2) and capacitors ($C_1$and C_2) have the same inductance and capacitance values respectively [46].

$$\begin{cases} V_{L1} = V_{L2} = V_L \\ \quad and \\ V_{C1} = V_{C2} = V_C \end{cases} \tag{III.1}$$

The Z-source network uses two modes of operation to achieve boost and inversion in a single stage:

III.5.1 Shoot-through state (STS):

The ZSI advantageously utilizes the shoot-through states to boost the DC bus voltage by gating on both the upper and lower switches of a phase leg [46].

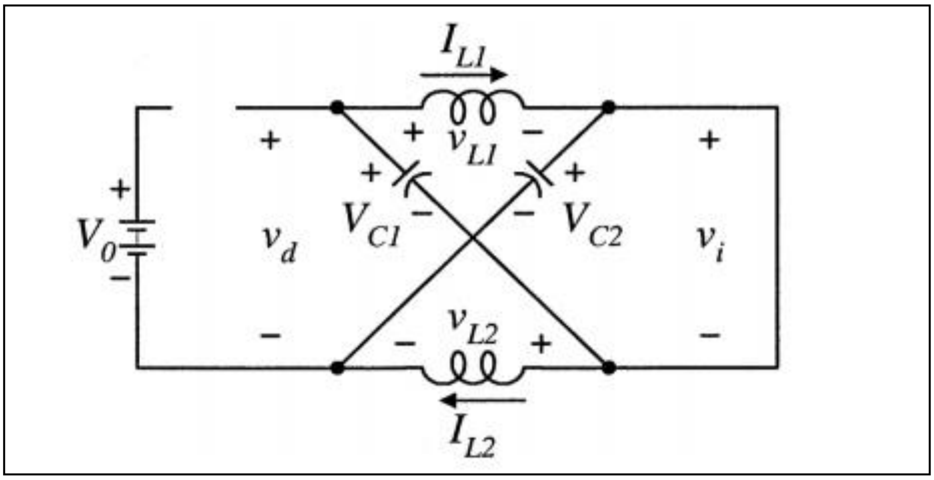


Figure III.4: Equivalent circuit shoot-through zero state of the ZSI viewed from the dc link.

The circuit is in a shoot-through zero state, as a result, the capacitor voltage is boosted during this state, the sum of the two capacitors voltage is greater than the dc source voltage ($V_{C1}+V_{C2}> V_0$), the diode is reverse biased, and the capacitors charge the inductors. The voltages across the inductors are [46]:

$$\begin{cases} V_{L1} = V_{C1} \\ and \\ V_{L2} = V_{C2} \end{cases} \tag{III.2}$$

The inductor current increases linearly assuming the capacitor voltage is constant during this period. Because of the symmetry ($L_1=L_2=L$) and ($C_1=C_2=C$) of the circuit, ($V_{L1}=V_{L2}=V_L$), ($I_{L1}=I_{L2}=I_L$) and ($V_{C1}=V_{C2}= V_C$) [46].

This means,

$$V_C = V_L \text{ , } V_D = 2V_C \text{ and } V_i = 0 \tag{III.3}$$

III.5.2 Active state (Non-shoot-Through State):

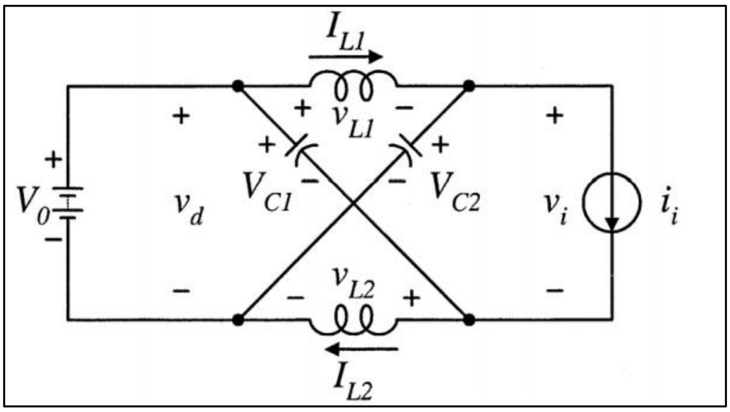


Figure III.4: Equivalent circuit non-shoot-through zero state of the ZSI viewed from the dc link.

The inverter is in a non-shoot through state and the inductor current meets the following equation [46].

$$I_L > \frac{1}{2} I_i \quad \text{(III.3)}$$

Again because of the symmetry of the circuit, the capacitor current I_{C1} and I_{C2} and the inductor current I_{L1} and I_{L2} should be equal to each other respectively. In this mode, the input current from the dc source becomes [46]:

$$I_{in} = I_{L1} + I_{C1} = I_{L1} + I_{L2} - I_i = I_L - I_i > 0 \quad \text{(III.4)}$$

Therefore, the diode is conducting and the voltage across the inductor is:

$$V_L = V_0 - V_c \quad \text{(III.5)}$$

which is negative (the capacitor voltage is higher than the input voltage during boost operation when there is a shoot-through state), thus the inductor current decreases linearly assuming the capacitor voltage is constant. As time goes on, the inductor current keeps decreasing to a level that no longer the condition of (2) can be met. At this point, the input current I_{in} of the diode current is decreased to zero, Mode 2 ends and the inverter enters a new mode [46].

Shoot-through state and Active state are the main two operation modes for the z network but there are other modes which are:

II.5.3 Mode 3:

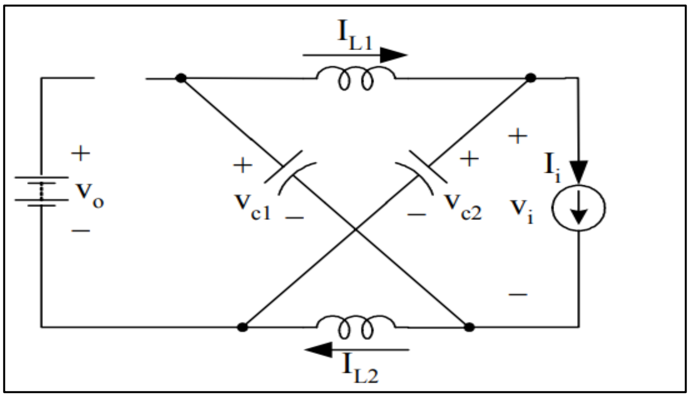


Figure III.5: Equivalent circuit during the 3rd operation mode of the Z network.

At the end of the Active state *(Non-shoot-Through State)*, the inductor current decreases to half of the inverter dc side current, I_i. As a result, the input current becomes zero and the diode becomes reverse-biased. Assuming that the inverter load is inductive and has a much larger inductance than that of the inductor L_1andL_2, the inductance of L_1 and L_2 are negligible and the inductor current and inverter voltage $V_i$are respectively [46].

$$I_L = \frac{1}{2} I_i \tag{III.6}$$

And

$$V_i = V_c \tag{III.7}$$

II.5.4 Mode 4:

The diode stops conducting and the inverter is an open circuit to the Z-source network because of I_i=0. The inductor current becomes zero and maintains zero until the next switching action. Therefore in this mode, the Z-source circuit is isolated from both the dc source and the load [46].

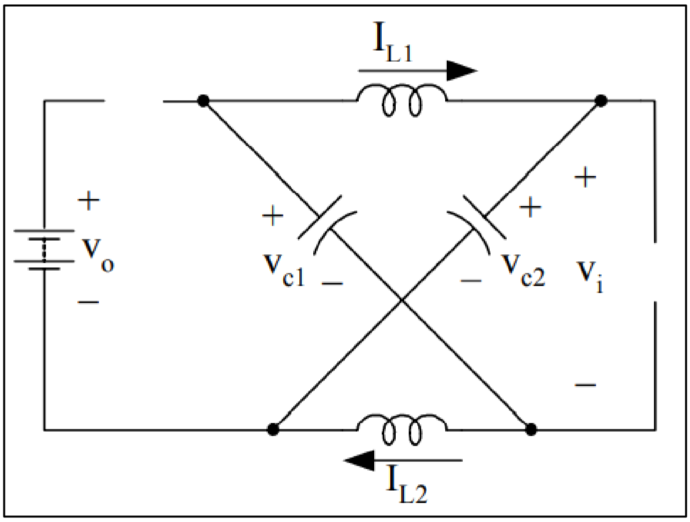


Figure III.6: Equivalent circuit during the 4th operation mode of the Z network.

III.6 Design of Z network:

III.6.1 Calculation of the Elevation Factor β:

The boost factor β can be controlled by the duty cycle of the shoot-through zero state over the non-shoot through states of the PWM inverter. The shoot-through zero state does not affect PWM control of the inverter, because it equivalently produces the same zero voltage to the load terminal. The available shoot-through period is limited by the zero state periods that are determined by the modulation index [47].

Set non-shoot-through states for an interval of T_1, in one switching cycle T, we have $T = T_0 + T_1$. So from **Figure III.4** equivalent circuit, we have [48]:

$$V_i = V_c - V_L \qquad \text{(III.8)}$$

According to the relationship (III.5) we have:

$$V_i = 2V_c - V_0 \qquad \text{(III.9)}$$

The relationship between switching period and voltage of capacitor and dc source is:

$$\frac{V_c}{V_0} = \frac{T_1}{T_1 - T_0} \qquad \text{(III.10)}$$

The peak dc-link voltage across the inverter bridge is expressed in (III.3) and can be rewritten as:

$$V_i = V_c - V_L = 2V_c - V_0 = \frac{T}{T_1 - T_0} V_0 = \beta V_0 \qquad \text{(III.11)}$$

- $\boldsymbol{\beta}$ is boosting factor: $\beta = \frac{T}{T_1 - T_0} \geq 1$

Where T is the total period, T_0 is the shoot-through period, and D_0 is the Shoot-Though duty ratio

$$D_0 = \frac{T_0}{T_S} \qquad \text{(III.12)}$$

III.6.1.1 Maximum Shoot-Through Duty Ratio:

The maximum shoot through ratio for a given application is described by the following equation [49]:

$$D_{0\,max} = \frac{V_{c\,max} - U_{pv\,min}}{2V_{c\,max} - U_{pv\,min}} \qquad \text{(III.13)}$$

Where, $\boldsymbol{V_{C\,max}}$ is the maximum capacitor voltage for the application and Upv is the minimum voltage of the PV array connected to the ZSI [49].

The output peak phase voltage from the inverter can be expressed as:

$$V_{AC} = M\frac{V_i}{2} = M\beta\frac{V_0}{2} \qquad \text{(III.14)}$$

Where M is the modulation index

From this equation, we know the output AC voltage can be controlled by the value of M and β, the boost factor [48].

III.6.2 Z-network Inductor Design:

The inductors are designed for the shoot-through state when the capacitor voltage V_c is impressed on the inductors for the duration of the shoot-through duty cycle D_0[49].

$$V_C = V_L \tag{III.15}$$

$$L = L_1 = L_2 = \frac{V_{c\,max} \times D_{0\,max}}{f_{sw} \times \Delta i_L} \tag{III.16}$$

Where, $\boldsymbol{V_{C\,max}}$ is the maximum voltage across the capacitor, $\boldsymbol{D_{0\,max}}$ is the maximum shoot-through duty ratio [49].

III.6.3 Z-network Capacitor Designs:

The capacitors for a single-phase topology are designed to absorb the second-order voltage harmonic (120 Hz) [49].

$$C = C_1 = C_2 = \frac{P}{2\omega V_{C\,min} \times \Delta V_C} \tag{III.17}$$

The voltage rating of the capacitor should be at least the peak voltage across the capacitor V_C. Electrolytic capacitors are usually used in single-phase inverters to suppress second-order harmonics. For less than 5% 120 Hz ripple [49].

III.7 Four Switch Three Phase Inverter (FSTPI) model:

The main power circuit of the FSTPI fed resistive load is shown in **Figure III.7**, four switches q_1, q_2, q_3, and q4 and DC link capacitors C_1 and C_2 are employed in this circuit, Phase « a » and « b » are taken from the legs, which have the switches. Phase « c » is connected in the midpoint of the two dc-link capacitors [47].

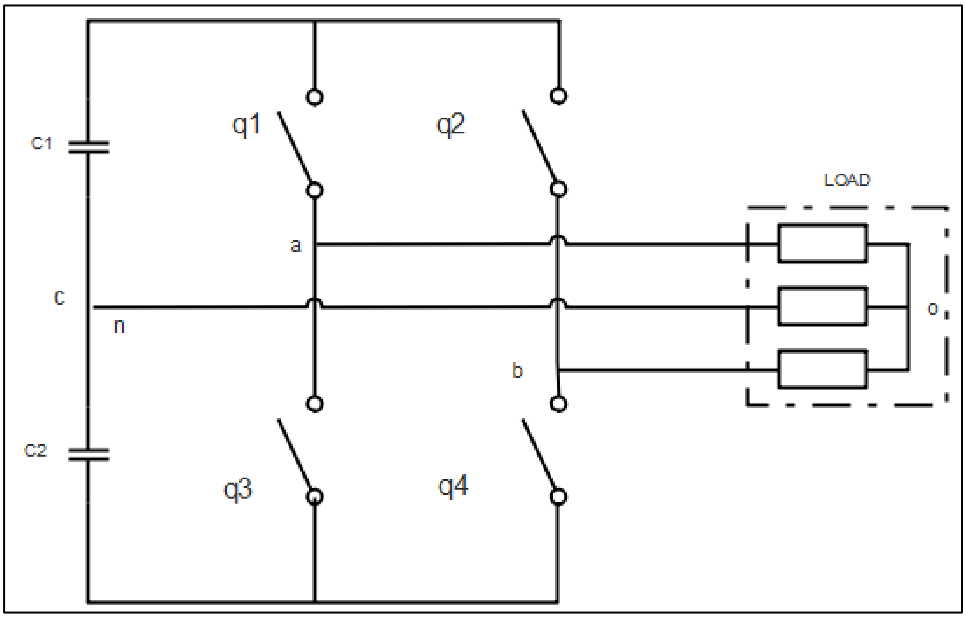


Figure III.7: Three Phase Four Switch Inverter

Four switches have generated the line-to-line voltages, V_{13} and V_{23} whereas V_{12} is generated according to Kirchhoff's voltage law from a split-capacitor bank in the dc-link. The conduction states of the power switches are included with binary variables from q_1 to q_4. Therefore, a binary value 1 indicates a switch is on, while 0 indicates the switch is off. The complementary pairs are q_1q_3 and q_2q_4 and, as a consequence,

$$q_3 = (1 - q_1) \text{ and } q_4 = (1 - q_2) \quad \text{(III.18)}$$

The assumed stiff voltage available across the two dc-link capacitors, are

$$V_{c1} = V_{c2} = \frac{V_{dc}}{2} \quad \text{(III.19)}$$

Where V_{dc} corresponds to a stiff dc-link voltage. The pole voltages V_1, V_2, V_3 are depending on the switching states of the power switches in the inverter. They can be expressed in terms of the binary variables q_1 and q_2, and the dc-link voltage as follows [47]:

$$V_1 = 2q_1 - \frac{V_{dc}}{2} \quad \text{(III.20)}$$

$$V_2 = 2q_2 - \frac{V_{dc}}{2} \quad \text{(III.21)}$$

$$V_3 = 0 \tag{III.22}$$

(0, 0), (0, 1), (1, 0), and (1, 1) are the four switching states of FSTPI. Here the load is represented by a resistive load. In the case of the six switches converter, switching states (0, 0) and (1, 1) are represented as zero-vectors, these zero vectors cannot supply the dc-link voltage to the load so that current cannot flow through the load. In this FSTPI inverter, any one phase of the load is always connected to the midpoint of the dc-link capacitors, so that current can flow through the load even at the zero-vectors. During the switching states of (0, 1) and (1,0) the phase which is connected to the midpoint of dc-link capacitors is uncontrolled and the resultant current of the other two phases flows through this phase [47].

The capacitor voltages are equal when the load is ideally symmetric. So that, during (0, 1) and (1, 0) vector states current cannot flow. The large variations of the voltage across the two dc-link capacitors are caused by one phase current circulating through the capacitive bank, Which will make the inverter output current get significant ripples, distortions, and unbalances. The unequal loading of the split dc-link capacitors can be achieved by Two of the inverter switching states (1, 1), (0, 0). This causes one-half of the links to discharge at a faster rate than the other, resulting in the generation of a voltage imbalance [47].

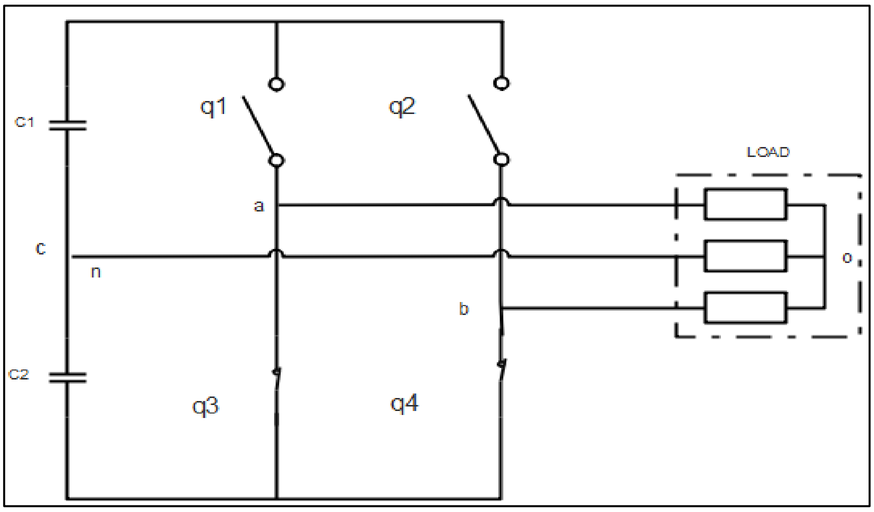


Figure III.8: Inverter Switching State (0,0)

$$V_1 = V_2 = -\frac{V_{dc}}{2}, \text{ when } q_1 = q_2 = 0 \tag{III.23}$$

$$V_1 = \frac{V_{dc}}{2}, V_2 = -\frac{V_{dc}}{2}, \text{ when } q_1 = 1, q_2 = 0 \tag{III.24}$$

$$V_1 = V_2 = \frac{V_{dc}}{2}, \text{ when } q_1 = q_2 = 1 \qquad \text{(III.25)}$$

$$V_1 = -\frac{V_{dc}}{2}, V_2 = \frac{V_{dc}}{2}, \text{ when } q_1 = 0, q_2 = 1 \qquad \text{(III.26)}$$

The phase to neutral voltage can be defined as follows:

$$V_{01} = V_1 - V_{n0} \qquad \text{(III.27)}$$

$$V_{02} = V_2 - V_{n0} \qquad \text{(III.28)}$$

$$V_{03} = V_3 - V_{n0} \qquad \text{(III.29)}$$

$$V_{n0} = \frac{V_{dc}}{3}(2q_1 + 2q_2 - 2) \qquad \text{(III.30)}$$

The phase to neutral voltage can be derived as follows Substituting Equations (III.30) and (III.20) in (III.27):

$$V_{01} = V_1 - V_{n0} \qquad \text{(III.31)}$$

$$V_{01} = \frac{V_{dc}}{3}(4q_1 - 2q_2 - 1) \qquad \text{(III.32)}$$

The same procedure is followed to arrive at V_{02} andV_{03}:

$$V_{02} = \frac{V_{dc}}{3}(4q_2 - 2q_1 - 1) \qquad \text{(III.33)}$$

$$V_{03} = \frac{V_{dc}}{3}(-2q_1 - 2q_2 + 2) \qquad \text{(III.34)}$$

Switching Function		Switch on		Output Voltage Vector		
q_1	q_2	$T_1 = q_1,$ $T_3 = q_2$ $T_4 = T_2$		V_{01}	V_{02}	V_{03}
0	0	T_2	T_4	$\frac{-V_{dc}}{3}$	$\frac{-V_{dc}}{3}$	$\frac{2\,V_{dc}}{3}$
0	1	T_2	T_3	$-V_{dc}$	V_{dc}	0
1	0	T_1	T_4	V_{dc}	$-V_{dc}$	0
1	1	T_1	T_3	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{3}$	$\frac{-2\,V_{dc}}{3}$

Table III.2: Switching Functions and the Output Voltages from Inverter [50].

The entries in **Table III.2** relate to the output voltage vector corresponding to each switching function [47].

III.8 Control strategies for Z-source inverter:

Control techniques are so many from analog to digital from traditional to new inventor techniques but the most used technique is the PWM which stands for plus within modulation, this technique has its unique simplicity and very efficient performance.

III.8.1 General Theory of Pulse Width Modulation (PWM):

PWM technology was put forward based on an important conclusion in the sample control theory that when two groups of pulses with the same impulse area but different waveforms are input to an inertial link, the effectiveness of these two groups of impulses are the same. The main principle of the PWM technique can be briefly described as Through ON/OFF control on the semiconductor switching components, a series of pulses with the same amplitude and different width are generated on the output port to replace the sinusoidal wave or other waveforms required. The duty cycle of the output waveform needs to be modulated by a certain rule and as a result, both the output voltage and output frequency of the inverter can be regulated [50].

The advantages of using PWM are [51]:

- The output voltage control is easier and can be achieved without any additional components.
- The lower-order harmonics are either minimized or eliminated.

- It has very low power consumption.
- The entire control circuit can be digitized which reduces the susceptibility of the circuit to interference.

The classification of PWM techniques includes [50]:

- Sinusoidal PWM (SPWM)
- Selective Harmonic Elimination (SHE) PWM
- Minimum Ripple Current PWM
- Space Vector Pulse Width Modulation (SVPWM)
- Random Pulse Width Modulation (RPWM)
- Hysteresis band current control PWM
- Sinusoidal PWM with instantaneous current control

The most widely used techniques for implementing the pulse with modulation (PWM) strategy for multilevel inverters are Sinusoidal PWM (SPWM) and space vector PWM (SPWM). The SVPWM is considered a better technique of PWM implementation as it has advantages over SPWM in terms of good utilization of dc bus voltage, reduced switching frequency, and low current ripple, and other advantages as:

- Better fundamental output voltage.
- Useful in improving harmonic performance and reducing THD.
- Extreme simplicity and its easy and direct hardware implementation in a Digital Signal Processor (DSP).
- SVPWM can be efficiently executed in a few microseconds, achieving similar results compared with other PWM methods

III.8.2 Principle of SVPWM:

The output phase voltages of the inverter depend on the relationship between the switching variables [S_1; S_3; S_5] and the DC voltage as follows:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_3 \\ S_5 \end{bmatrix} \quad \text{(III.35)}$$

SVPWM works on the principle that when the upper switch is ON; the corresponding lower switch is OFF. The ON and OFF state of the upper switches (S1, S3, S5) evaluates the output voltages.

The SVPWM strategy approximates the reference voltage vector V_{ref} during each modulation period by a combination of eight vectors, each relating to a given configuration or state of the inverter, the six active vectors divides the plane into six sectors, (60° or $^{\pi}/_{3}$) for each sector, V_{ref} must be generated during each modulation period by two adjacent active vectors (V_1 to V_6) and two vectors of zero states (V_0 or V_7)

III.8.3 Analysis Of Space Voltage Vectors for FSTPI:

According to the scheme in **Figure III.7** the switching status is represented by binary variables q_1 to q_4, which are set to "1" when the switch is closed and "0" when open. In addition, the switches in one inverter branch are controlled complementary (1 on, off), therefore [53]:

$$q_1 + q_3 = 1$$
$$q_2 + q_4 = 1 \qquad \text{(III.36)}$$

Phase to common point voltage depends on the turning off signal for the switch:

$$V_{an} = 2q_1 - \frac{V_{dc}}{2} \qquad \text{(III.37)}$$

$$V_{bn} = 2q_2 - \frac{V_{dc}}{2} \qquad \text{(III.38)}$$

$$V_c = 0 \qquad \text{(III.39)}$$

Combinations of switching $q_1 - q_4$result in 4 general space vectors $\vec{V_1} \rightarrow \vec{V_4}$(Table III.3), components $\alpha\beta$ of the voltage vectors are gained from ABC voltages by using Clark's transformation:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} -1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \text{(III.40)}$$

Where V_a, V_b, V_c: phase voltages on the load (Y connection), defined by:

$$\begin{cases} V_a = \frac{1}{3}(2V_{an} - V_{bn}) \\ V_b = \frac{1}{3}(2V_{bn} - V_{an}) \\ V_c = -\frac{1}{3}(V_{an} - V_{bn}) \end{cases} \quad \text{(III.41)}$$

To form the required voltage space vector $\overrightarrow{V_{ref}}$ we can use 3 or 4 vectors in one sampling interval T_s. The constant value 0 (zero) vectors can be formed by dividing t_0(duration of zero vector) among 2 opposite vectors ($\overrightarrow{V_1}$,$\overrightarrow{V_3}$) or ($\overrightarrow{V_2}$,$\overrightarrow{V_4}$).

q_1	q_2	$\vec{V} = V_\alpha + jV_\beta$
0	*0*	$\overrightarrow{V_1} = \frac{V_{dc}}{3} e^{-j\frac{2\pi}{3}}$
1	*0*	$\overrightarrow{V_2} = 2\frac{V_{dc}}{3} e^{-j\frac{\pi}{6}}$
1	*1*	$\overrightarrow{V_3} = \frac{V_{dc}}{3} e^{j\frac{\pi}{3}}$
0	*1*	$\overrightarrow{V_1} = 2\frac{V_{dc}}{3} e^{j\frac{5\pi}{6}}$

Table III.3: combinations of switching and voltage space vectors

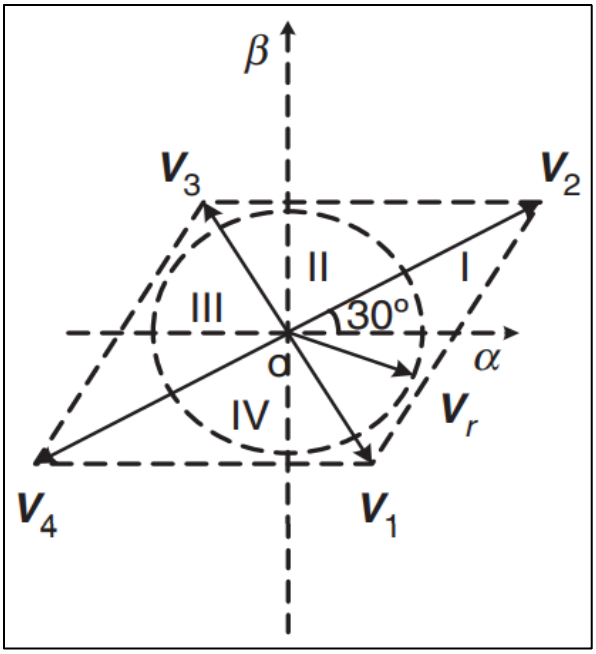


Figure III.9: Voltage vector distribution of FSTPI [52]

The performance index used for evaluating the output voltage is the Total Harmonic Distortion factor THD%, defined as follows:

$$THD\% = \frac{\sqrt{\sum_{n=2,3,\dots}\left(\frac{V_n}{n}\right)^2}}{V_1} \times 100\% \qquad \text{(III.42)}$$

Where:

n: harmonic number.

III.9 Simulation Model:

III.9.1 Simulink model of the circuit:

Figure (III.10) shows a three-phase inverter model, there are consists of a DC power supply, FSTPI circuit, both of them build with Simulink.

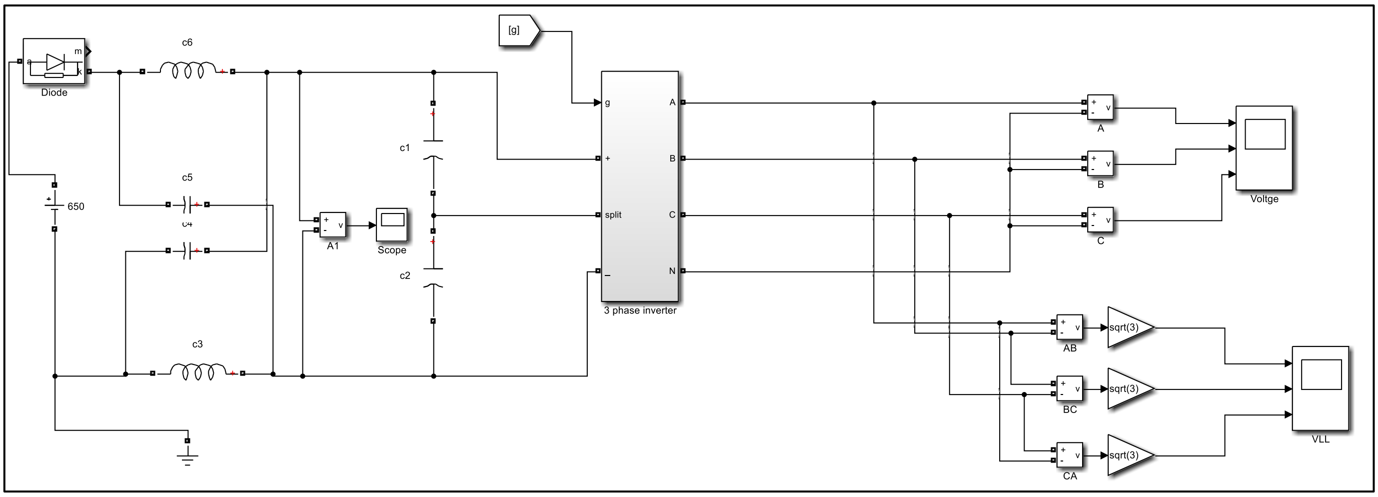


Figure III.10: Simulink model of FSTPI Z-Source system.

III.9.2 FSTPI circuit:

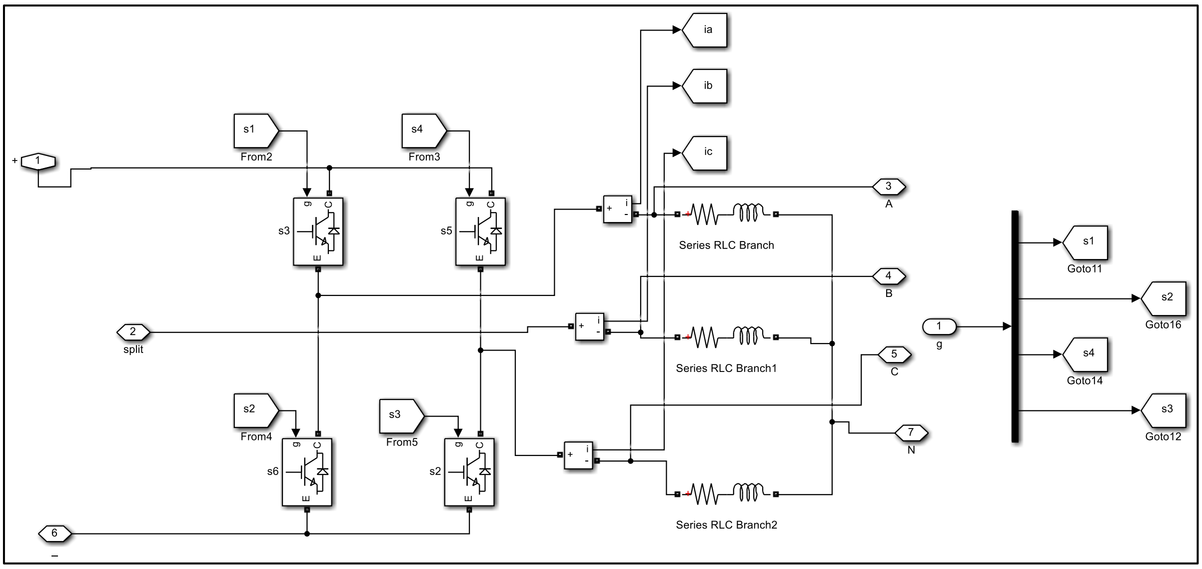


Figure III.11: Simulink model of FSTPI system.

III.9.3 Simulink model of SVPWM signal generator:

The SVPWM control system model is used to generate the SVPWM control signal for the FSTP Z-source inverter [See annex]. The whole SVPWM control system is shown in **Figure III.12.**

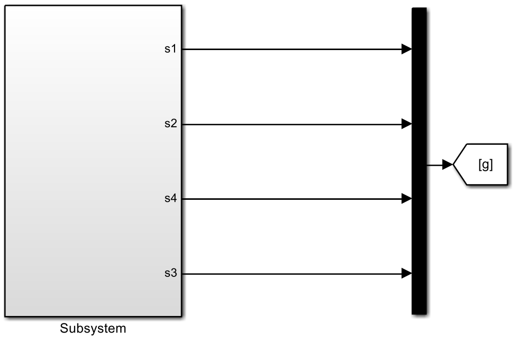


Figure III.12: SVPWM signal generator.

Simulation test beds using MATLAB/Simulink 2016 were constructed to validate the effectiveness of the system models and control algorithms proposed. Parameters used for the simulation are shown in **Table III.3**

Parameter	Value
DC bus voltage	300V
Z-source inductance (L_1 and L_2)	1mH
Z-source capacitance (C_1 and C_2)	4.7µF
DC split capacitance	330µF
Fundamental frequency	50Hz
Modulation Index (M)	0.8

Table III.3: Parameters used for simulation.

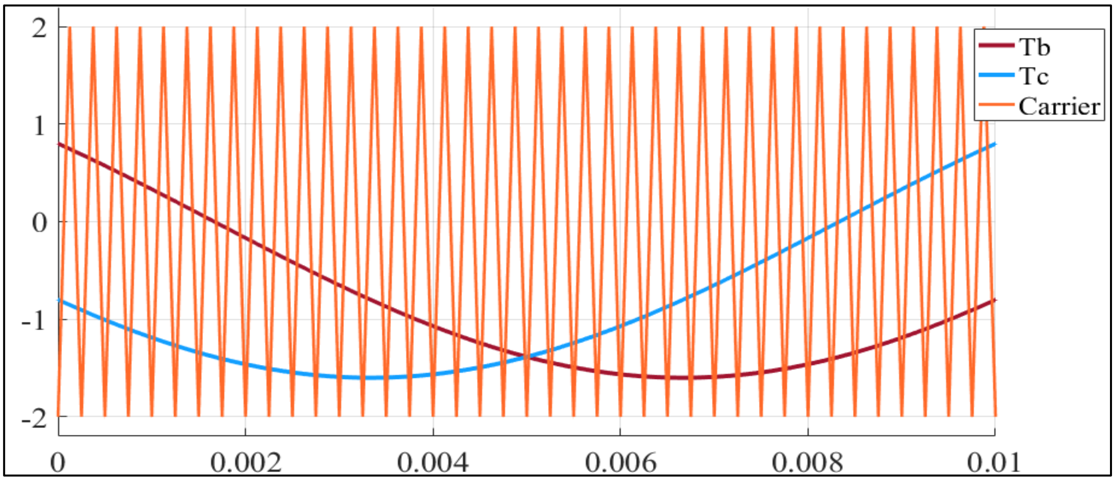


Figure III.13: Reference voltage and carrier wave

III.10 Simulation Results and Analyze:

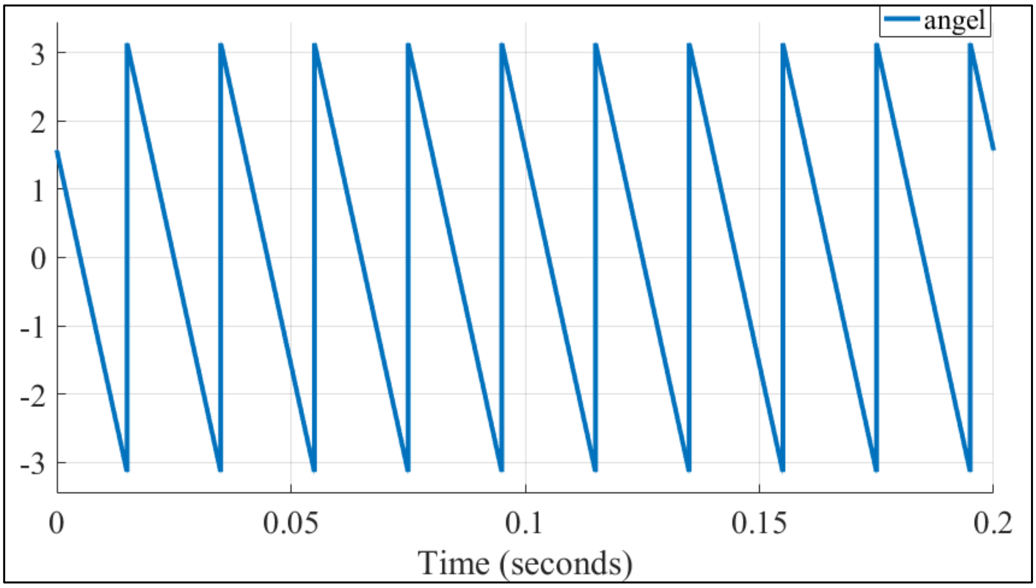


Figure III.14: PWM signal generator

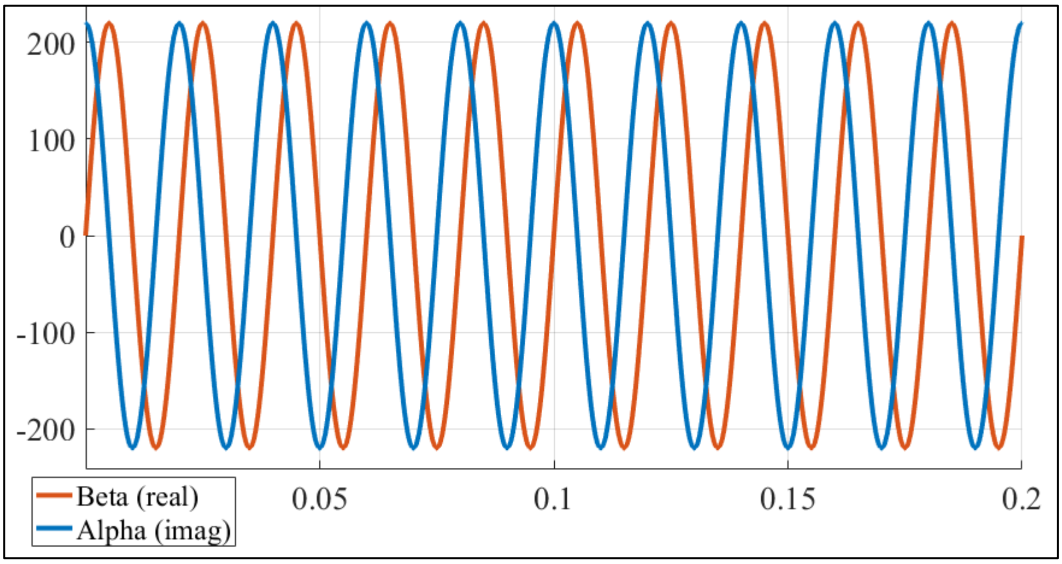


Figure III.15: Clarke transformations block and output waveform.

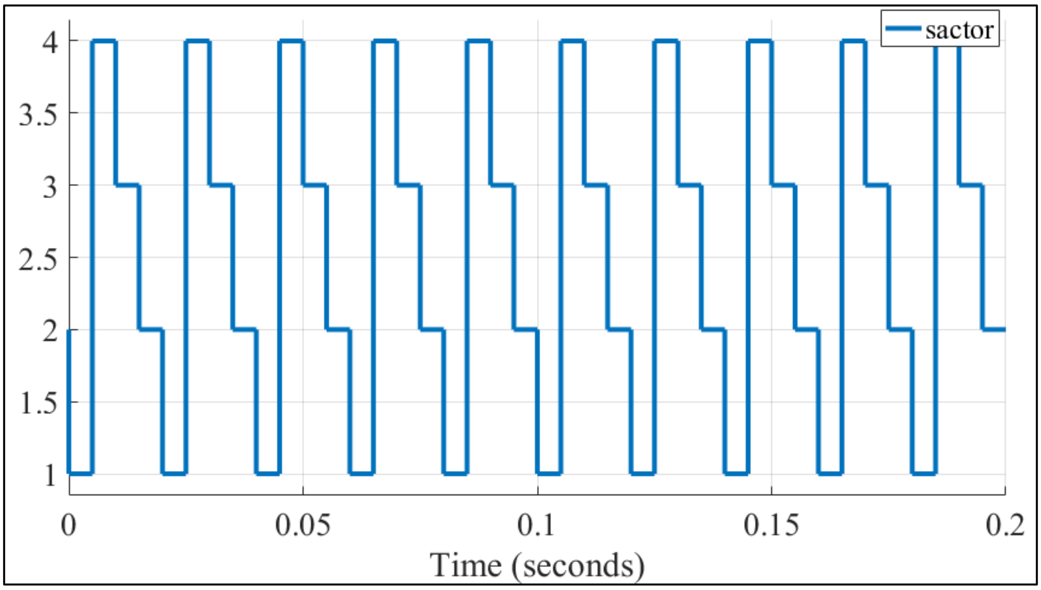


Figure III.16: Reference angel sector block.

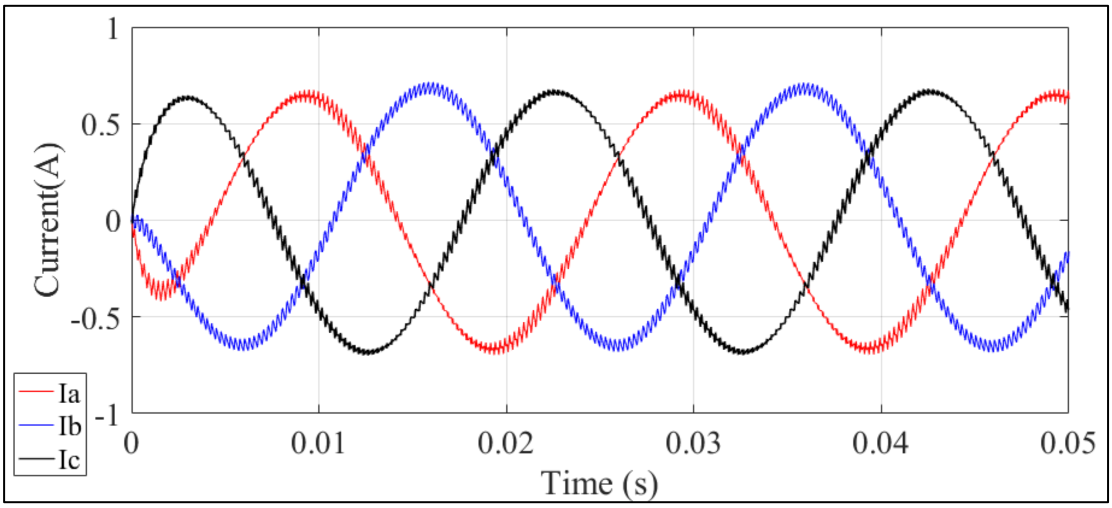


Figure III.17: Three Phase Current waveform of FSTP z source inverter across Load

- **Figure III.17**shows the waveform of the three-phase current output generated by the FSTP Z source inverter, as we can see the output does have a sinusoidal form in general due to the correct control method and the reduced number of switches but there are some little perturbations caused by the higher-order harmonics.

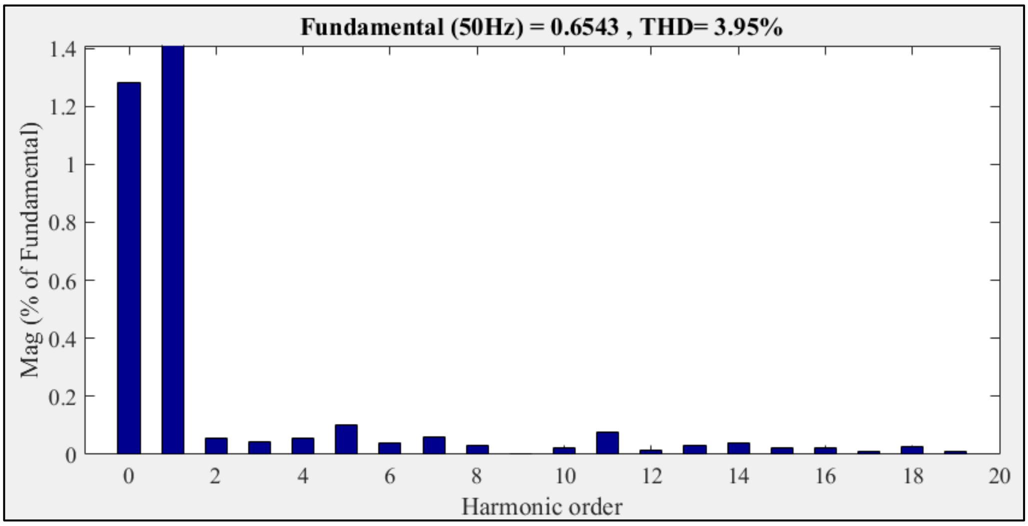


Figure III.18: FFT Analysis of Output Current (I_a) of FSTP z source inverter

- we can see in **Figure III.18,** there are high order harmonics that can be removed by adding a simple Low pass filter which will improve the THD, we will design it in the next chapter to connect the FSTP Z source inverter with the power grid.

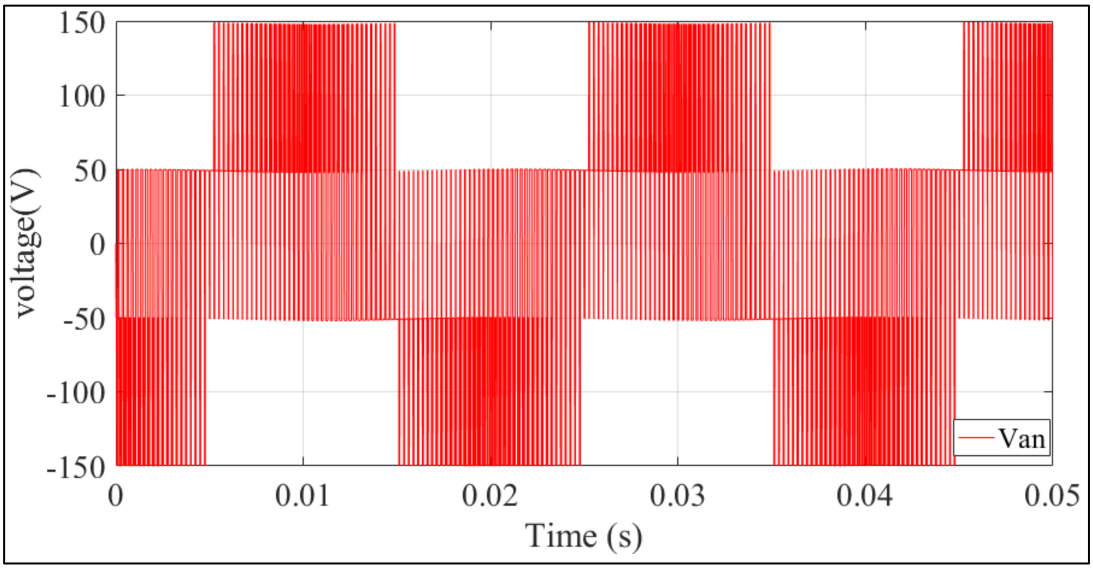


Figure III.19: V_{an} (Line to Neutral voltage) of FSTP z source inverter across Load for MI=0.8.

- The waveform of the Voltage from line to neutral shown in **Figure III.19** represent Van with RL load (R=10 Ω, L=1mH) with MI=0.8, as we can see the sinusoidal form is hard to detect due to the high amplitude to the higher-order harmonics(5th,7th, and 11th)

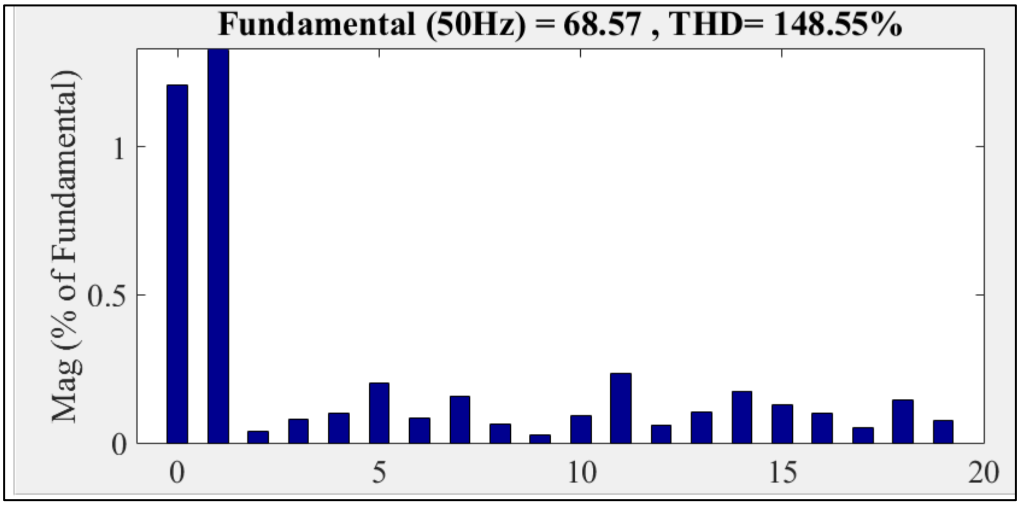


Figure III.20: FFT Analysis of Output voltage (Van) of FSTP z source inverter

- As shown in **Figure III.20**, and as mentioned before, these harmonics shall be eliminated later by adding a low pass filter.

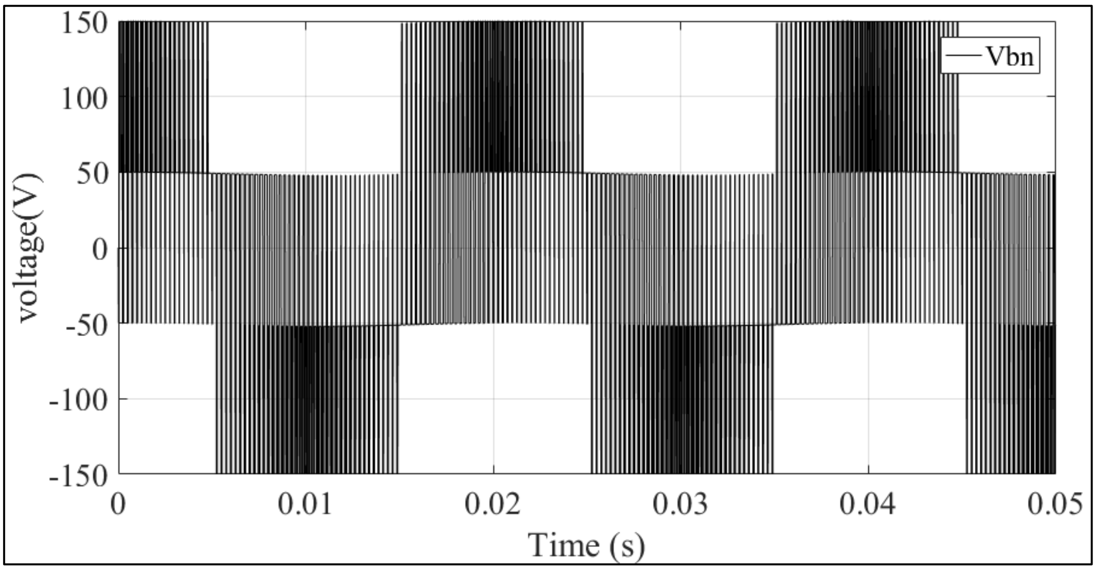


Figure III.21: V_{bn} (Line to Neutral voltage) of FSTP z source inverter across Load for MI=0.8.

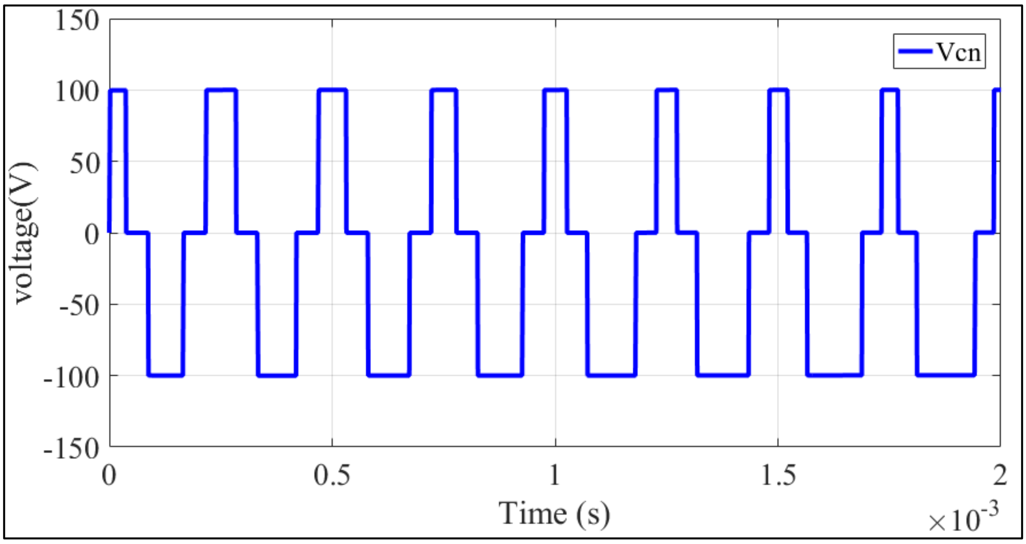


Figure III.22: V_{cn} (Line to Neutral voltage) of FSTP z source inverter across Load for MI=0.8

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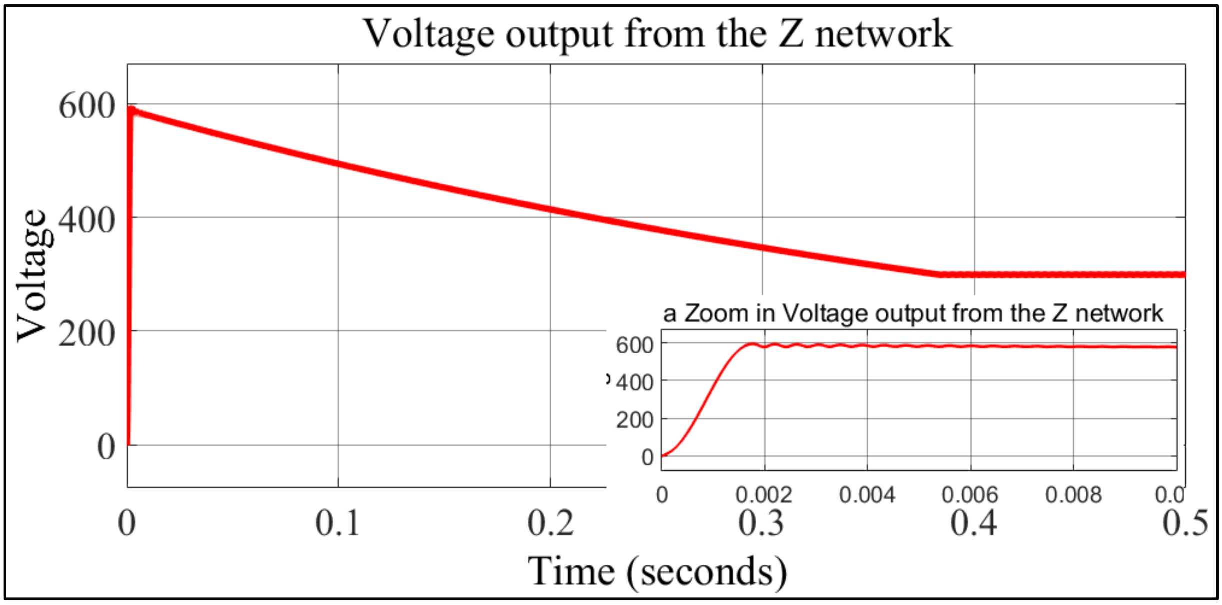

Figure III.23: Voltage output from the Z network

- Through the curve of voltage across Impedance Network of FSTPI for modulation index M= 0.8 **(Figure III.24),** we observed the performance of the LC network to boost voltage. As result, the enhanced Z-source inverter system provides a ride-through capability to reduce capacitor voltage stress, inrush current, and extended output voltage range. Therefore, to achieve better performance of the inverter, the modulation index should be controlled, and the output voltage has a linear relationship with the modulation index.

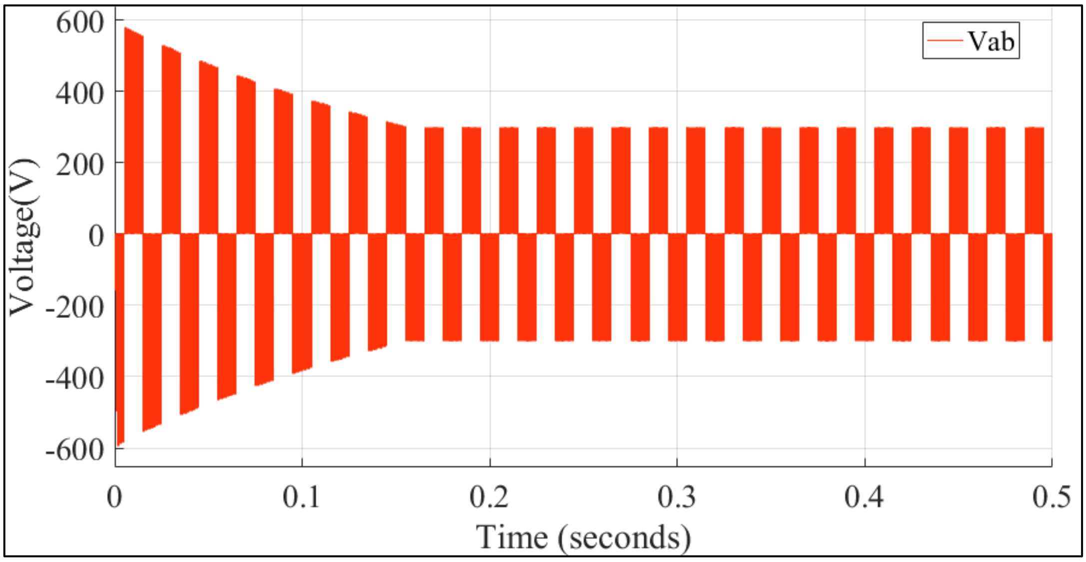

Figure III.24: V_{ab} (Line to Line voltage) of FSTP z source inverter for MI=0.8.

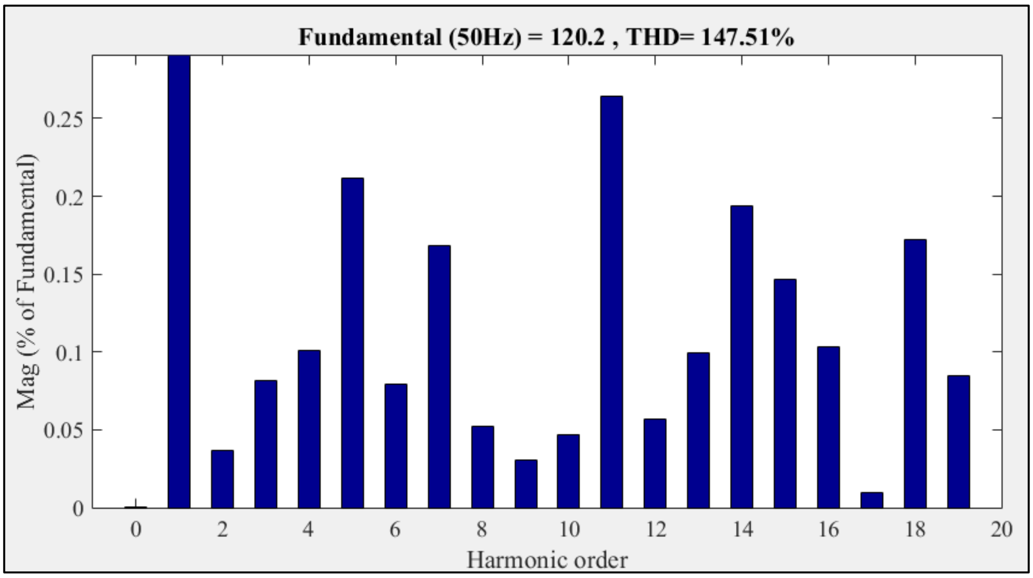

Figure III.25: FFT Analysis of Output voltage (V_{ab}) of FSTP z source inverter

III. 11Conclusion:

In this chapter, a new three-phase inverter topology was provided and studied, the FSTPI is a promising technology due to its incredible ability to reduce Harmonic Distortion; we also introduced the operating principle of the z-source inverter, as well as the best control strategy of this inverter. The z-source inverter offers the advantage of boosting the input voltage without using a step-up converter (boost chopper).

Space vector pulse with modulation (SVPWM) control tech was chosen to test the performance of the FSTP z source inverter, SVPWM successfully achieved the desired shoot-through time and also give a good THD percentage which will make the filtering process easier.

However, the filtering process is necessary to connect the output of the FSTPI to a power grid, so the output can be suited and identical to the three-phase (voltage and current) of the power grid, in the next chapter we will discuss the most important elements of the power grid and how to connect the GPV and the FSTPI with it.

CHAPTER VI:

The FSTP Z-source Inverter Integrated Into the Power Grid

IV.1 Introduction:

The increasing electricity demand leads the world energy sector, to focus on renewable sources which are growing their importance day by day. This is mainly because of limited resources and the bad environmental impacts of conventional energy.

After all the studies we made in the past three chapters it's time to introduce one of the main applications of the Photovoltaic System which is grid-connected PV systems.

In the past, grid-connected PV systems were such a small fraction of national generating capacity that they were only considered as sources of energy and took no part in maintaining the stable operation of the power system. However, in many countries, the number and capacity of grid-connected PV systems are now so large (and growing) that they must be considered a significant form of electricity generation making an important contribution to international electricity supplies and having measurable impacts on all aspects of the power system. The days when PV generation could be treated merely as a small reduction in load are past and the opportunities and challenges, posed by grid-connected PV systems are now of major concern to those developing and operating power systems.

IV.2 Electrical grid:

An electrical grid is an interconnected network for electricity delivery from producers to consumers. Electrical grids vary in size and can cover whole countries or continents [54].

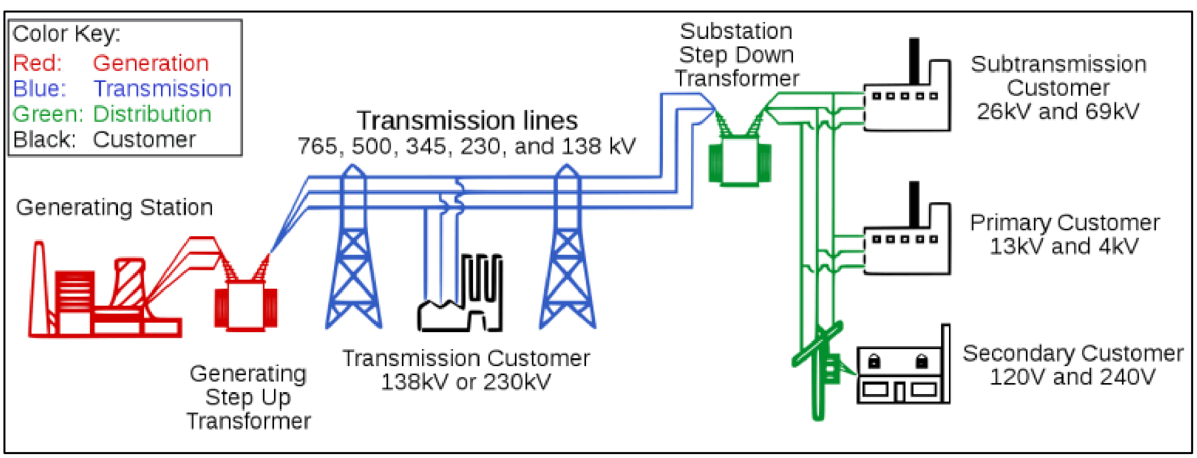

Figure IV.1: Diagram of an electric power system and generation system

It consists of:

- **Power Stations (generating station):**

Electricity generation is the process of generating electric power from sources of primary energy typically at power stations soften located near the energy and away from heavily populated areas. Usually, this is done with electromechanical generators driven by heat engines or the kinetic energy of water or wind. Other energy sources include solar photovoltaic and geothermal power [54]

- **Electric power transmission (transmission line):**

Electric transmission plays the role of sending electricity over very long distances at very high voltage levels. Electric power is transmitted at higher voltages to limit the power losses that can occur in long-distance transmission lines. Power can be transmitted across states, from one side of the country to the other, or across different countries. Electricity is transmitted over transmission lines suspended in the air on very tall transmission towers with large insulators to maintain proper electrical potential clearances from the ground, structures, or phases. These transmission conductors are not insulated and are comprised of several steel-aluminum alloy strands. Transmission towers can house multiple circuits or multiple conductors. A particular tower can have one set of 3-phase transmission lines (A, B, and C phases) on one side and another set on the other side, ultimately, delivering two sets of 3-phase transmission lines. Figure IV.1 below shows a picture of a typical 3-phase transmission system with transmission towers and transmission lines [55].

- **Electrical substations:**

Substations may perform many different functions but usually, transform voltage from low to high (step-up) and from high to low (step down). Between the generator and the final consumer, the voltage may be transformed several times [56].

The three main types of substations, by function, are [57]:

- Step-up substation: these transform the voltage coming from the generators and power plants to a higher voltage so that it can be transmitted long distances more efficiently.

- Step-down substation: these transform the voltage coming from the transmission lines to a lower voltage which can be used in industry or sent to a distribution substation.
- Distribution substation: these transform the voltage lower again for the distribution to end-users.

Electric power distribution:

Distribution is the final stage in the delivery of power; it carries electricity from the transmission system to individual consumers. Substations connect to the transmission system and lower the transmission voltage to medium voltage ranging between 2 kV and 35 kV. Primary distribution lines carry this medium voltage power to distribution transformers located near the customer's premises. Distribution transformers again lower the voltage to the utilization voltage. Customers demanding a much larger amount of power may be connected directly to the primary distribution level or the Substations level [58]. Distribution networks are divided into two types, radial or network [59].

IV.3 Grid-Connected PV Systems:

Grid-connected PV power-generation systems can be found in different sizes and power levels for different needs and applications, ranging from a single PV module from around 200 W to more than a million modules for PV plants over 100 MW. Therefore the generic PV energy conversion systems' structure (Fig.IV.2) can vary significantly from one plant to another. For simplicity, grid-connected PV systems are subdivided depending on their power rating: small scale from a few watts to a few tens of kilowatts, medium-scale from a few tens of kilowatts to a few hundred kilowatts, and large scale from a few hundreds of kilowatts to several hundreds of megawatts. In addition, PV systems can be classified further depending on the PV module arrangement: a single module, a string of modules, and multiple strings and arrays (parallel-connected strings) [60].

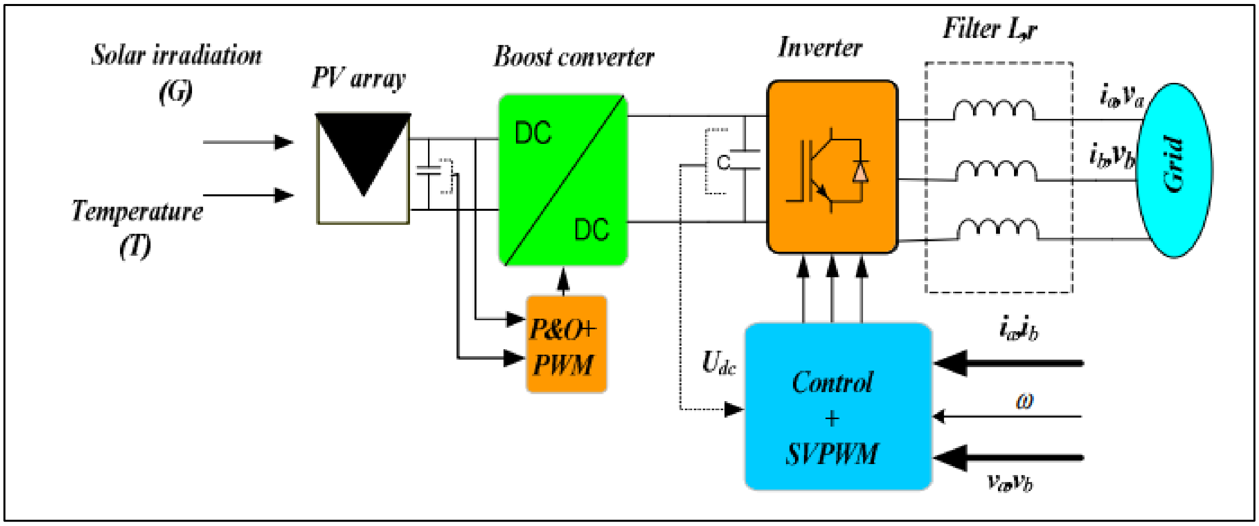

Figure IV.2: The generic structure of a grid-connected photovoltaic (PV) system

IV.4 Simulation Model:

Our goal from this simulation is to determent which inventor is better in terms of a better current output and power quality.

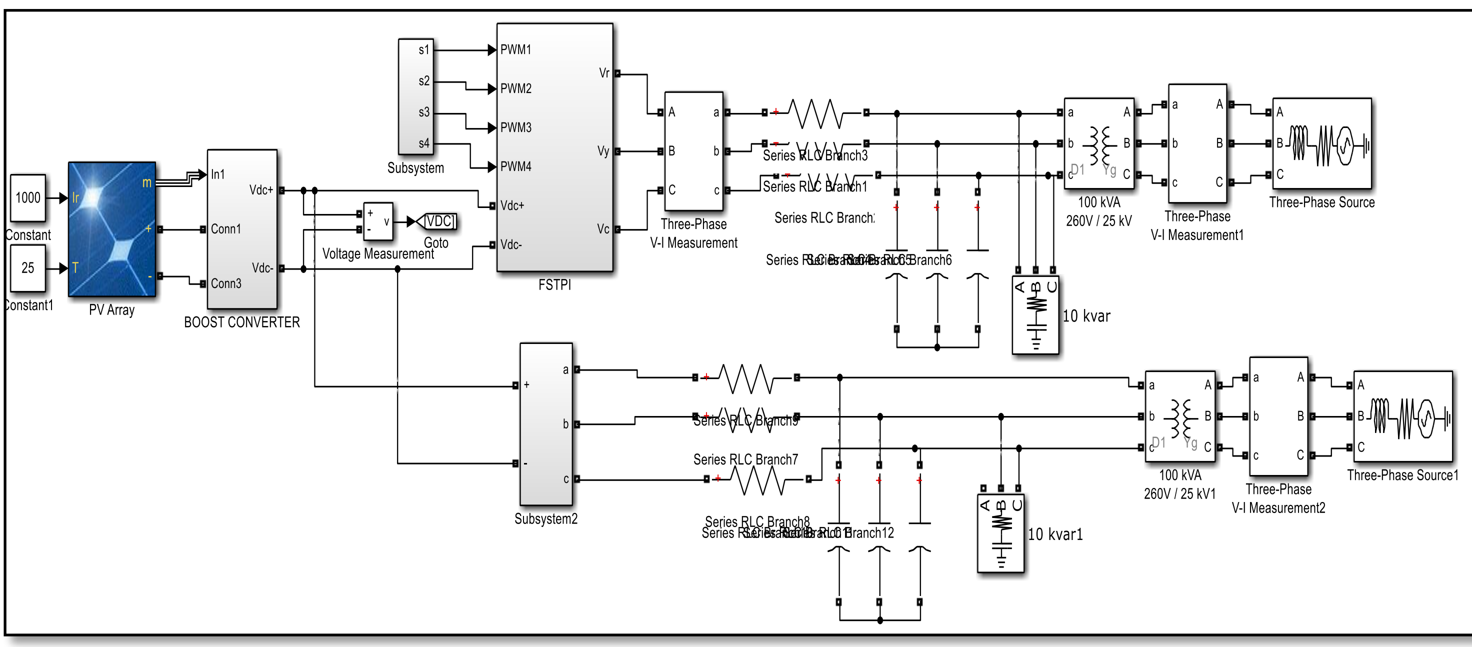

Figure IV.3: Simulation Model of GPV and FSTP Z-source inverter and VSC connected to the power grid

Figure IV.3 shows the entire process of generating electricity from a PV system and delivering it to a 3-phase power grid, the system contains: 100Kw PV Array, Boost converter with MPPT *(P&O)* connected with an FSTP Z-source inverter and VSC, RC Filter, transformer 100KWA 250V/25Kw and a three-phase power grid.

Simulation test beds using MATLAB/Simulink 2016 were constructed to validate the effectiveness of the system models and control algorithms proposed. Parameters used for the simulation are shown in **Table IV.1**

Block	Parameter	Value
Boost converter	inductance	1.45mH
	capacitance	3227μF
	Filter capacitance	1000 μF
	DC bus voltage	363V
	Switching frequency	5kHz
FSTPI	Z-source inductance (L1 and L2)	1mH
	Z-source capacitance (C1 and C2)	4.7µF
	DC split capacitance	330µF
Power Grid	Voltage	230V
	Frequency	50Hz
RC Filter	resistance	10ohm
	capacitance	318mF

Table IV.1: Parameters used for simulation.

IV.5 Simulation results and Analysis:

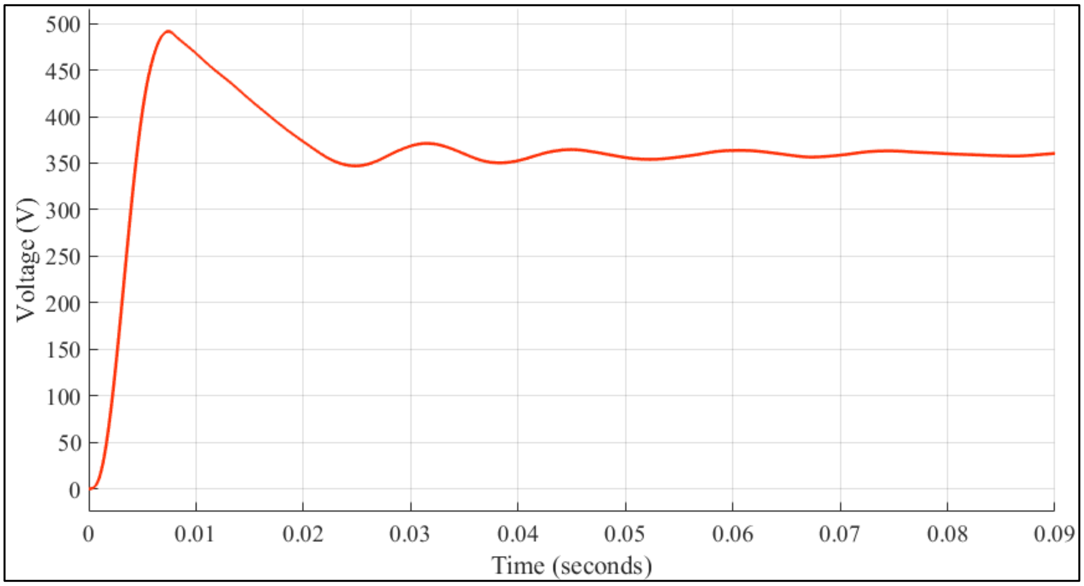

Figure IV.4: The output Voltage of the Boost converter

Figure IV.4 shows the output Voltage of the Boost converter, the perturbations at the beginning are caused by the MPPT controller (P&O) trying to detect the MPP, but as we can see the controller Succeeds in tracking the maximum value and stabilize at the desired value of 363V.

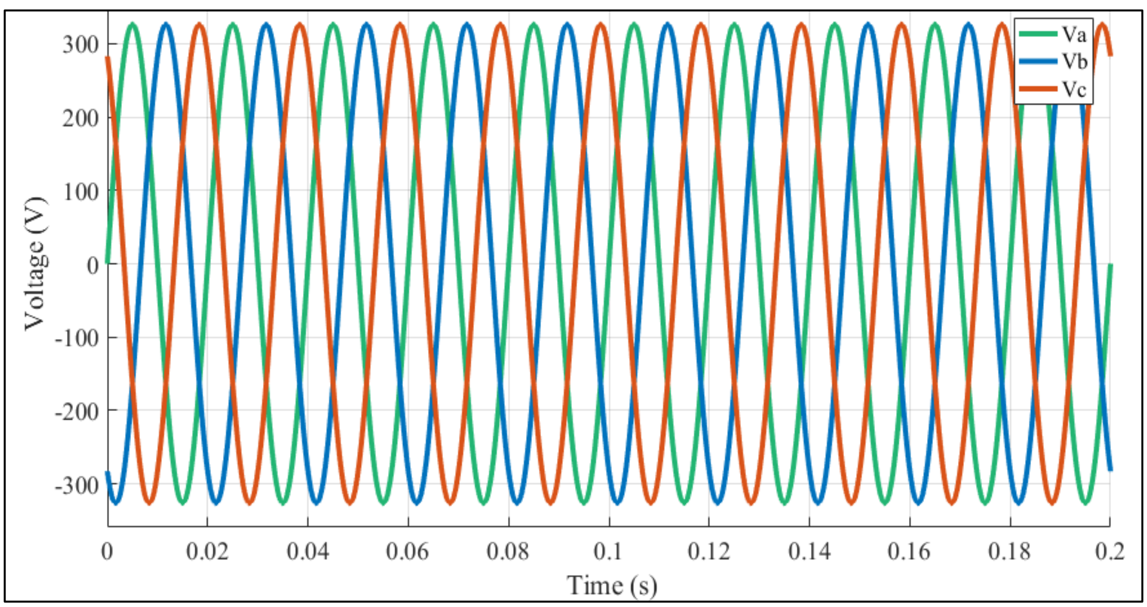

Figure IV.5: The three-phase Voltage output after Filtering

Figure IV.5shows the three-phase Voltage entering the power grid, and it has the perfect sinusoidal form cause of the correct control strategy used on the FSTPI and the right filter

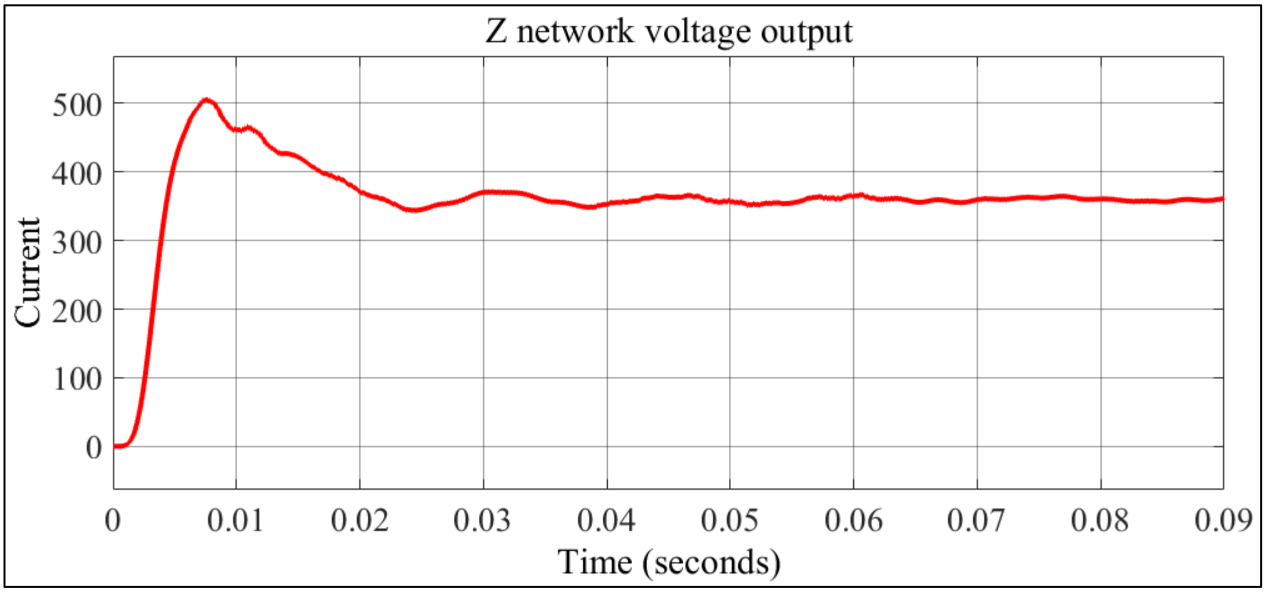

Figure IV.6: The output voltage of Z network

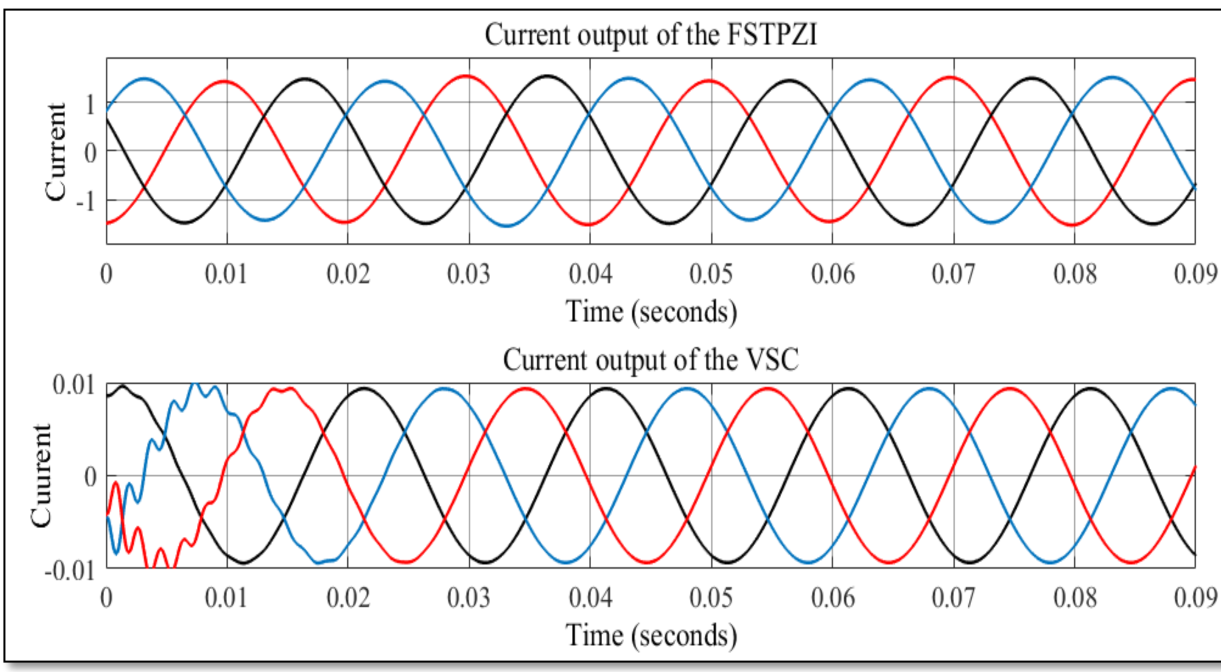

Figure IV.7: The three-phase Current output of the FSTPI and the VSC after Filtering

Figure IV.7 shows The three-phase Current output of the FSTPI and the VSC after Filtering, we see that the FSTPI seceded in generating a perfectly sinusoidal waveform, on the other hand, the VSC current output suffers from perturbations in the beginning.

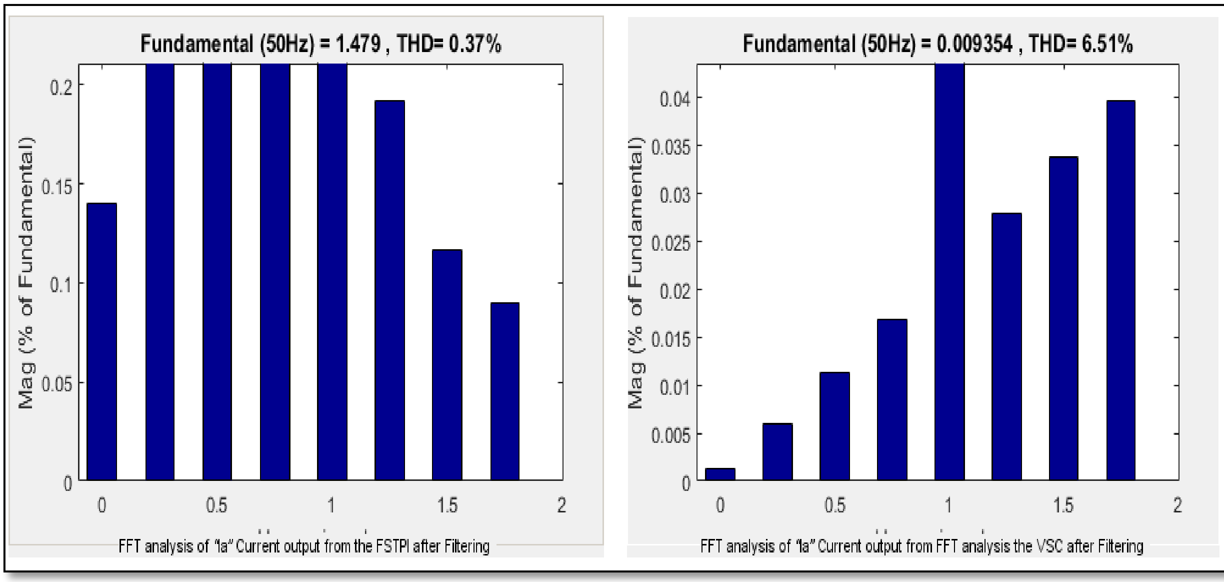

Figure IV.8: The FFT analysis of "Ia" Current output from the FSTPI and the VSC after Filtering

Figure IV.8 shows The FFT analysis of "Ia" Current output from the FSTPI and the VSC after Filtering, as a reminder, in the previous chapter we got 4% THD from the FSTPI without filtering, after filtering we see that the THD 0.37% while in the VSC we got 6.5%

IV.6 Interpretation of results:

After comparing the performance of both inverters, we noticed several advantages in our proposed topology, which are:

- A low THD with and without filter: this feature is caused by the reduced number of switches and with a very simple RC filter can make the THD even lower contrary to what we saw in the performance of the VSC, which if we want to improve it, we will need a complex and more expensive filter.
- Absence of perturbations at the beginning: this advantage is due to the two capacitors that replaced two switches in one of the inverter's legs, these capacitors absorbed the current perturbations caused by the MPPT controller while it was detecting the MPP.

IV.7 Conclusion:

This chapter is considered as a collection of the studies that we dealt with in previous chapters, where we connected the blocks to form a PV system connected to a power grid. These blocks are PV array, boost converter, and MPPT controller which we presented in the second chapter, and FSTP Z-source inverter with SVPWM control strategy that was explored in the third chapter, we also did a simple performance comparison between the traditional VSC and FSTP Z-source inverter.

The obtained results show how these blocks work together perfectly, as we can see the form of the voltage and current entering the grid from the FSTPI, is pure sinusoidal and the power quality is almost ideal by comparison to the traditional VSC that shows that if we desire a better output, we need to design a much expensive filter.

General Conclusion

Photovoltaic power is the most usable renewable source due to the availability of sunlight and the long life of solar panels, but most of its applications are offline with the power grid, like electric cars or smart greenhouses, …etc, The most important reason why it is not suitable for connecting to a power grid is that it is affected by temperature and radiation, and that's our main study in this project.

The work presented in this project falls within the framework of the development of power electronics in general and converters in particular, to improve systems for producing electrical energy from renewable sources. The objective of this project is to studythe FSTP Z-source inverter and SVPWM control strategy, to integrate it into a photovoltaic system that feeds a power grid.

We started with a currentstate of systems that extract electricity from renewable energy sources, mainly focusing on the photovoltaic systems because we find that, PV system generation is probably the most efficient way to utilize solar energy. It has many attractive features like operating without moving parts, no emissions, high temperature, no noise,etc.., and gave a general overview of the recently introduced Z-source converter, some topologies are given to show how advanced this type of converter is.

The second chapter containsthe mathematical modelof a photovoltaic cell and presents its main characteristics (P-V, I-V), then we introduce the MPPT control techniquesand we test both the P&O algorithm and Fuzzy logic controller. Through the latest, we have observed that the PV generator has maximum power, and it is too sensitive to changes in irradiation and temperature.

The third chapter has presented the theoretical analysis and design of the FSTP Z-source inverter. The Z-source employs a unique impedance network to couple the four-switch three-phase inverter two levels main circuit of the power source the use of four switches instead of six help reduces the number of switching stages, as well as the number of switches. This means better efficiency, optimized volume, and lower construction costs.

The control methods with the insertion of shoot-through states of the Z-Source inverter have been studied. The proposed scheme under SVPWM control is simulated with the assistance of MATLAB/SIMULINK and the simulation results are obtained for a constant value of modulation index.

Simulation results show that the sinusoidal load current can be achieved by the FSTP ZSIwithout using a filter with 4% THD which is a great percentage knowing that we didn't use a filter, and also the resultsprove that the output voltage matches with the design analysis.

In the last chapter, we connected both the PV system and the FSTP Z-Source inverterintothe power grid and also compared its performance with the traditional VSC, the results show that the FSTP Z-Source inverter with a simple RC filter has a better performance cause we got 0.36% THD while the VSC got 6% THD and that's even worst than the results we got from the FSTP Z-source inverter without the filter.

Future Works:

- In This Project the proposed topology is connected to a solar-based system in the future it can likewise be tied to different other renewable energy sources like wind energy systems.
- Some other MPPT algorithms can be tried and tested.
- Improve the FLC we proposed by adding more rules and functions to get better setting time
- In this work we used SVPWM as control strategies, in the future it would be better if we used simple boost or max boost controllers
- The typology proposed in this project is four switches Z-source inverterthree-phase has two levels, in the future, it can also be used other topologies of ZSI like the quasi-Z-source inverter or the Trans-Z-source inverter are coupled with the solar system or other renewable energy.

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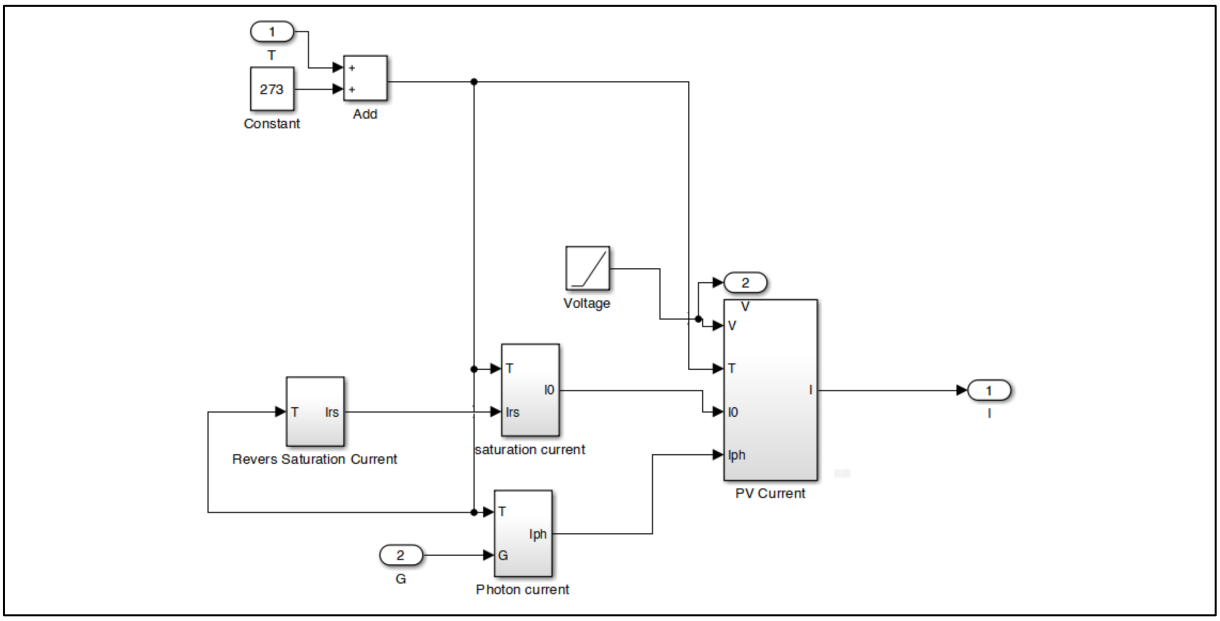
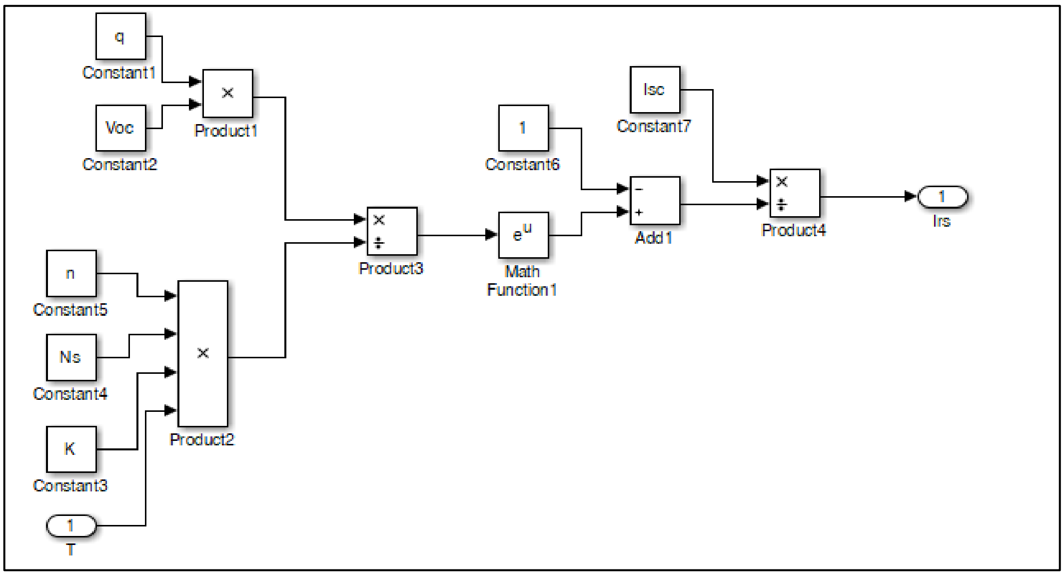
Annex

Annex A:

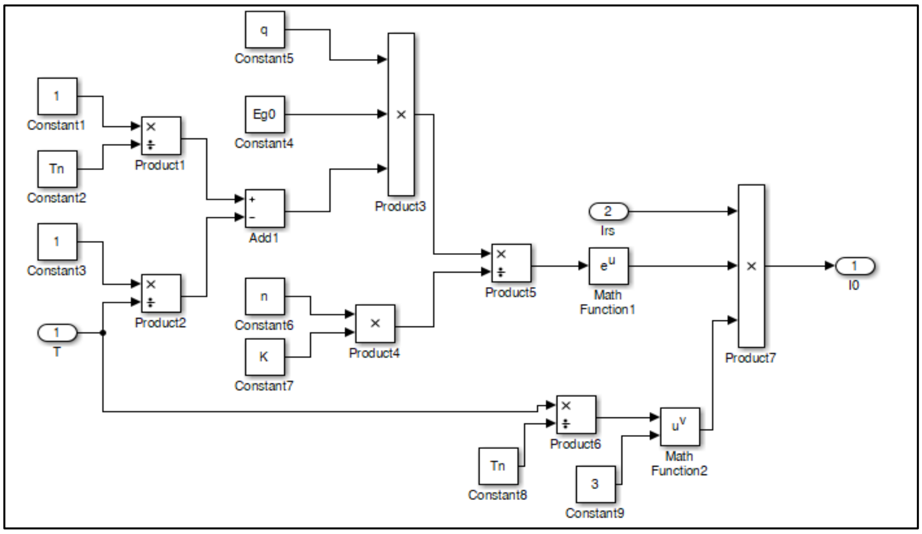
1. The internal view of PV module:



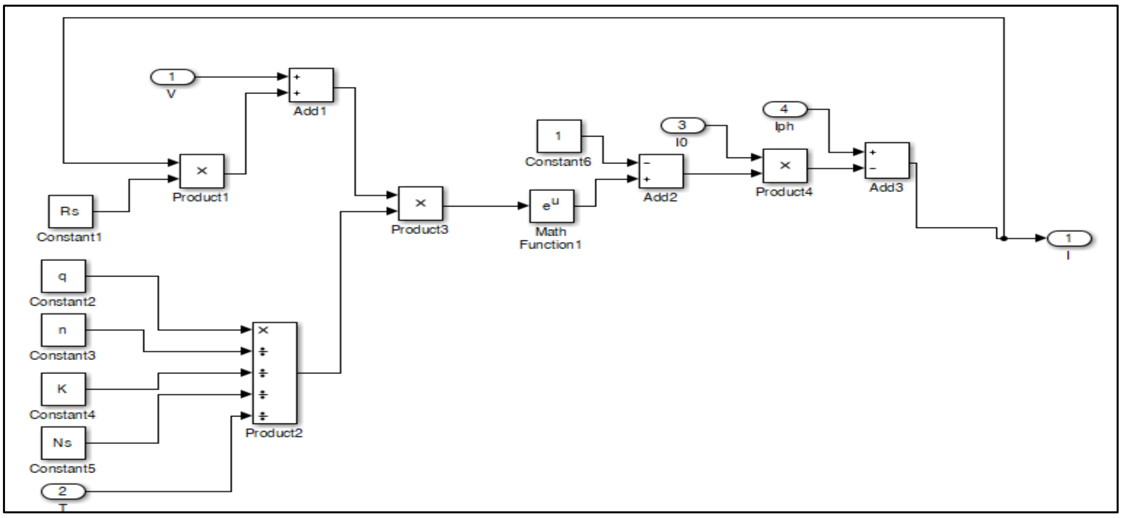
1.1. Reveres Saturation Current :



1.2. Saturation Current :



1.3. PV Current :



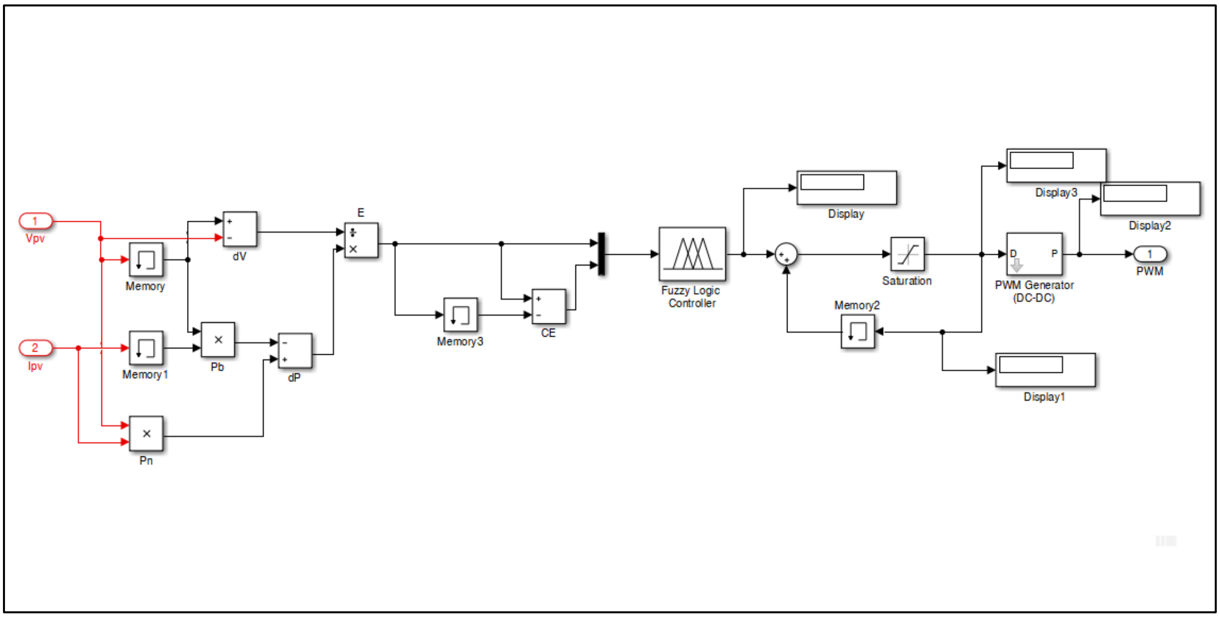
Annex B:

2. MPPT Techniques:

2.1. P&O Algorithm Script:

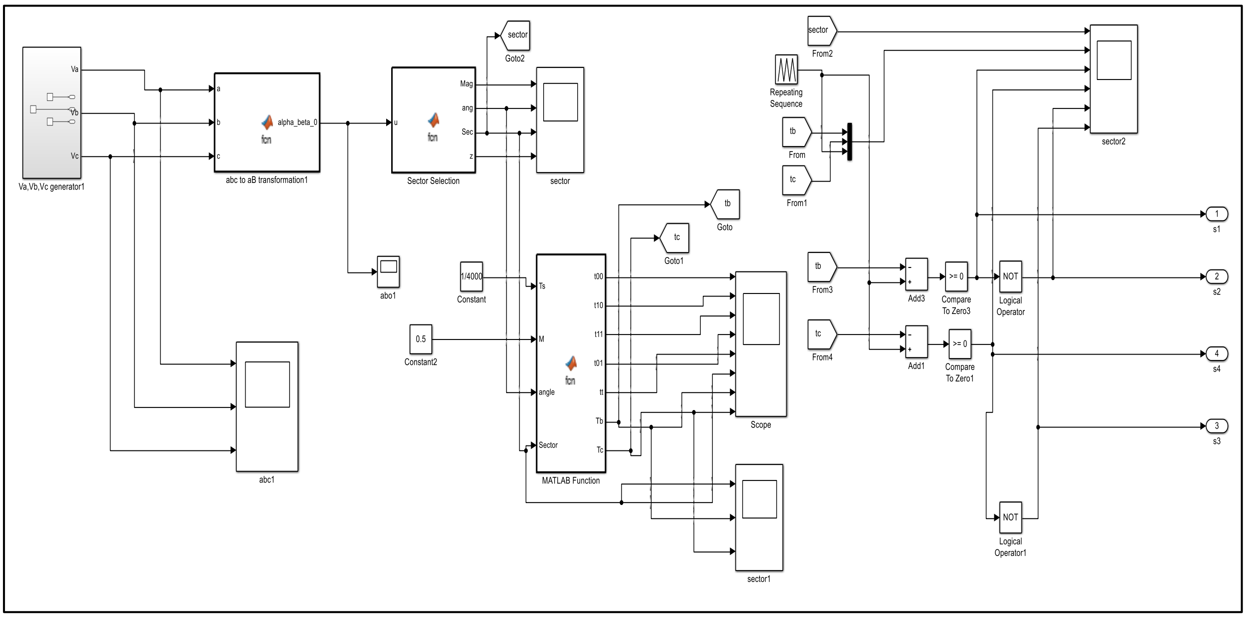
```
functionD  =PandO(Param, Enabled, V, I)
% MPPT controller based on the Perturb & Observe algorithm.
% D output = Duty cycle of the boost converter (value between 0
and 1)
% Enabled input = 1 to enable the MPPT controller
% V input = PV array terminal voltage (V)
% I input = PV array current (A)
% Param input:
Dinit = Param(1);  %Initial value for D output
Dmax = Param(2);   %Maximum value for D
Dmin = Param(3);   %Minimum value for D
deltaD = Param(4); %Increment value used to increase/decrease
the duty cycle D
% ( increasing D = decreasing Vref )
persistentVoldPoldDold;
dataType = 'double';
ifisempty(Vold)
Vold=0;
Pold=0;
Dold=Dinit;
end
P= V*I;
dV= V - Vold;
dP= P - Pold;
ifdP ~= 0 & Enabled ~=0
ifdP< 0
ifdV< 0
            D = Dold - deltaD;
else
            D = Dold + deltaD;
end
else
ifdV< 0
            D = Dold + deltaD;
else
            D = Dold - deltaD;
end
end
else D=Dold;
end
if D >= Dmax | D<= Dmin
    D=Dold;
end
Dold=D;
Vold=V;
Pold=P;
```

2.2. Simulink Block of Fuzzy Logic controller:



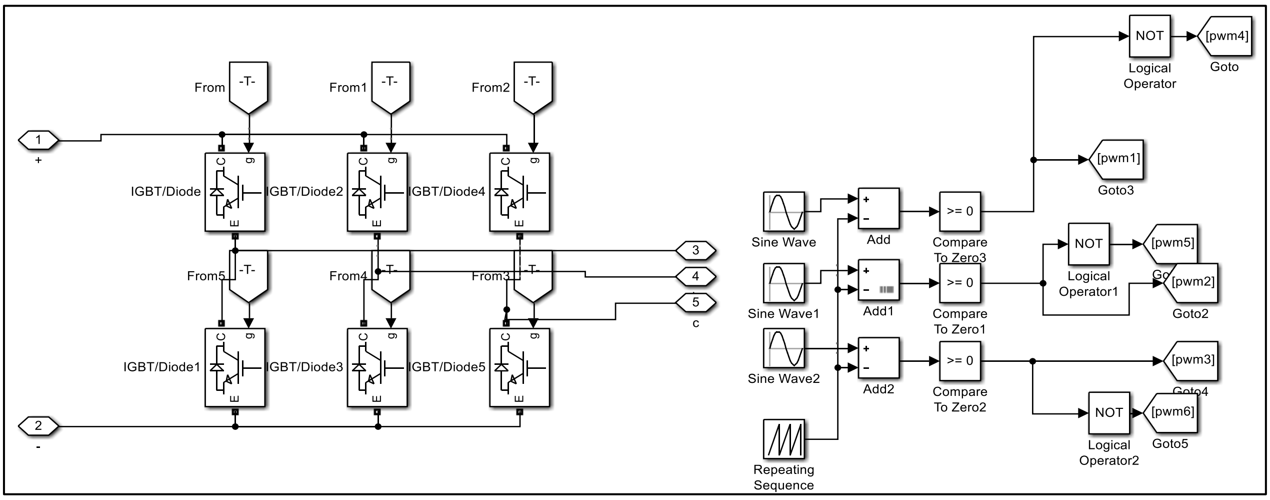
Annex C:

3. SVPWM control block :



Annex D:

4. VSC Block :



Abstract

This work aims to study the Z-source four-switch three-phase inverter connected with a PV generator, to improve the performance of the classic inverter. This system is used to feed a power grid. Moreover, this inverter makes sure that both function of the booster chopper and the inverter in one stage. In addition, a space vector pulse-width modulation (SVPWM) control method has been used to control the FSTP Z-source inverter by insertion of shoot-through state with the Z-source network together to achieve the best efficiency and reduce the Total Harmonic Distortion (THD). The MPPT technique is used to obtain optimal power performance of the photovoltaic generator (GPV). The simulation results have been obtained by MATLAB/Simulink Software to validate the proposed study.

Keywords: Z-source four switches three-phase inverter (Z- source FSTP), photovoltaic generator (GPV), Shoot through State, PWM Control, and MPPT technique.

ملخص

يهدف هذا العمل إلى دراسة المموج ثلاثي الأطوار ذو المصدر z بأربعة مبدلات المعذى بمولد كهروضوئيو الموصل بشبكة كهربائية, لتحسين عمل المموج التقليدي . بالإضافة إلى ذلك ، يقوم هذا المموج بوظيفة رافع للتوتر(Booster)والمموج (Inverter) في مرحلة واحدة .إلى جانب ذلك ، تم استخدام طريقة التحكم بتعديل عرض النبضة (SVPWM)للتحكم في المموج Z-source FSTP عن طريق إدخال حالة قصر الدائرة مع شبكة Z-source معًا لتحقيق أفضل كفاءة وتقليل منالتشوه التوافقي الكلي (THD) .بالإضافة استخدمنا تقنية تتبع الطاقة العظمى (MPPT) للحصول على أفضل مردود ممكن مهما تغيرت الضروف المناخية المؤثرة على الاواح الشمسية . تم إجراء المحاكات والتحصل على النتائج بستخدام برنامج MATLAB/Simulink

الكلمات المفتاحية: عاكس ذو أربعة مفاتيح Z-Source ، مولد ضوئي (GPV) ، حالة الدارة القصيرة، تقنية تتبع الطاقة العظمى MPPT ، نمذجة عرض النبضات.(PWM).