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Thème

**Development of a MOSFET-Based Reversible Static Converter for
Photovoltaic Energy Systems**

Présenté Par :

Mr MARIKITE TAONGA NIGEL

Mr MUPAYA TANAKA SHONGEDZAI

Devant le jury composé de :

Dr ADJOU DJ REDOUANE

MAA UAT.B.B (Ain Temouchent) Président

Dr. BENAZZA BAGHDADI

MCB UAT.B.B (Ain Temouchent) Examineur

Pf. FLITTI MOHAMED

MAA UAT.B.B (Ain Temouchent) Encadrant

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We dedicate this project to the Almighty God our creator, our strong pillar, and our source of inspiration, wisdom, knowledge and understanding. He has been the source of our strength throughout this academic journey.

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ABSTRACT

This thesis presents the design and implementation of a reversible electric converter utilizing MOSFET technology. The primary objective is to develop a bidirectional power conversion system capable of operating efficiently in both rectification and inversion modes. Such converters are essential in modern power electronics, particularly in renewable energy systems, electric vehicles, and energy storage applications, where power flow needs to be controlled in both directions.

The work begins with a detailed analysis of the principles of reversible converters and the role of MOSFETs as fast-switching, high-efficiency components. The design process includes selecting appropriate topology, component sizing, and developing a control strategy to ensure stable and reliable operation. Simulation models are developed using specialized software to validate the theoretical approach, followed by hardware implementation and experimental testing.

The results demonstrate that the proposed MOSFET-based converter achieves high efficiency, fast switching performance, and robust bidirectional control. This study highlights the potential of MOSFETs in advancing compact, reliable, and energy-efficient power conversion systems.

Keywords: Reversible electric converters, MOSFET technology, Renewable energy systems, Electric vehicles.

RESUME

Ce mémoire présente un convertisseur électrique réversible basé sur la technologie MOSFET. L'objectif principal est de développer un système de conversion d'énergie bidirectionnel, capable de fonctionner efficacement en mode redressement comme en mode onduleur. Ce type de convertisseur est essentiel dans les systèmes électroniques de puissance modernes, notamment dans les domaines des énergies renouvelables, des véhicules électriques et du stockage d'énergie, où le contrôle du flux d'énergie dans les deux sens est indispensable.

Le travail débute par une analyse approfondie des principes de fonctionnement des convertisseurs réversibles et du rôle des MOSFETs en tant que composants à commutation rapide et à haut rendement. La démarche de conception comprend le choix de la topologie, le dimensionnement des composants, ainsi que le développement d'une stratégie de commande assurant un fonctionnement stable et fiable. Des simulations sont réalisées à l'aide de logiciels spécialisés pour valider l'approche théorique, suivies par la mise en œuvre matérielle et des essais expérimentaux.

Les résultats obtenus montrent que le convertisseur proposé, basé sur des MOSFETs, offre une haute efficacité, une commutation rapide et un contrôle bidirectionnel robuste. Cette étude met en évidence le potentiel des MOSFETs dans la conception de systèmes de conversion d'énergie compacts, fiables et économes en énergie.

Mots-clés: Convertisseurs électriques réversibles, Technologie MOSFET, Systèmes d'énergie renouvelable, Véhicules électriques.

ملخص

ثنائي طاقة تحويل نظام تطوير هو الرئيسي الهدف. MOSFET تقنية على قائم عكسي طاقة محول الأطروحة هذه تقدم الطاقة إلكترونيات أنظمة في أساسيًا المحولات من النوع هذا يُعد. والعاكس المقوم وضعي في بكفاءة العمل على قادر الاتجاه كلا في الطاقة تدفق في التحكم يُعد حيث، الطاقة وتخزين الكهربائية والمركبات المتجددة الطاقة مجالات في وخاصةً، الحديثة الأهمية بالغ أمرًا الاتجاهين.

الكفاءة وعالية التبديل سريعة كمكونات MOSFETs ودور العكسية المحولات تشغيل لمبادئ متعمق بتحليل العمل يبدأ. وموثوقًا مستقرًا تشغيلًا تضمن تحكم استراتيجية وتطوير، المكونات حجم وتحديد، الطوبولوجيا اختيار التصميم نهج يتضمن والاختبارات الأجهزة تطبيق يليه، النظري النهج صحة من للتحقق متخصص برنامج باستخدام المحاكاة عمليات تُجرى التجريبية.

تُسلط قوياً الاتجاه ثنائي وتحكمًا، تبديل وسرعة، عالية كفاءة يوفر MOSFET على القائم المقترح المحول أن النتائج تُظهر الكلمات. للطاقة وموفرة وموثوقة مدمجة طاقة تحويل أنظمة تصميم في MOSFETs إمكانات على الضوء الدراسة هذه. الكهربائية المركبات، المتجددة الطاقة أنظمة، MOSFET تكنولوجيا، العكسية الطاقة محولات: المفتاحية

LIST OF ABBREVIATIONS

AC	Alternating Current
BJT	Bipolar Junction Transistor
CSP	Concentrated Solar Power
DC	Direct Current
EV	Electric vehicle
FCMI	Flying Capacitor Multilevel Inverter
FCI	Flying Capacitor Inverter
FTBO	Function Transfer Boucle Ouverte
FTBF	Function Transfer Boucle Ferme
FET	Field-Effect Transistor
GTOs	Gate Turn Off thyristors
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternative Current
IP	Internet Protocol controller
IC	Integrated Circuits
IGBTs	Insulated Gate Bipolar Transistors
LCC	Line Commutated Converters
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MLI	Multilayer Insulation
NOTC	Nominal Operating Cell Temperature
NPC	Neutral Point Clamped
PV	Photovoltaic
PWM	Pulse Width Modulation
PI	Proportional Integral controller
PID	Proportional Integral Derivative controller
RD	Direct Radiation
Rd	Diffuse Radiation
RG	Global Radiation
STATCOM	Static Synchronous Compensators
TFT	Thin-Film Transistor
U _t	Thermic Voltage (KT/q)
UPS	Uninterruptable Power Supplies
UPS	Uninterruptible Power Supplies
VSCs	Voltage Source Converter
VSC	Voltage Source Converter
V _{Gs}	Gate-Source Voltage

LIST OF NOMENCLATURES

W	Watts
VA	Volt-Ampere
VAR	Volt-Ampere Reactive
U	Voltage
I	Current
f	Frequency
R	Resistance
L	Inductance
C	Capacitance
Θ	Inclination angle
W/m ²	Watts per square meter
q	Change de L'électron (1.602×10^{-19})
K	Boltzmann Constant ($1,38.10^{-23}$ J/K)
Hz	Hertz
π	Pi
K _p , K _i	Gain
α	Switching Angle
m	Modulation Index
N _p	The Number of Modulations per Half Cycle
f_p	Frequency of the Carrier Signal
f_{ref}	Frequency of the Reference Signal
V _p	Peak Value of the Carrier Signal
V _{ref}	Amplitude of the Modulating Signal

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CHAPTER 1: STATE OF ART

1.1 Introduction to Renewable Energy

Renewable energy (also called green energy) is energy made from renewable natural resources that are replenished on a human timescale. The most widely used renewable energy types are solar energy, wind power, and hydropower. Bioenergy and geothermal power are also significant in some countries. Some also consider nuclear power a renewable power source, although this is controversial, as nuclear energy requires mining uranium, a non-renewable resource. Renewable energy installations can be large or small and are suited for both urban and rural areas. They are often deployed together with further electrification. This has several benefits: electricity can move heat and vehicles efficiently and is clean at the point of consumption. Variable renewable energy sources are those that have a fluctuating nature, such as wind power and solar power. In contrast, controllable renewable energy sources include dammed hydroelectricity, bioenergy, or geothermal power.[1]

1.2 Types of Renewable Energy[2]

- Solar: Sunlight harnessed for electricity and heat.
- Wind: Kinetic energy of wind converted into electricity.
- Hydropower: Energy from flowing water (rivers, tides) used for electricity generation.
- Geothermal: Heat from the Earth used for power generation and heating.
- Biomass: Organic materials used for heat, power, and biofuels.
- Ocean: Energy from tides, waves, and ocean temperature gradients.
- Hydrogen: Clean fuel produced using renewable energy for storage and transport.

a) Solar Energy

Potential: Africa has abundant sunlight, with countries near the equator receiving high levels of solar radiation. This makes solar energy one of the most promising renewable energy sources for the continent.

Distribution:

North Africa: Countries like Egypt, Morocco, and Algeria have been at the forefront of solar energy development. Morocco, for example, hosts one of the world's largest solar power plants, the Noor Ouarzazate Solar Complex.

Sub-Saharan Africa: Solar energy is increasingly being adopted, especially in Kenya, South Africa, and Ethiopia. South Africa is a leader in solar power, with significant solar farms like

KaXu - Solar One and De Aar - Solar Power.

Off-Grid Solar: There is also significant off-grid solar power generation, particularly in rural and underserved areas, providing electricity through solar home systems and solar mini-grids.

b) Wind Energy[3]

Potential: Wind energy potential is present along Africa's coasts and in areas with consistent wind patterns. Countries like Egypt, Kenya, and South Africa have good wind resources.

Distribution:

South Africa: South Africa is the leader in wind energy development, with projects like Jeffreys Bay Wind Farm and Gansbaai Wind Farm.

Kenya: The Lake Turkana Wind Power Project is one of Africa's largest wind farms and provides a significant share of Kenya's electricity.

Morocco: Wind energy is also developing in Morocco, particularly along the Atlantic coast.

c) Hydropower

Potential: Africa has a significant hydropower potential, with large rivers like the Nile, Congo, Zambezi, and Limpopo providing opportunities for large-scale hydropower generation.

Distribution:

Central Africa: The Democratic Republic of Congo (DRC) and Congo have substantial untapped hydropower potential, particularly the Inga Dam in the DRC, which could be one of the largest hydropower stations in the world.

West Africa: Countries like Ghana and Nigeria have significant hydropower capacity.

East Africa: Ethiopia has emerged as a major player in hydropower development with the Grand Ethiopian Renaissance Dam (GERD), which is expected to be one of Africa's largest hydroelectric projects.

Southern Africa: Zambia, Zimbabwe and Mozambique are also important producers of

hydropower.

d) Biomass Energy

Potential: Biomass, including wood, agricultural waste, and animal residues, is widely used in Africa for cooking and heating. Biomass can also be converted into electricity and biofuels.

Distribution:

West and Central Africa: Biomass is a primary energy source for rural households, with countries like Nigeria, Ghana, and Cameroon relying heavily on biomass for cooking.

Ethanol and Biofuel: Some countries, including South Africa and Ethiopia, are exploring the production of biofuels like ethanol from sugarcane and other crops.

e) Geothermal Energy

Potential: Geothermal energy, derived from the Earth's internal heat, is found in regions with volcanic activity, particularly along the East African Rift System.

Distribution:

East Africa: Kenya is the leader in geothermal energy production in Africa, with the Olkaria Geothermal Power Station being one of the largest in Africa. Ethiopia, Tanzania, and Djibouti are also exploring their geothermal resources.

f) Ocean Energy

Potential: Ocean energy, including tidal and wave energy, has some potential along the coasts of Africa, particularly in countries like South Africa, Mozambique, and Namibia.

Challenges: Ocean energy is still in the early stages of development in Africa due to the high costs of technology and infrastructure.

1.3 Photovoltaics

Photovoltaic solar energy is a renewable electrical energy produced by the sun's rays. This energy is produced using photovoltaic cells, an electrical component exposed to light to produce electricity in an amount proportional to the incident light power.

This chapter presents a presentation of the photovoltaic system, its architecture, and how it works.

1.4 Generality

For a very long time, humans have sought to use the energy emitted by the sun, the closest star to Earth. Most uses are direct, such as in agriculture through photosynthesis, or in various drying and heating applications. This energy is available in abundance across the entire Earth's surface and despite significant attenuation during its passage through the atmosphere, the remaining quantity remains significant when it reaches the ground. We can thus count on 1000 W/m² peak in temperate zones and up to 1400 W/m² when the atmosphere is slightly polluted with dust or water. The solar flux received at ground level depends on:

- The orientation, nature, and inclination of the Earth's surface.
- The latitude of the collection site, its degree of pollution, and its altitude.
- The time of year.
- The time of day considered.
- The nature of the cloud layers.

Thus, there are areas in the world that are more favored than others in terms of sunshine. They are listed in the form of an atlas and highlight solar deposits.

The main physical phenomena mentioned above are parameters to be taken into account for the installation and maintenance of photovoltaic generators. Indeed, the behavior of these energy generators is more or less random, depending on the operating site. Thus, if we consider areas with a dry climate and a high rate of sunshine throughout the year, the solar flux can be easily modeled and predicted according to the hours of the day and the days of the year. The operation of photovoltaic (PV) generators is then often close to that estimated. If, on the contrary, we consider more unfavorable areas, often windy and with cloudy weather alternating with periods of sunshine over several days per year, the irradiation changes rapidly and in large proportions.[4]

It is then difficult to make accurate predictions about the irradiation rate at a specific location and time. Experimental measurements have shown significant changes in

sunshine of less than 10 seconds, which can occur several times per minute. In this very unfavorable case, the exploitation of the solar resource becomes more difficult by PV generators, which must take this reality into account.

Similarly, let's take the case of a site with shadow areas linked to infrastructure or natural relief. The behavior of the PV generator will no longer be homogeneous and will often present degraded behaviors that must either be avoided or prevented. Energy production is often significantly degraded in this case. Finally, we must not neglect sudden changes in the operating point directly linked to the behavior of the load on which the PV generator must supply.

1.5 Solar Energy

Electricity is one of the most versatile forms of energy, adapting perfectly to every need. Its use is so widespread that today it is difficult to imagine a technically advanced society that does not use it.

The principle of photovoltaic solar energy consists of transforming solar radiation into electricity using a photovoltaic cell

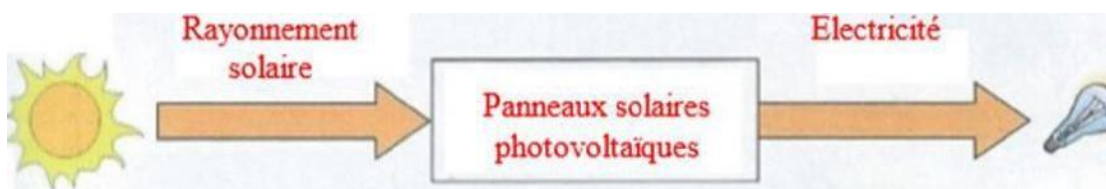


Figure 1.1 Principle of photovoltaic conversion of solar energy

The methods of harnessing solar energy are:

- **Photovoltaic (PV) Technology:** PV cells, commonly known as solar panels, convert sunlight directly into electricity through the photovoltaic effect. When sunlight strikes the cells, it excites electrons, generating an electric current.
- **Solar Thermal Energy:** This method uses mirrors or lenses to focus sunlight onto a small area, generating heat. This heat is then used to produce steam, which can power turbines to generate electricity or to provide direct heating for residential or commercial use.[5]

- Concentrated Solar Power (CSP): Large-scale systems that use mirrors or lenses to concentrate sunlight to generate electricity, typically used for industrial purposes.

1.5.1 Key Components of Solar Energy Systems

- Solar Panels (Photovoltaic Cells): These are the devices that convert sunlight into electricity. The cells are arranged in panels to create a solar array.
- Inverter: Converts the DC electricity produced by the solar panels into AC electricity, which is used in homes and businesses.
- Batteries (Optional): In some systems, solar energy can be stored in batteries for later use, helping address intermittency issues (e.g., when the sun isn't shining).
- Thermal Collectors: Used in solar thermal systems to collect and absorb sunlight and convert it into heat.

1.5.2 Type of Solar Energy

There are two types of solar energy:

- Photovoltaic
- Thermal.

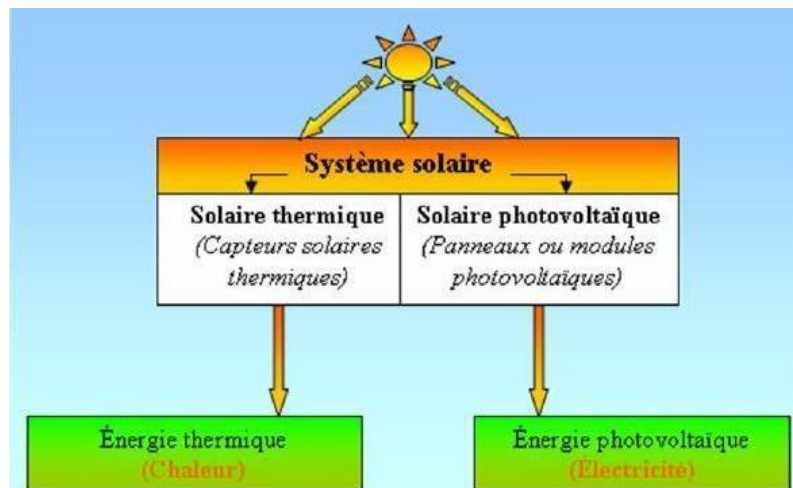


Figure 1.2 Type of solar energy

1.6 Solar radiation

Solar radiation is the raw material of solar energy, it is a propagation of a wave of length which varies between 0.2 and 4.10–6m, without the need for a physical support to move, it arrives at the ground after the loss of a large part of its intensity, because of a part of the ultraviolet, which is absorbed.

1.6.1 The Different Types of Radiation

- a) **Direct radiation RD** : Direct radiation is received directly from the sun, without being scattered by the atmosphere. The pencils are parallel to each other, so it forms shadows and can be reflected by modules.
- b) **Diffuse radiation Rd** : This is the portion of solar illumination reflected by the ground; this radiation depends directly on the nature of the ground (clouds, sand, etc.).
- c) **Reflected solar radiation** : Albedo is the portion reflected by the ground. It depends on the site's environment. It must be taken into account when assessing the radiation on the inclined plane.
- d) **Global radiation RG** : Global radiation refers to the overall intensity of solar flux on a receiving surface.

$$RG = RD + Rd$$

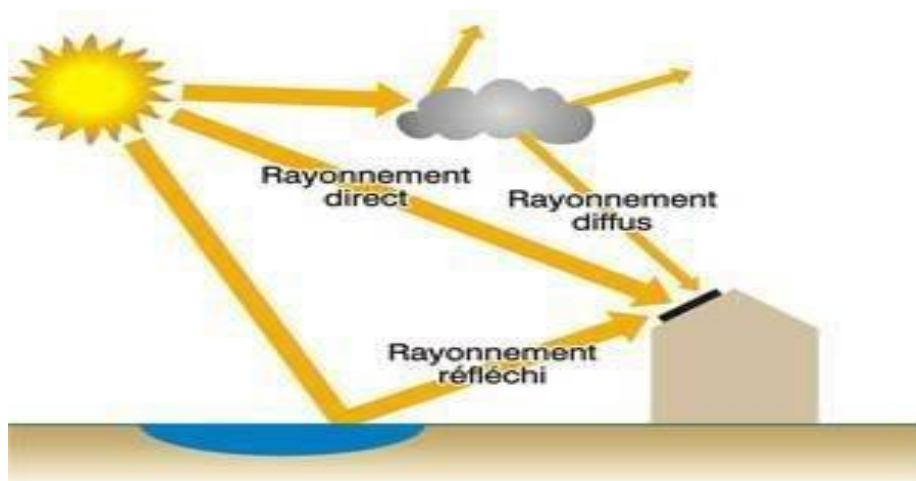


Figure 1.3 Components of solar radiation

1.6.2 Radiation in Algeria

Algeria has a significant solar deposit, due to its climate, the maximum solar power at any

point in our country is approximately 1Kw/m2. The average maximum daily energy (clear sky, month of July) exceeds 6Kw/m2 and the maximum annual energy in Algeria is around 2500 KW/m2. The map below represents the different energy zones of Algeria.

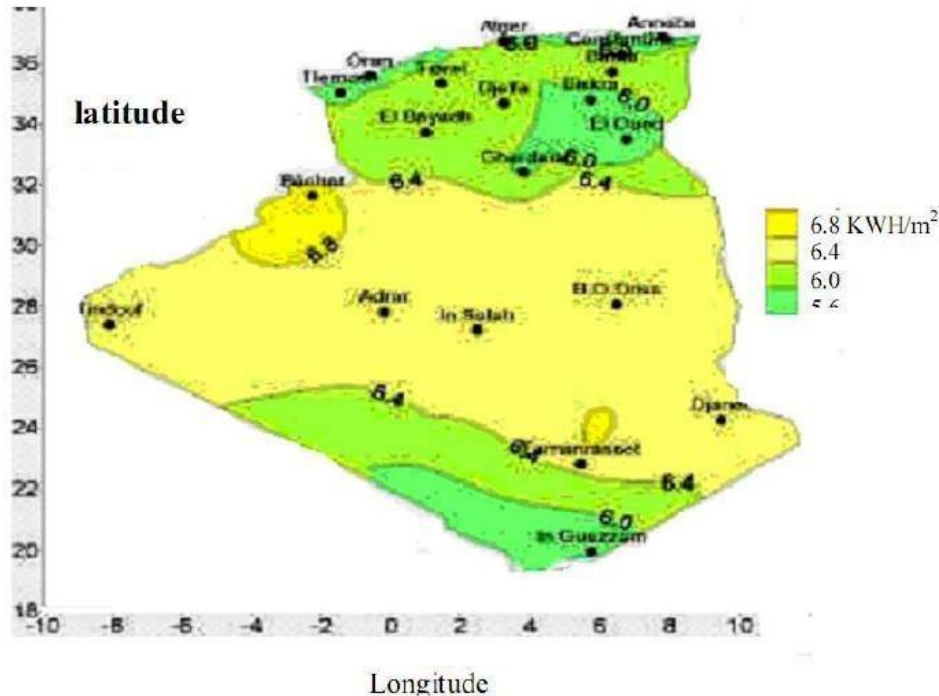


Figure 1.4 The different energy zones in Algeria

1.7 Distribution of Renewable Energy in Africa

The distribution of renewable energy in Africa varies significantly across the continent due to differences in geographical features, infrastructure, economic development, and access to renewable resources. While the potential for renewable energy in Africa is vast, the region faces challenges such as limited infrastructure, investment, and political instability in certain areas. Here's an overview of how renewable energy is distributed and utilized across Africa:

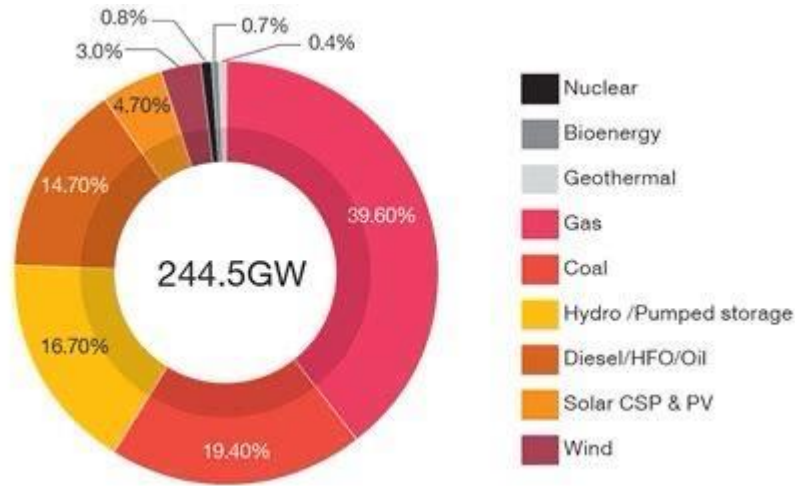


Figure 1.5 Distribution of renewable energy

1.8 A Photovoltaic Cell :

1.8.1 History :

The term "photovoltaic" refers to the physical process of converting light energy into electrical energy by transferring the energy from photons to the electrons in a material. The photovoltaic principle was discovered by the French physicist.

Becquerel in 1839 and explained by Albert Einstein in 1905 (for this explanation he received the Nobel Prize in Physics in 1921). The prefix Photo comes from the Greek "phos" which means light. "Volt" comes from the surname of Alessandro Volta (1745-1827), a physicist who contributed to research on Photovoltaic (PV) electricity, therefore literally means light electricity.

1.8.2 Definition :

The photovoltaic cell is the element that converts solar energy into electrical energy. A photovoltaic solar panel can be made up of certain photovoltaic cells. Several cells are connected together to form what is called a photovoltaic solar module. Subsequently, several modules are grouped together to form an installation or even a photovoltaic solar power plant (Figure (I.6)).[6]



Figure 1.6 Photovoltaic solar power plant

A photovoltaic cell (or solar cell) is a device that transforms light energy into electric current. The photovoltaic cell is the semiconductor electronic component that makes up a photovoltaic solar panel and which, when exposed to light, produces electricity.

1.8.3 Three main types of cells:

a) Monocrystalline cells

- First generation of solar cells.
- An excellent yield rate of 15% and up to 24% in the lab.
- Laborious and difficult production method, and therefore very expensive.
- It requires a large amount of energy to obtain a pure crystal.

b) Polycrystalline cells

- Lower production costs.
- Less energy-intensive process.
- Efficiency of 13% and up to 20% in the lab.

c) Amorphous cells

- Much lower production costs.
- Efficiency of only 6% per module and 14% in the lab.

1.8.4 The Different Types of Silicon Cells:

Silicon was chosen to make photovoltaic solar cells for its electronic properties; it is characterized by the presence of four electrons on its peripheral layer.

a) Amorphous silicon cells :

Silicon, during its transformation, produces a gas which is projected onto a sheet of glass. The cell is dark gray.

➤ Advantages :

- Operates in low light conditions.
- Less expensive than other technologies.
- Less sensitive to high temperatures than monocrystalline or multicrystalline cells.

➤ Disadvantages

- Low yield in full sunlight (5 to 10%).
- Performance declines over time.

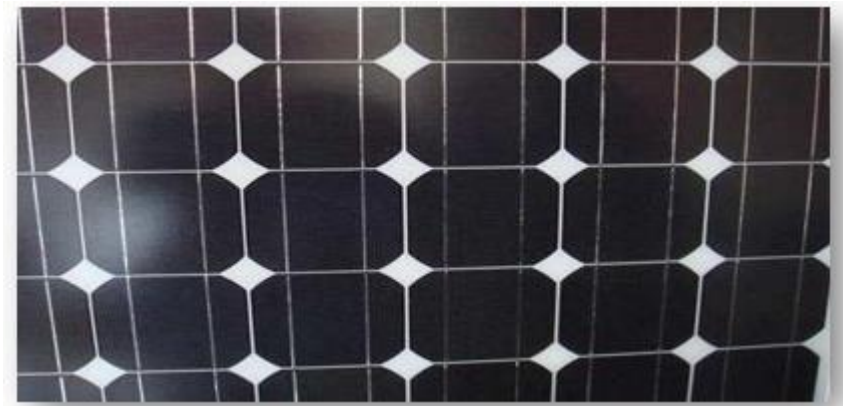


Figure 1.7 Photo of an amorphous cell

b) Monocrystalline silicon cells :

Monocrystalline technology, which is more expensive, uses pure silicon rods, also used in the manufacture of electronic chips. It is generally obtained by melting. Upon cooling, the silicon solidifies, forming a single, large crystal. The crystal is then cut into thin slices, which will then form the cells. These cells are generally a uniform blue.

➤ Advantages :

- Very good yield (15 to 22%).

➤ **Disadvantages :**

- High cost.
- Low efficiency in low light.



Figure 1.8 Photo of monocrystalline cell

c) Multicrystalline silicon cells :

Polycrystalline silicon is obtained by remelting monocrystalline silicon scraps from squaring operations (the action of bringing the part to the desired dimensions). As the silicon cools, several crystals form. The photovoltaic cell has a bluish appearance, but is not uniform; patterns created by the different crystals can be seen.

➤ **Advantages :**

- Good conversion efficiency, but slightly lower than monocrystalline.
- Less expensive to produce than monocrystalline.

➤ **Disadvantages :**

- Low frequency under low light (10 - 13%).



Figure 1.9 Photo of a multicrystalline cell.

1.9 The Photovoltaic Effect:

1.9.1 Definition :

The photovoltaic effect is the photoelectric effect, characterized by the production of an electric current between two parts of different materials that are in contact and exposed to light or general electromagnetic radiation. This photovoltaic effect is the principle of photovoltaic cells and is therefore essential for the production of solar electricity. When a material (semiconductor) is exposed to sunlight, the atoms exposed to the radiation are "bombarded" by the photons constituting the light. Under the action of this bombardment, the electrons are detached. The "detached" electrons create a low continuous electric voltage. Part of the kinetic energy of the photons is thus directly transformed into electrical energy: this is the photovoltaic effect.[7]

1.9.2 How a solar panel works:

- a) Absorption of Sunlight: Solar panels are made of semiconductor materials, usually silicon. When sunlight hits the surface of the PV cells, the energy from the sunlight is absorbed by the semiconductor material.
- b) Excitation of Electrons: The energy from the sunlight excites electrons in the material, causing them to become energized and move around.

- c) Generation of Electric Current: When these free electrons move, they create an electric current. The PV cell has an electric field built into it, which directs the flow of these electrons and generates direct current (DC) electricity.
- d) Conversion to AC: The DC electricity generated by the solar panel is then typically converted to alternating current (AC) using an inverter so it can be used to power homes, businesses, and electrical grids.

The photoelectric effect is the fundamental physical principle behind PV technology. It occurs when light photons hit a material and knock electrons loose from their atoms. This process creates a flow of electricity.

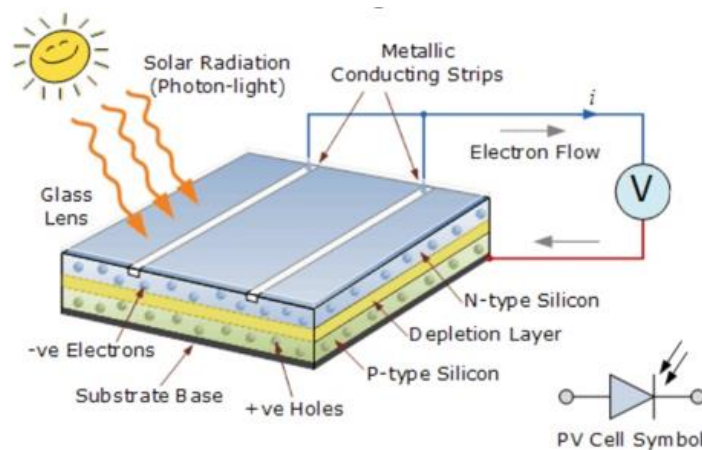


Figure 1.10 How a solar panel works

Not all sunlight is used by the solar panel. Only a portion of the spectrum is usable: the wavelength needed to remove an electron. Sunlight, the driving force behind the process, provides the energy that is converted into an electric current. This light is composed of small particles of energy (photons) that behave like projectiles. When a photon strikes a photovoltaic cell, it can bounce off it, pass through it, or be absorbed by it. Only absorbed photons provide energy that can be converted into electricity. When the material (semiconductor) absorbs enough sunlight (energy), electrons are stripped from the material's atoms by the solar photons. These electrons are then free to circulate and create an electric current.[6]

The direct conversion of solar energy into electricity is achieved through a semiconductor material, generally silicon, which is found in abundance on Earth (extracted from silica found in sand). When photons are absorbed by a semiconductor material, they give up all their energy to

the atoms belonging to the PN junction, this gives rise to several electron/hole pairs. The number of these pairs formed depends on the energy of the incident photons and the material used

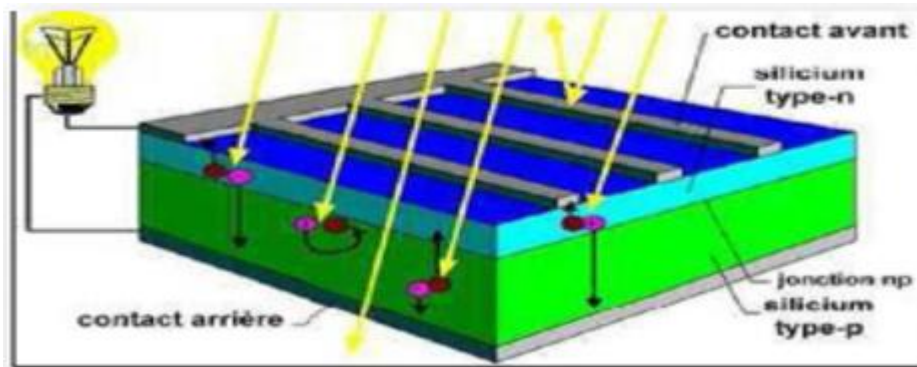


Figure 1.11 Operating principle of a photovoltaic cell

1.10 Two Doping Methods

- N-type (Negative) doping, which involves introducing foreign atoms into the semiconductor crystal structure, each of which has the property of donating an excess electron, free to move within the crystal (e.g., phosphorus).
- P-type (Positive) doping uses atoms whose insertion into the crystal lattice will produce an excess hole (e.g., boron).

1.10.1 N-type (Negative) doping

N-type semiconductors are called extrinsic semiconductors. The purpose of N-doping is to produce an excess of carrier electrons in the semiconductor. To understand how such doping occurs, consider the case of silicon (Si). Silicon atoms have four valence electrons, each bound to a neighboring silicon atom by a covalent bond. If an atom with five valence electrons, such as those in group V of the periodic table (e.g., phosphorus (P), arsenic (As), or antimony (Sb)), is incorporated into the crystal lattice, then this atom will have four covalent bonds and one free electron. This electron, which is not a bonding electron, is only loosely bound to the atom and can be easily excited to the conduction band. The materials thus formed are called N-type semiconductors because they contain an excess of negatively charged electrons.

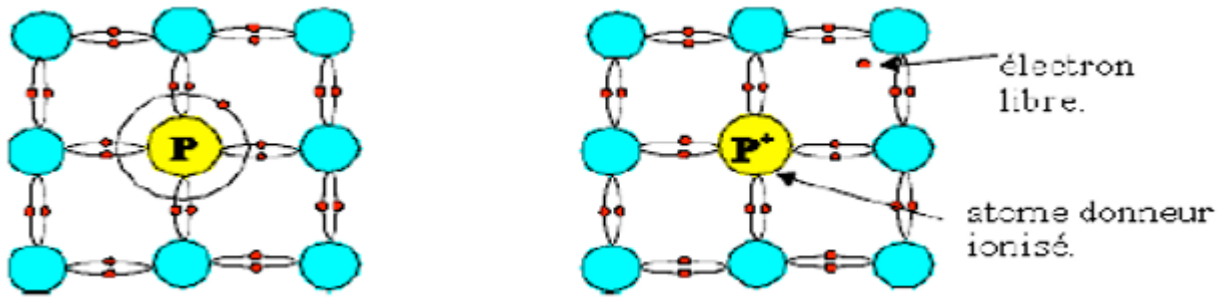


Figure 1.12 N-type doping

1.10.2 P-type (Positive) doping

P-type semiconductors are also extrinsic semiconductors. The purpose of P doping is to create an excess of holes. In this case, a trivalent atom, usually a boron atom, is substituted for a silicon atom in the crystal lattice.

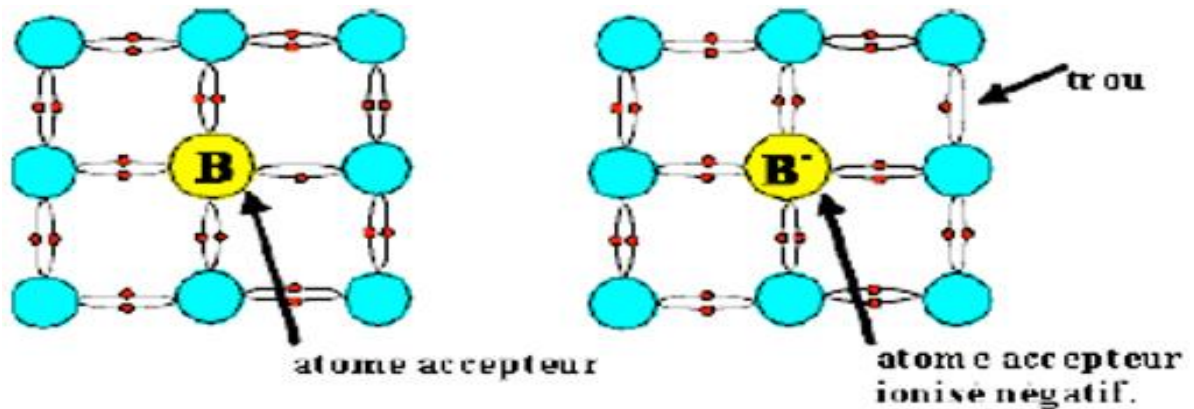


Figure 1.13 P-type doping

As a result, one of the four covalent bonds of adjacent silicon atoms is missing an electron, and the atom can accept an electron to complete this fourth bond, thus forming a hole. When doping is sufficient, the number of holes far exceeds the number of electrons.

1.10.3 P-N junction:

The P-N junction is created when the two types of silicon are brought into contact. This junction must allow electrons to flow between the two plates.

In the case of a photovoltaic cell, the gap of the N-type semiconductor is calculated so that

the current cannot be established on its own: there must be an input of energy, in the form of a photon of light, for an electron from the N layer to be torn off and placed in the P layer.

When a photon of light strikes a piece of silicon, two things can happen: the photon can pass directly through the silicon (if the photon's energy is lower than the silicon semiconductor's band gap energy), or the photon is absorbed by the silicon (if the photon's energy is greater than the silicon's band gap energy).

When a photon is absorbed, it gives its energy to an electron. Usually, this electron is in the valence band and is firmly bound by covalent bonds to neighboring atoms and is therefore unable to move away. The energy given by the photon "ejects" the electron to the conduction band, where it is free to move within the semiconductor lattice. The covalent bond that the electron previously had is now in the place where an electron is missing - this is called an electron hole. The absence of the covalent bond allows electrons from neighboring atoms to move into this "hole", thus leaving another hole behind and in this way the hole can move within the lattice. Thus, we can say that photons absorbed in the semiconductor create mobile electron holes. A photon only needs to have an energy greater than that of the valence band to extract an electron from the valence band to the conduction band: an electric potential difference (voltage) and an electric current are created.

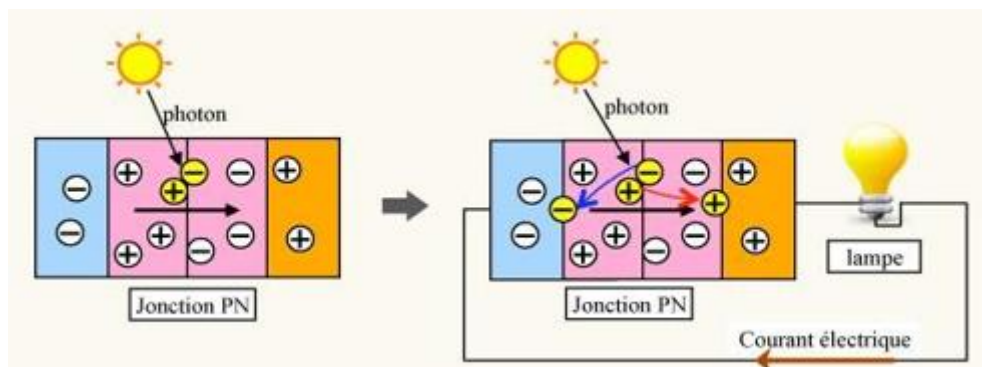


Figure 1.14 The PN junction

1.11 Configuration of PV Cells to Produce Usable Quantities of Power:

Photovoltaic cells are electrically connected in series and/or parallel to produce higher voltages and/or currents. Photovoltaic modules consist of photovoltaic cells connected together; these modules can form a unit of a complete photovoltaic panel. Photovoltaic panels include more than one PV module assembled as a pre-wired unit and can be installed on site,

which is the complete power generating unit.

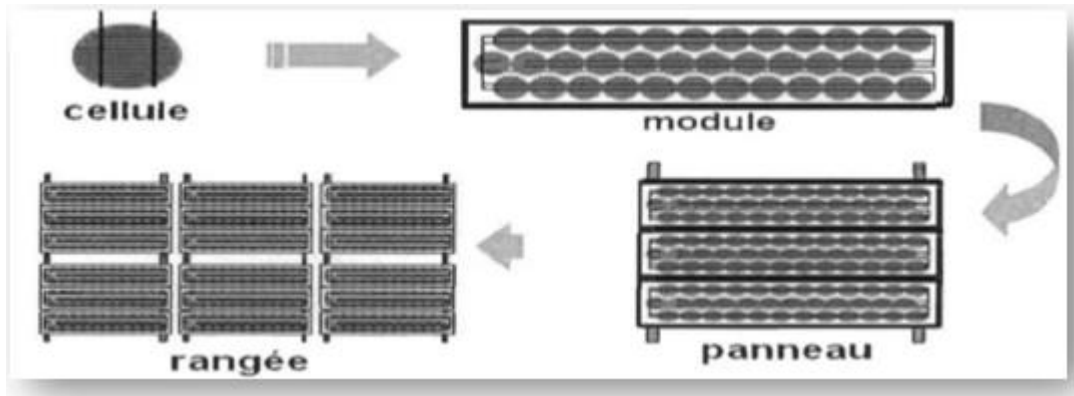


Figure 1.15 Configuration of photovoltaic cells

1.12 Ideal Electrical Circuit:

The photovoltaic cell can be represented by the equivalent electrical circuit given in Figure 1.16 composed of a current generator and a parallel diode. The current I generated by the cell is then written.[8]

In this case the current generated by the cell is written:

$$I = I_{ph} - I_D \dots\dots\dots (1.2)$$

$$I_D = I_S \cdot (e^u - 1) \dots\dots\dots (1.3)$$

$$I = I_{ph} - I_S \cdot (e^u - 1) \dots\dots\dots (1.4)$$

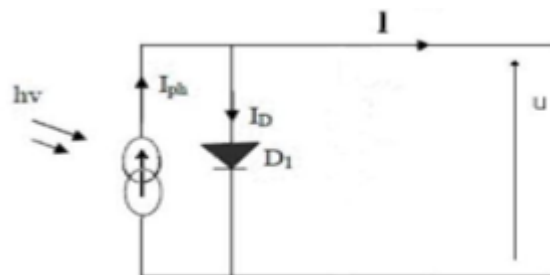


Figure 1.16 Ideal electrical circuit of the photovoltaic cell

With:

U : Voltage.

U_t : KT/q Thermic Voltage.

K : 1.38×10^{-23} Boltzmann Constant.

q : 1.602×10^{-19} Electron Charge.

T : Absolute Temperature in °K.

I_s : Saturation Current of the Diode.

I_{ph} : Photo Current .

1.13 Real Electrical Circuit :

The real photovoltaic cell can be represented by the equivalent electrical circuit given in Figure 1.17, which is composed of a current generator and a parallel diode plus series and parallel resistors.

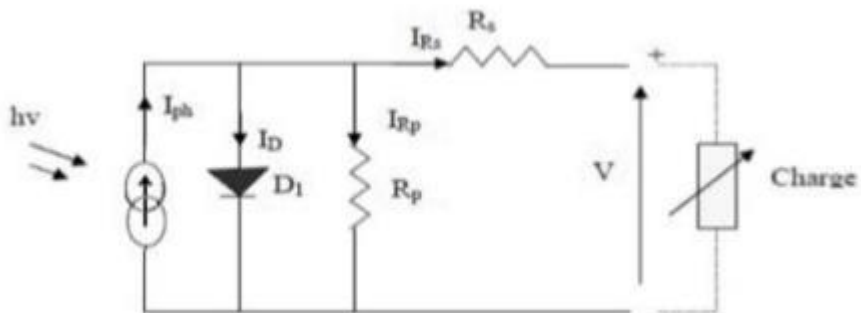


Figure 1.17 Electrical diagram of a real photovoltaic cell

The current-voltage characteristics for a given temperature and fixed solar is given below [21]:

The current generated by the cell is expressed as follows:

$$I_{RS} = I_D - I_{Rp} \dots\dots\dots (I.5)$$

$$I_D = I_0 \cdot (e^{\frac{q(V+R_s I_{RS})}{A \cdot K \cdot Tc}} - 1) \dots\dots\dots (I.6)$$

$$I_{Rp} = \frac{(V+R_s I_{RS})}{R_p} \dots\dots\dots (I.7)$$

$$I = I_{ph} - I_0 \cdot \left(e^{\frac{q(V+R_s I_{Rs})}{A \cdot K \cdot T_c}} - 1 \right) - \frac{(V+R_s I_{Rs})}{R_p} \dots\dots\dots (I.8)$$

A : the ideality factor of the junction ($1 < A < 3$)

I_{ph} : Photo current created by the cell (proportional to the incident radiation).

I_0 : Diode current, represents the internal leakage current within a cell caused by the P-N junction of the cell.

R_p : Shunt resistors represent leakage around the P-N junction due to impurities and at cell corners.

R_s : Series resistance symbolizes the mass resistance of the semiconductor material, as well as the ohmic and contact resistances at the cell connections.

q : The charge of the electron ($1,6 \cdot 10^{-19} \text{C}$).

K : Boltzmann constant ($1,38 \cdot 10^{-23} \text{ J/K}$).

T_c : Junction temperature (K).

$$T_c = T + (NOCT - 20) E_g / 800.$$

T : Room temperature.

E_g : Illumination.

NOCT : (Nominal Operating Cell Temperature), nominal operating temperature of the cell which is measured under the following conditions :

- Clear sunny day 800(w/m²).
- Room temperature of (20°C).
- Average wind speed (1m/s).

Neglecting the term $\frac{(V+R_s I)}{R_p}$ for a very large shunt resistance, it turns out that the current generated by the cell becomes:

$$I = I_{ph} - I_0 \cdot \left(e^{\frac{q(V+R_s I)}{A \cdot K \cdot T_c}} - 1 \right) \dots\dots\dots (I.9)$$

1.14 The performance of a PV panel:

1.14.1 Power produced:

The efficiency of a photovoltaic solar panel depends on the technologies used in its manufacture. There are several types, the best known of which are PV panels based on polycrystalline silicon cells, monocrystalline silicon, amorphous silicon, multi-junction cells,

etc. Each of these technologies has advantages and disadvantages. In particular, the efficiency, which is generally the selection criterion, depends on the climatic conditions of the installation site (in regions characterized by high temperatures, amorphous silicon systems are preferred to mono or polycrystalline ones). [9]

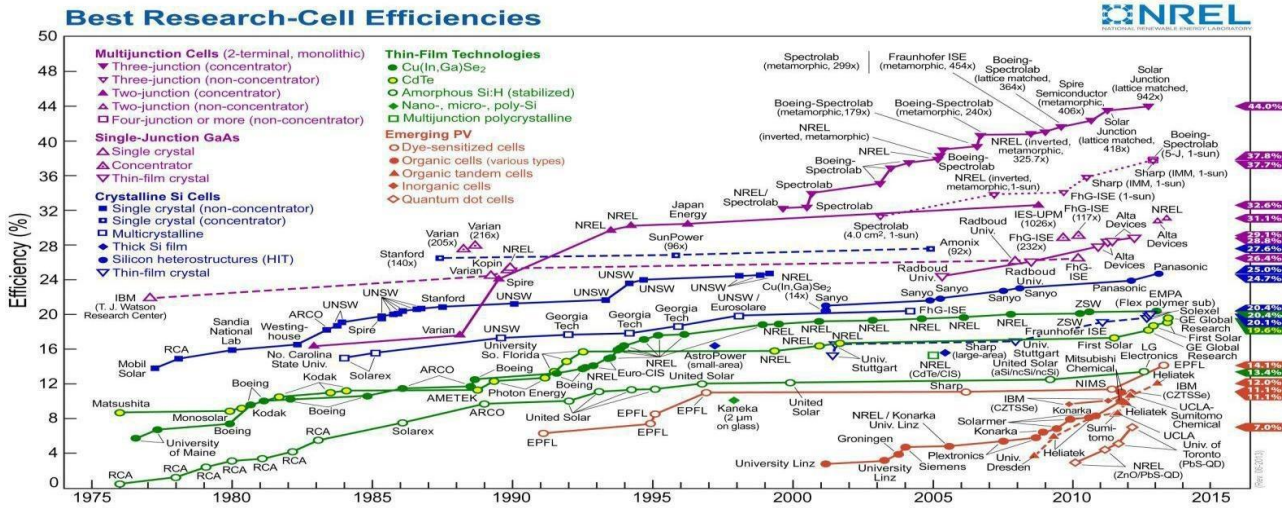


Figure 1.18 Rendement pour différents types de technologies au cours des années

For a PV panel, the efficiency, R expressed as a percentage (%), is defined by the ratio of the electrical power produced by the PV panel (PEP) to the solar power received (PSR).

1.15 N.N.N Positioning:

As mentioned before, the energy provided by the PV panel strongly depends on the amount of solar irradiance absorbed by the latter. This amount depends on the orientation of the panel relative to the sun. To collect the maximum amount of energy, the PV panel must be constantly oriented perpendicular to the sun's rays (Figure (1.19)).

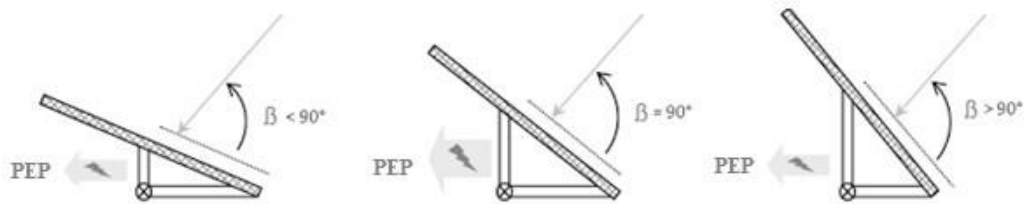


Figure 1.19 Dependence of the performance of a PV panel on the angle β

With: β the angle formed between the plane of the panel and the incident light rays; the optimal angle corresponds to an angle of 90° as indicated in Figure (1.20).

Each time this angle decreases or increases, the surface area (m^2) of the panel exposed to the rays decreases and therefore, starting from the power produced, the efficiency also decreases, hence the importance of the orientation of the panels in relation to the position of the Sun.

The efficiency in exploited solar power can be calculated using the following equation :

$$RN = \sin(\beta) \times 100 \quad [I.10]$$

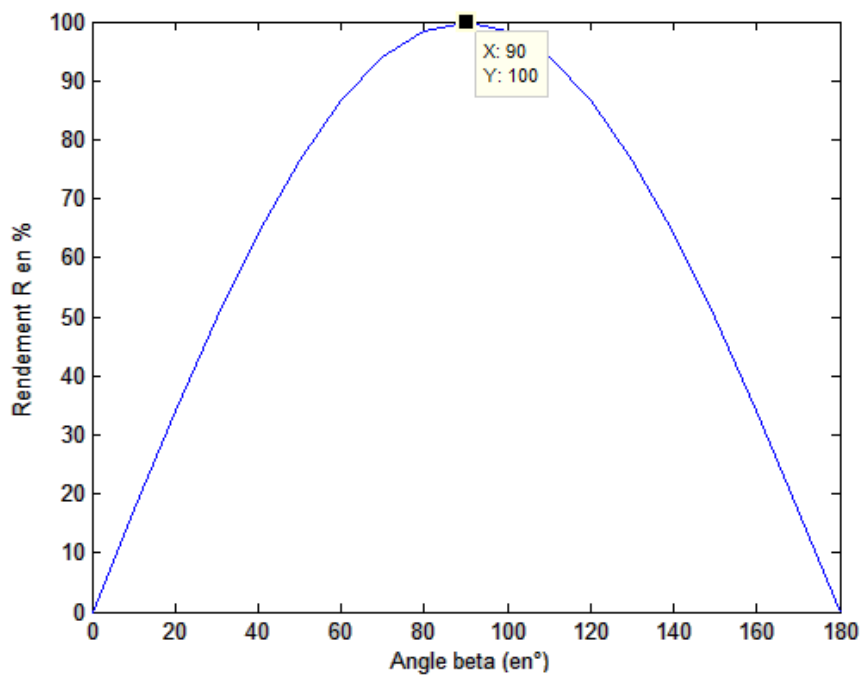


Figure 1.20 Yield in solar power exploited as a function of the angle β of the solar rays

1.15.1 Tilt Angle

Another factor that influences the performance of the PV panel is the tilt angle, which corresponds to the angle formed by the plane of the solar panel in relation to the horizontal (the ground plane).

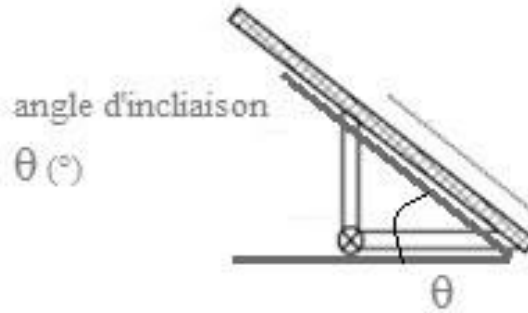


Figure 1.21 Representation of the inclination angle θ .

In fact, the evolution of the sun's trajectory varies according to the seasons (the inclination of the earth varies), the angle of inclination is smaller in summer and larger in winter. the earth in relation to its plane of translation around the sun.

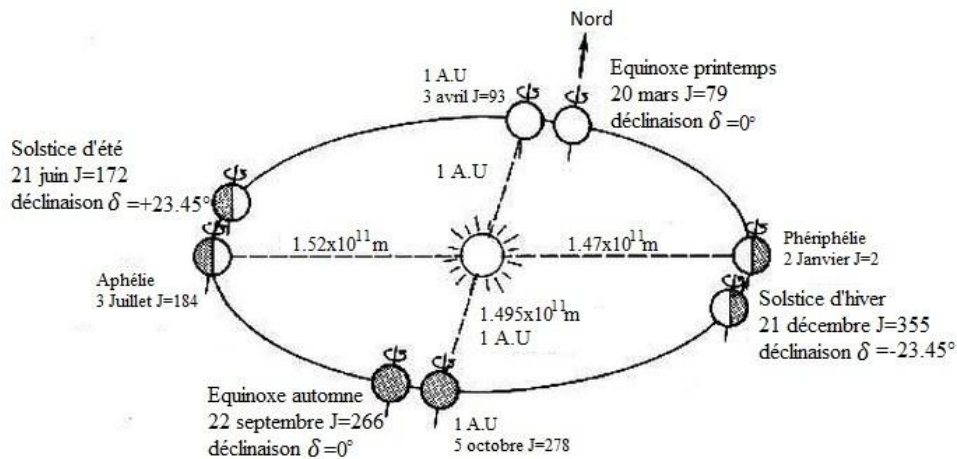


Figure 1.22 Representation of equinoxes and solstices and inclination of the axis of rotation

However, if we want to maximize the power generated by a PV panel and have optimal performance, we must take into account all these parameters and constraints related to the orientation of the module as well as the position of the sun. This can be ensured by a solar tracking system (sun tracker or also called solar tracker (common name)) allowing to follow the sun throughout the day. For this, the structure has two degrees of freedom: a horizontal rotation to adjust the azimuth and a vertical rotation for the inclination. This system thus allows the photovoltaic panels to continuously and in real time follow the trajectory of the sun to ensure maximum electrical production, hence the need to define with precision the trajectories taken by the sun, in order to define the best way in which the automatic tracking will be carried out.

1.16 Advantages and Disadvantages of PVs:

a) Advantage:

- First, it's highly reliable. The system has no moving parts, making it particularly suitable for remote regions. This is why it's used on spacecraft.
- Second, the modular nature of photovoltaic panels allows for simple installation and adaptability to diverse energy needs. Systems can be sized for power applications ranging from milliwatts to megawatts.
- Operating costs are very low, given the reduced maintenance requirements, and it requires no fuel, transportation, or highly specialized personnel.
- Finally, photovoltaic technology offers ecological benefits because the finished product is non-polluting, silent, and causes no environmental disturbance, except for the space required for large-scale installations.

b) Disadvantages:[10]

- The manufacture of photovoltaic modules is a high-tech process and requires significant investment.
- The actual conversion efficiency of a module is low, around 10-15% (i.e., between 10 and 15 MW/km² per year for the BENELUX region), with a theoretical limit of 28% for a single cell. Photovoltaic generators are only competitive with diesel generators for low energy demands in remote regions.
- When chemical energy storage (battery) is required, the cost of the generator increases.
- Storing electrical energy still poses many challenges. The low efficiency of photovoltaic panels is explained by the way the cells operate. To move an electron, the radiation energy must be at least 1 eV. Therefore, not all incident rays with lower energy will be converted into electricity. Similarly, light rays with energy greater than 1 eV will lose this energy, the rest will be dissipated as heat.

1.17 The Battery Technology

Lithium-ion (Li-ion) batteries are the most widely used rechargeable batteries in various applications, including solar energy storage, electric vehicles (EVs), portable electronics, and more. Their popularity arises from their high energy density, long lifespan, and lightweight design, making them an ideal choice for solar energy storage systems and other modern technologies.

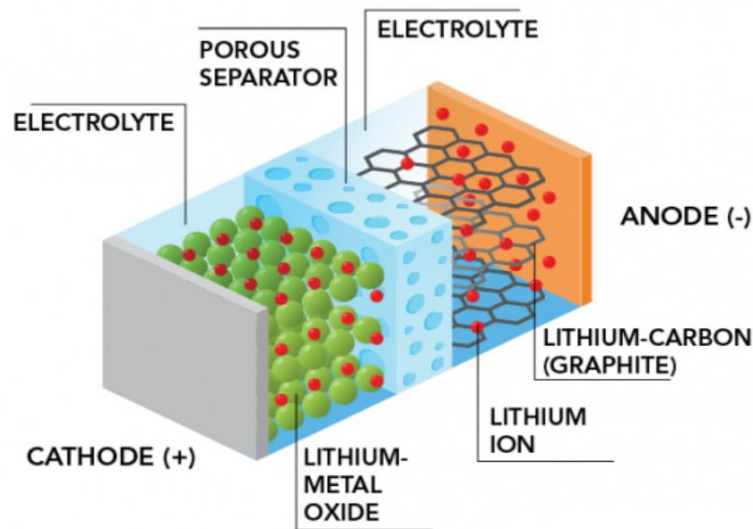


Figure 1.23 The Battery Technology[11]

What is a Lithium-Ion Battery?

Lithium-ion batteries are a type of rechargeable battery that uses lithium ions as the key component in their chemistry. The battery consists of three main parts:[12]

- Anode (Negative Electrode): Usually made of graphite, this is where the lithium ions are stored during charging.
- Cathode (Positive Electrode): Typically made from a compound like lithium cobalt oxide or lithium iron phosphate, the cathode releases lithium ions during discharge.
- Electrolyte: A chemical medium that allows the movement of ions between the anode and cathode.
- Separator: A layer that prevents the anode and cathode from touching while allowing the flow of ions.

Discharging and charging

During discharge, lithium ions (Li⁺) carry the current within the battery cell from the negative to the positive electrode, through the non-aqueous electrolyte and separator diaphragm.

During charging, an external electrical power source applies an over-voltage (a voltage greater than the cell's own voltage) to the cell, forcing electrons to flow from the positive to the negative electrode. The lithium ions also migrate (through the electrolyte) from the positive to the negative electrode where they become embedded in the porous electrode material in a process known as intercalation.[13], [14]

Energy losses arising from electrical contact resistance at interfaces between electrode layers and at contacts with current collectors can be as high as 20% of the entire energy flow of batteries under typical operating conditions.

During the *constant current* phase, the charger applies a constant current to the battery at a steadily increasing voltage, until the top-of-charge voltage limit per cell is reached.

During the *balance* phase, the charger/battery reduces the charging current (or cycles the charging on and off to reduce the average current) while the state of charge of individual cells is brought to the same level by a balancing circuit until the battery is balanced. Balancing typically occurs whenever one or more cells reach their top-of-charge voltage before the other(s), as it is generally inaccurate to do so at other stages of the charge cycle. This is most commonly done by passive balancing, which dissipates excess charge as heat via resistors connected momentarily across the cells to be balanced. Active balancing is less common, more expensive, but more efficient, returning excess energy to other cells (or the entire pack) via a DC-DC converter or other circuitry. Balancing most often occurs during the constant voltage stage of charging, switching between charge modes until complete. The pack is usually fully charged only when balancing is complete, as even a single cell group lower in charge than the rest will limit the entire battery's usable capacity to that of its own. Balancing can last hours or even days, depending on the magnitude of the imbalance in the battery.[15]

During the *constant voltage* phase, the charger applies a voltage equal to the maximum cell voltage times the number of cells in series to the battery, as the current gradually declines towards 0, until the current is below a set threshold of about 3% of initial constant charge current.[16]

Periodic topping charge about once per 500 hours. Top charging is recommended to be

initiated when voltage goes below 4.05 V/cell. Failure to follow current and voltage limitations can result in an explosion.

Charging temperature limits for Li-ion are stricter than the operating limits. Lithium-ion chemistry performs well at elevated temperatures but prolonged exposure to heat reduces battery life. Li-ion batteries offer good charging performance at cooler temperatures and may even allow "fast-charging" within a temperature range of 5 to 45 °C. Charging should be performed within this temperature range. At temperatures from 0 to 5 °C charging is possible, but the charge current should be reduced. During a low-temperature (under 0 °C) charge, the slight temperature rise above ambient due to the internal cell resistance is beneficial. High temperatures during charging may lead to battery degradation and charging at temperatures above 45 °C will degrade battery performance, whereas at lower temperatures the internal resistance of the battery may increase, resulting in slower charging and thus longer charging times.[17]

1.17.1 Advantages and Disadvantages of Lithium Ion Batteries[18]

Advantages:

- High Efficiency: Lithium-ion batteries have an energy efficiency (round-trip efficiency) of 90-95%, meaning most of the energy stored can be retrieved when needed.[19]
- Long Lifespan: They can last for 10-15 years, depending on usage and conditions.
- Compact and Lightweight: Lithium-ion batteries take up less space and are lighter than other types, making them ideal for residential use.
- Rechargeable

Disadvantages:

- Protection required: Lithium-ion cells and batteries are not as robust as some other rechargeable technologies; they require protection from being over charged and discharged.
- Aging effect: Lithium-ion battery will naturally degrade as they suffer from ageing. Normally Lithium-ion batteries will only be able to with stand 500 – 1000 charge and discharge cycles before their capacity falls to 50%.
- Transportation problems: This Lithium-ion battery disadvantage has come to the fore in recent years. A lot of restrictions are in place for the transportation of Lithium-ion batteries

especially large quantities by air.

- Deep discharge: Lithium-ion battery has low self-discharge. The general integrity of this battery remains intact even if partially discharged. However, deep discharge or when the voltage of a Lithium-ion cell drops below a certain level, it becomes unusable.
- Safety concerns: Lithium-ion battery may explode when overheated or overcharged. This is because gasses formed by electrolyte decomposition increases the internal pressure of the cell. Overheating or internal short circuit can also ignite the electrolyte and cause fire.
- Sensitivity to high temperature: Lithium-ion battery is susceptible to the downside of too much heat caused by overheating of the device or overcharging. Heat causes the cells or packs of this battery to degrade faster than they normally would.

1.17.2 Future of Solar Battery Technology

- Solid-State Batteries: Emerging solid-state batteries promise higher efficiency, safety, and energy density, which could dramatically improve solar energy storage in the future.
- Artificial Intelligence and Smart Grids: AI and smart grid technologies could enable better management of energy storage, optimizing when to charge and discharge batteries based on energy demand and availability.
- Integration with Electric Vehicles (EVs): Battery storage for solar energy could also be integrated with electric vehicles (EVs), allowing for bi-directional charging (V2G) to store solar energy in car batteries

1.18 Conclusion

In this chapter, we provided a general overview of photovoltaic systems, including an explanation of the principle of converting solar energy into electricity using photovoltaic cells. We also presented the most common cell types, highlighting their efficiencies, advantages, and disadvantages. The next chapter will focus on the core of our study: the operation of static converters, particularly those based on reversible structures. An overview will be provided, followed by an analysis of the main control techniques used.

CHAPTER II:
OPERATION OF STATIC CONVERTERS

2.1: Introduction to Static Converters

Recently, significant progress has been made in the development of high-power semiconductors, particularly with the advent of GTOs (Gate Turn-Off thyristors) and IGBTs (Insulated Gate Bipolar Transistors). Converter design has taken advantage of these technologies. We now encounter them in the form of voltage source converters (VSCs) or what are known as reversible converters. These converters are of the four-quadrant type. In addition, they operate at any power factor and can be combined with controls designed using Pulse Width Modulation (PWM). These controls approximate the output reference voltage by achieving an average voltage of the same value over a switching period. To achieve this, they use time modulation of the closest possible levels. Their AC output voltage profile is better from a harmonic point of view. [20]

The presence of reversible converters brings valuable advantages:

- Low-order harmonics can be significantly attenuated if the converter switching frequency allows it, thus reducing the size of filtering equipment.
- These types of VSC converters are capable of absorbing and generating reactive power. VAR components connected to the AC side of the converters are no longer required.
- The active power carried by the DC line and the reactive powers of each terminal are controlled independently.
- Response times are shorter thanks to the increased switching frequency of PWM controls. This frequency was lower than 300 Hz when the switches were made from thyristors. It now exceeds 1 kHz with GTOs or IGBTs.
- VSC converters are independent and can operate at different frequencies.

Nevertheless, these converters represent the future for HVDC system design and they can be ideal candidates for the following application areas:[21]

- Connecting renewable energy sources such as wind turbines.
- Transmitting electricity to islands.
- Providing energy to large cities that are subject to environmental and security constraints.

In this context, this chapter is devoted to a detailed study of voltage source converters/or

reversible converters, and their different modulation strategies will be presented. Reversible static converters; There are mainly four types:

- DC-AC Inverter (Onduleur)
- AC-DC Rectifier (Redresseur)
- DC-DC Chopper (Hacheur)
- AC-AC Dimmer (Gradateur)

2.2 Power Converters

Power electronic converters are those converters that are used to control the high voltages and currents in large industrial equipment, households, and so on.

Power Electronic Converters are those converters that are converted from one form to another. The most significant factor that affects the Power converter is conditioning. It is impossible to have clean signals, so conditioning signals are used for clean, pure input signals. Power electronic converters have various switches that are Power BJT, Thyristors, Power MOSFET, capacitors, and inductors. In Power Converters, capacitors are used because the power loss in these capacitors is zero compared to resistors, which leads to power loss.

In power electronic systems, there are two main parts: the converter and the controller. The converter modifies the electricity based on instructions from the controller, which uses an integrated circuit to determine what those instructions should be.

A key task for converters is to ensure that the electricity they produce is clean, meaning it does not contain excessive noise or disturbances, known as harmonics. Although it is difficult to get rid of all harmonics, using something like a low-pass LC filter can really help reduce them. This makes electricity cleaner and better for powering sensitive devices and machines.

2.2.1 Advantages and Disadvantages of Power Converters

Advantages of Power Converters

- Highly reliable and have a long life.

- Using capacitors in power electronic converters helps this converter reduce the loss of power.
- Very efficient, small, and have less weight

Disadvantages of Power Converters

- Low overload capacity.
- Very expensive.

2.3 Topologies of Reversible Converters

2.3.1 DC/AC Inverters (Converters)

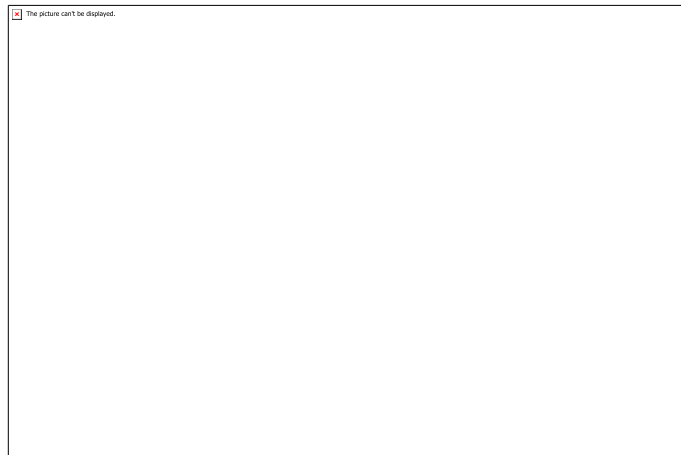


Figure 2.1 DC/AC Converter

DC-AC converters are just the opposite of AC-DC Converters. They are also known as Inverters. Inverters are devices that change direct current (DC), such as batteries, to alternating current (AC), which we use in our homes by in solar panels and various home appliances. They use components like power transistors, MOSFETs, and thyristors to manage this conversion. The choice of component depends on how much power is needed - for high-power tasks, thyristors are common, while transistors are better for smaller jobs.[22]

These devices are used in various places. For instance, they help drive machines with induction and synchronous motors, which are common in factories. They are also crucial for emergency power supplies (UPS) that keep critical systems running during power outages, such as in hospitals or data centers. Inverters are also used in airplanes and spacecraft to ensure a stable power supply.

Additionally, they play a role in high-voltage power transmission over long distances, which helps reduce energy losses. Inverters are also used in induction heating, which is the process of heating metal in industrial settings and even in some cooking appliances. On a smaller scale, they help power devices like flashes in cameras, showing how versatile they are from small gadgets to large industrial systems.

2.3.2 Inverter in Reversible Static Converters (AC/DC Rectifiers)[22]

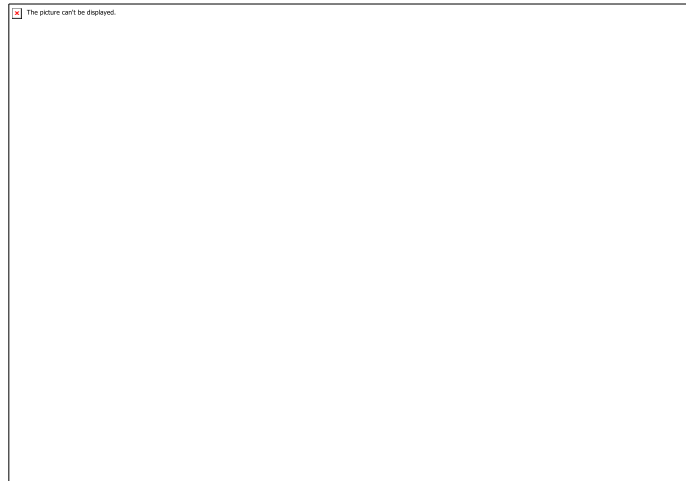


Figure 2.2 AC/DC Converter in Reversible Static

AC to DC converters, or rectifiers, convert alternating current (AC) to direct current (DC). AC to DC converters can be used in laptops, televisions, and mobile phone chargers.

An inverter is a key power electronic device used to convert direct current (DC) into alternating current (AC). In the context of reversible static converters, the inverter plays a critical role in enabling bidirectional power flow, meaning it can not only generate AC power from a DC source but also, in certain configurations, operate in reverse to allow energy to flow back into the DC side - a feature essential for regenerative systems and smart energy applications.

An inverter operates using fast switching components such as MOSFETs, IGBTs, or thyristors, which are controlled to generate an alternating voltage with desired frequency and amplitude. By inverting the direction of current flow in a controlled manner, the inverter creates AC waveforms, often using pulse width modulation (PWM) techniques to approximate sinusoidal outputs.

2.3.3 Applications of Reversible Inverters

Reversible inverters are widely used in applications where bidirectional power control is required:

- Electric motor drives: Enable energy regeneration during braking.
- Electric vehicles (EVs): Manage both propulsion (DC to AC) and regenerative braking (AC to DC).
- Grid-connected renewable energy systems: Convert and inject solar or wind power into the utility grid.
- Battery energy storage systems (BESS): Control charge and discharge cycles using the same interface.

2.3.4 Advantages and Challenges of Reversible Inverters

Advantages of Reversible Inverters

- Bidirectional energy transfer
- Energy recovery and regeneration capabilities
- Precise control of output waveform and direction
- Improved overall energy efficiency

Designing a reversible inverter involves several challenges:

- Switching losses: Resulting from high-frequency operation.
- Thermal management: Requires efficient heat dissipation.
- Electromagnetic interference (EMI): Needs proper filtering and layout techniques.
- Protection mechanisms: For overvoltage, overcurrent, and short-circuit scenarios.

2.3.5 Types of Inverters

Inverters can be classified according to various criteria:

a. Based on Phase Configuration:

- Single-phase inverter: Used for low-power or residential applications.
- Three-phase inverter: Common in industrial and high-power systems.

b. Based on Circuit Topology:

- Full-bridge inverter: Consists of four switching devices; allows full AC voltage swing.
- Half-bridge inverter: Uses two switches; lower voltage output.
- Multilevel inverter: Produces output voltages closer to pure sine waves; suitable for high-voltage applications.

c. Based on Application :

- Stand-alone inverter: Powers isolated loads, often used in off-grid systems.
- Grid-tied inverter: Synchronizes with the utility grid and allows power injection.

2.3.6 Control of the Inverter

Control of the inverter is typically performed through PWM (Pulse Width Modulation) techniques:

- Sinusoidal PWM: Approximates a sine wave for smoother output.
- SVPWM (Space Vector PWM): Used in three-phase systems for optimized performance.
- Scalar or Vector Control: Applied in motor control for precise torque and speed regulation.

These strategies enable control over:

- Output frequency
- Output voltage amplitude
- Direction of power flow (in reversible operation)

2.4 Basic structure of the DC/AC Converter

In order to get to the different topologies and before observing the evolution of its basic structure which is a "DC/AC" converter, it is necessary to understand the operating sequences of the simple assembly like the one in figure 2.3.a. This assembly represents one phase of the two-level converter and it is made up of two cells. Each cell includes a semiconductor-based switch which is unidirectional in voltage and current, with an antiparallel diode which allows the reversible passage of current. The DC side includes a DC voltage source which can be made using one (or more) capacitors or independent sources (battery). The AC side can have an active (the AC source) or passive (without source) receiver and an inductor. The role of the inductor is twofold: to smooth the current and to allow the exchange of energy between the two sides. It should be noted that the energy exchange is possible only in the case of the active receiver on the AC side (which can play the role of the source or the role of the receiver) and the capacitors on the DC side (which can also play both roles). The fact that each cell is reversible in current and irreversible in voltage allows us to see that such a cell operates in two quadrants, but that on the other hand the converter operates in four quadrants.

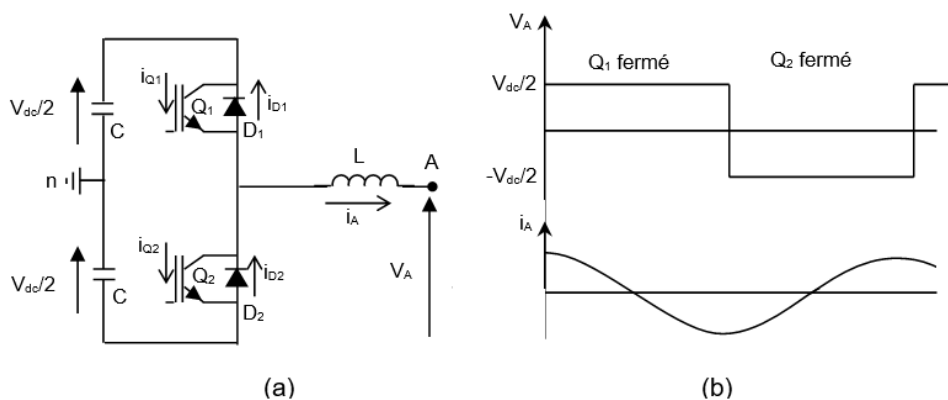


Figure 2.3 (a) Arm of a converter, (b) Waveform at the output of a converter

Switches Q_1 and Q_2 have two stable states: open state and closed state, which together make four possible combinations:

- 1) Q_1 open and Q_2 closed
- 2) Q_1 open and Q_2 open
- 3) Q_1 closed and Q_2 open
- 4) Q_1 closed and Q_2 closed

In general, combinations 1 and 3 are permissible, so the two switches are complementary

(they are always in opposite states). State 4 causes a short circuit on the DC side and state 2 gives an undetermined voltage on the AC side. If switch Q_1 is closed (conduction state) and Q_2 is open (blocking state), the voltage seen at point A (Figure 2.3.a) is $V_{cc}/2$. In the complementary case, so Q_1 is open and Q_2 is closed, this voltage is $-V_{cc}/2$.

The converter current is imposed by the load. The sign of this current and its phase shift with respect to the converter output voltage determine the direction and rate of energy transfer between the DC and AC sides. Figure 2.3.b shows the converter output voltage with the current imposed by any load. Initially, current $i > 0$ and $V_A > 0$, Q_1 is closed. In this case, the current flows through diode D_1 and $i_A = i_{D_1}$. The converter operates as a rectifier and the energy transfer takes place from the AC side to the DC side.

It should be noted that thanks to the inductance L (figure 2.3.a), this transfer takes place, despite the fact that the voltage on the AC side may be higher than the voltage on the DC side. Diode D_1 is reverse biased and it is the magnetic energy stored in the magnetic field of the inductance that will push the current through the diode. If the current goes through zero and becomes negative while Q_1 is closed (figure 2.3.a), the current will naturally switch in the same cell and it will pass through Q_1 , $i_A < 0$, $i_{D_1} = 0$, $i_{Q_1} = -i_A$. The energy transfer is now from the DC side to the AC side and the converter operates as an inverter. If switch Q_2 is commanded to close and Q_1 is commanded to open while the current is negative. The current will switch from Q_1 to diode D_2 and $i_A < 0$, $i_{D_1} = 0$, $i_{Q_1} = 0$, $i_{Q_2} = 0$, and $i_{D_2} = -i_A$. The energy transfer is from the AC side to the DC side and the converter operates in rectifier mode. Finally, if the current becomes positive and Q_1 remains closed, the current will switch from diode D_2 to transistor Q_2 and $i_A = i_{Q_2}$, $i_{D_2} = 0$. The converter becomes an inverter.

In Figure 2.4, four extreme cases can be seen. In the first case, the current i_A and the voltage V_A are in phase. The energy flow is from the AC side to the DC side and the converter operates in rectifier mode. The second case represents the operation in inverter mode (the phase shift between current and voltage is 180 degrees) and the energy is transferred from the DC side to the AC side.

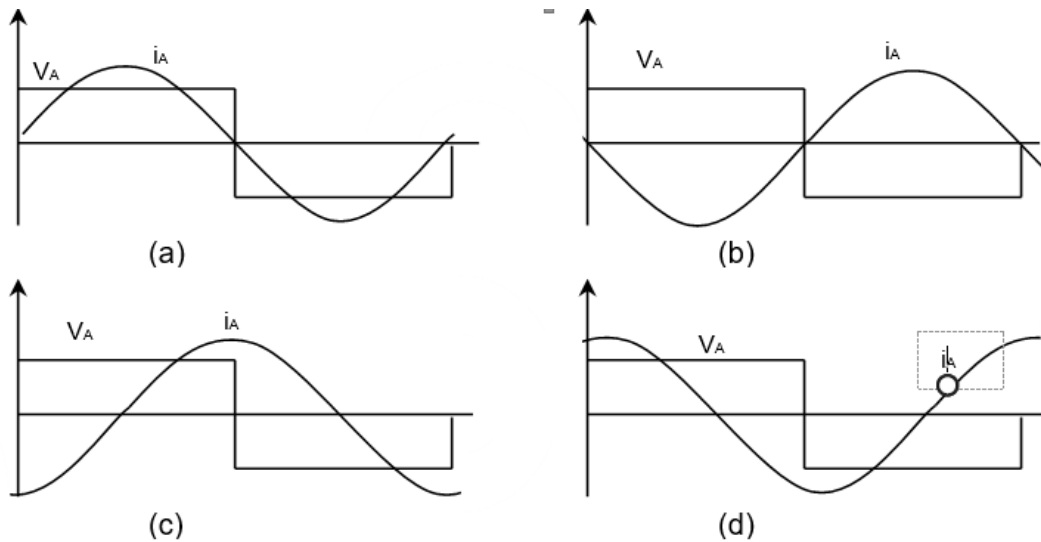


Figure 2.4 Waveform of voltage and current at the output of a converter (a) operation in rectifier mode, (b) in inverter mode, (c) in capacitive mode, (d) in inductive mode

In the last two cases, the phase shift between voltage and current is 90 degrees. The converter changes the operating mode from rectifier to inverter and vice versa every quarter cycle. This shows that, despite the instantaneous energy exchange between the two existing sides, the average energy transfer is zero and the converter takes on the behavior of pure reactive load.

2.5 Multilevel Converter

Multilevel converters are combinations of semiconductors and voltage sources that provide an output voltage above the unit ratings of each switch and an apparent frequency higher than the switching frequency of each switch. The most important advantages of multilevel topology over conventional bilevel topology are:

- The output voltage is scaled across at least three voltage levels, thus providing a better frequency spectrum. As a result, the required filter elements are smaller and less expensive.
- Using higher output voltages allows for increased converter power without increasing current.
- Increasing the apparent output frequency allows for greater system dynamics.

However, these converters also have some disadvantages:

- As voltage levels increase, the control structure becomes more complex.
- Capacitor voltage imbalance problems arise.

A review of publications from recent years shows us that the study of multilevel converters (topology analysis, control, modulation, etc.) is now one of the most important subjects in power electronics.

The development of multilevel technology has been driven by two factors. On the one hand, the technological evolution of semiconductor materials has enabled the production of higher power and voltage converters. On the other hand, even though the control of multilevel converters is complicated, the development of digital signal processors with very high computing capacity and reaction speed and low cost have made the implementation of this control possible.

2.5.1 Multilevel topologies

Multilevel converters are increasingly connected in high power applications. In a summary of the evolution of multilevel converter topologies is made based on patents.

The first patent dates back to 1975, when the cascade inverter, or Full-Bridge with separate DC sources, was defined as "the structure that separately connects a diode bridge in series to obtain a stepped output voltage." Its application was not developed until the mid-1990s. At that time, two patents demonstrated the superiority of cascade converters for industrial applications and motor control.

By adding diodes to the cascade converter to block the sources, the diode-clamped converter was patented, better known by its English name diode-clamped (DC). This converter was also called neutral point clamped (NPC) converter when it was first used in the three-level topology, in which the mid-point voltage level was the neutral point. The NPC application and its extension to multilevel converters were developed in.

The latest patents date back to the 90s when the floating capacitor converter (in the English literature flying capacitor) was presented. This converter is composed of several switching cells separated from each other by floating capacitors. It was initially used in high voltage applications of DC/DC converters.

2.5.2 Floating capacitance converter

The topology of the floating capacitance inverter (Flying Capacitor Multilevel Inverter) was proposed by T. Meynard and H. Foch in 1992[23]. This structure is proposed to solve, on the one hand, the problem of voltage balance, and on the other hand to reduce the excessive number of diodes.

Figure 2.5.a, shows the topology of a three-level floating capacitor inverter (also known as "nested cells" and "Flying Capacitor inverter"). In this structure and for an "n" level converter, (n-1) DC capacitors (n-1) x (n-2) / 2 auxiliary capacitors per arm are required. These capacitors are known as floating capacitors. The first advantage of these converters is the reduction of voltage constraints on the switches. Floating voltage sources impose a voltage constraint equal to $V_{dc}/2$ on each cell (where P_i is the number of cells per half-arm). On the other hand, the current rating of the switches is identical to that of a conventional structure. Floating capacitor converters also improve the output voltage waveform and allow more flexibility to obtain different voltage levels (compared to the NPC structure). On the other hand, the constraint of these converters is the need for a large number of capacitors, particularly for a three-phase configuration, which means a very high cost.[23]

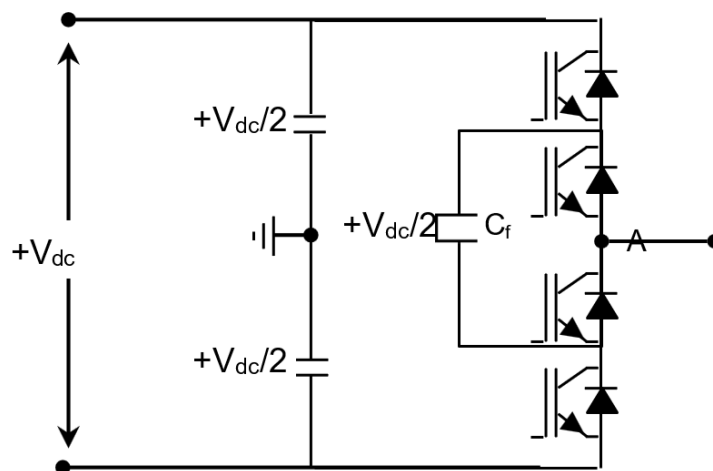


Figure 2.5.a Arm of a three-level converter with "floating capacitors"

2.5.3 Cascade Converters

Another widely used structure for generating multilevel voltage is the cascade converter. The basic principle of this structure (fig. 2.5.b) is the connection of several single-phase bridge inverters, with separate DC sources. The first use of this type of converter was plasma stabilization.

Each unit is powered by a separate DC capacitor and no other voltage balancing circuits or switching devices are required. There is no need to add blocking diodes or voltage balancing capacitors in this topology, which results in a relatively simple construction. The main disadvantage of this topology is the requirement for multiple independent power supplies.

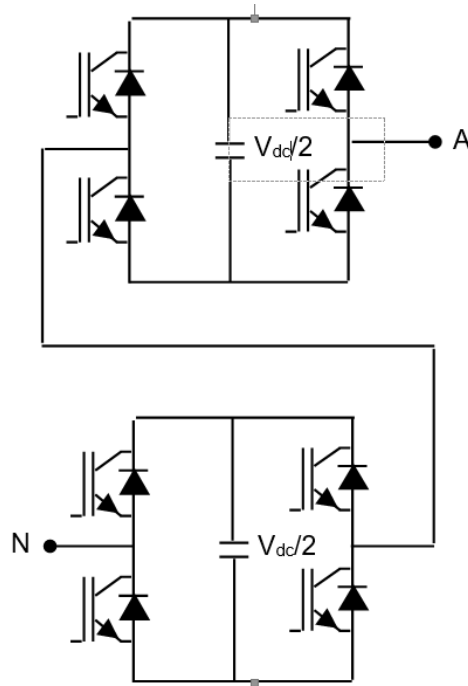


Figure 2.5.b Arm of a three-level converter “Cascade topology”

2.5.4 Diode-clamped converter

Different authors define the three-level diode-clamped topology also known as Neutral Point Clamped as the most suitable topology for most applications in the voltage range between 2.3 and 4kV and which require low or medium switching frequencies, because the cost of passive components is reduced (this topology uses a DC bus capacitor and does not use additional capacitors (fig. 2.5.c)). To obtain higher output frequencies, it would be necessary to increase the number of levels. [24]

By adding two switching cells and two clamping diodes as shown in Figure 2.5.c, we obtain the diode-clamped three-level converter. One phase of the three-level converter consists of four main switches Q_1 , Q_2 , Q_2' , and Q_1' , four diodes connected in antiparallel with them, and two clamping diodes. Switches Q_1 and Q_1' are complementary. Therefore, while Q_1 is conducting, Q_1' is in the blocking state and vice versa. The same logic is valid for switches Q_2 and Q_2' .

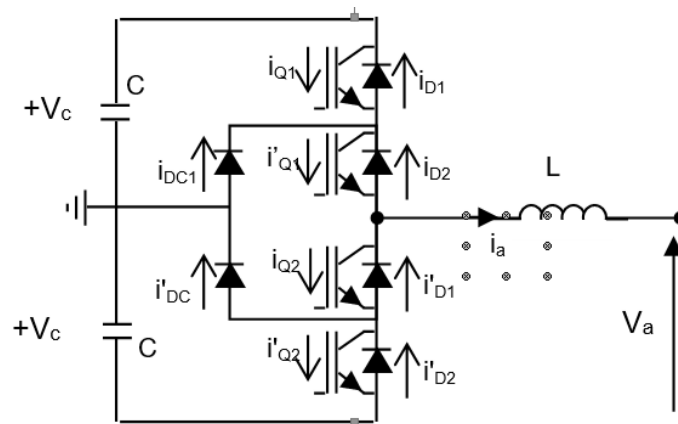


Figure 2.5.c Arm of a three-level "diode-clamped" converter

The operating sequences are as follows:

- Both switches Q_1 and Q_2 are closed (so Q_1' and Q_2' are open). The voltage seen on the AC side of the converter is V_c . If the current is negative, it will flow through both switches Q_1 and Q_2 , or through the main diodes D_1 and D_2 if it is positive.
- Q_1 is controlled to open (so Q_1' to close). The voltage on the AC side is zero. The current path will pass through switch Q_1' and clamping diode D_{c1}' in the case of positive current or through diode D_{c1} and transistor Q_2 , in the case of negative current. Switch Q_1 blocks voltage V_c .
- Q_2 is controlled to open and transistor Q_2' to close. The voltage seen from the AC side is $-V_c$. The current path now takes place through switches Q_1' and Q_2' in the case of positive current, or through diodes $D_{1'}$ and $D_{2'}$ in the case of negative current. Q_1 and Q_2 each block voltage V_c , and the clamping diode D_{c1}' blocks the same voltage.

By repeating the three sequences, the phase voltage waveform generated at the AC side is three-level, which is schematically shown in Figure 2.5.d.

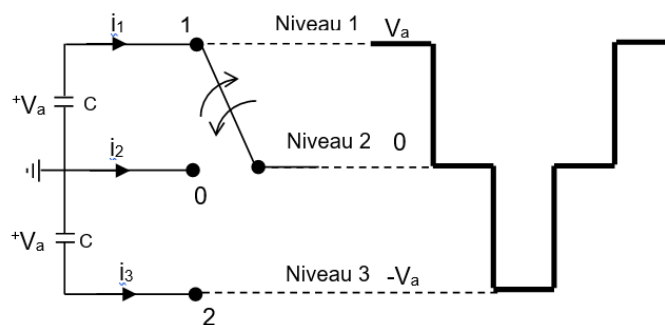


Figure 2.5.d Three-level phase voltage waveform

It should be noted that it is possible to choose the switching angle of the switches in order to minimize the distortion. If the voltage on the AC side is zero, so Q_2 and Q_1' are in conduction state, and by controlling the closing of the switch Q_1 and the opening of Q_2' at the time $\omega t = \alpha$ where $\omega = 2\pi f$ (f : the frequency of the voltage on the AC side produced by the inverter) and if the angle is chosen forward, and by repeating the sequences symmetrically with respect to this angle and the period of the voltage $T=1/f$, then the resulting voltage at the inverter output will be optimized, which gives one degree of freedom. The current distribution in the converter for the cases of purely capacitive and purely inductive current and its path are shown in Figure 2.5.e. It is possible to see that the current distribution in the converter components depends on the switching angle α . [25][26]

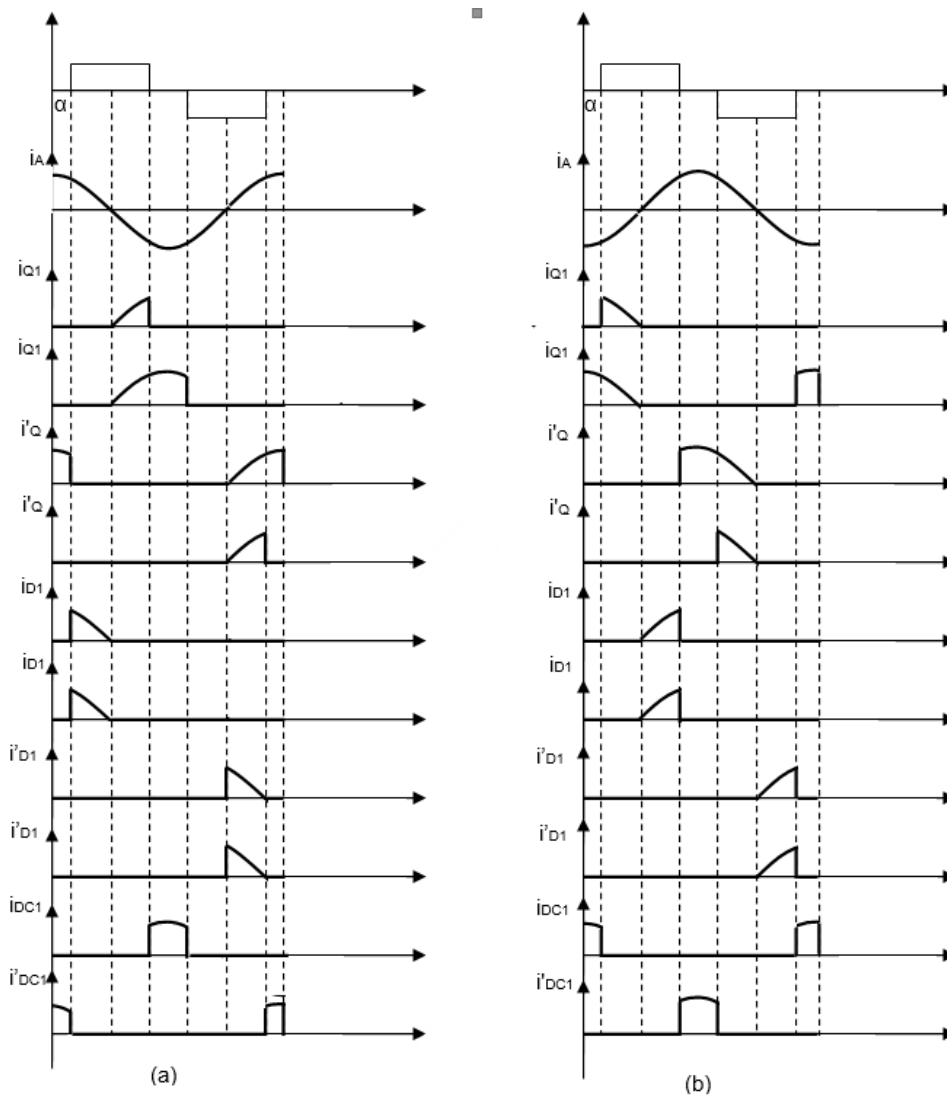


Figure 2.5.e Current distribution in a three-level converter. (a) capacitive current, (b) inductive current

2.6 DC-DC Converters (Chopper)

DC-DC converters are used to change the voltage of DC. They are used in mobile devices and computers that require different voltage levels. DC choppers are devices that help you adjust the voltage of direct current (DC) to the required level. They work by varying the output voltage, which may be different from the input voltage. These devices use components such as power transistors, MOSFETs, and thyristors to regulate voltage.

These devices are controlled by a small, low-power signal that comes from a central control unit. This helps in switching power components on or off as required. When using a DC chopper, it is necessary to actively turn off the devices being used, especially in situations where the circuit needs to be turned off quickly. For smaller, less powerful setups, power transistors are usually sufficient. For larger systems that require more power, thyristors are more common.

DC choppers are classified based on how they close their components and the direction in which power flows in the circuit. It is widely used in many practical applications such as electric vehicles, DC motor drives, power supplies for computers, subway cars, and electric trucks. This technology is crucial to managing how much power different systems use, making them more efficient and effective in different applications.

Operating Principle of a Chopper:

Chopper's function using power semiconductor switches, such as MOSFETs, IGBTs, or thyristors. By turning the switch ON and OFF at high frequency, the average output voltage is controlled. The output voltage can be smoothed using inductors and capacitors, resulting in a controlled DC output. Basic Control Principle :

- The duty cycle (D) — ratio of ON time to total switching period — determines the output voltage:

$$V_{out} = D \cdot V_{in}$$
- For higher D , the output voltage increases; for lower D , it decreases.

2.6.1 Chopper in Reversible Static Converters

A chopper is a type of DC-DC converter used in power electronics to control the voltage level of a DC supply. It operates by rapidly switching the DC input voltage on and off, producing a variable DC output voltage. In the context of reversible static converters, choppers are designed to

allow power flow in both directions, meaning they can both step-down or step-up voltage and reverse current flow from load to source and vice versa.

A reversible chopper allows power to flow in both directions between two DC sources or between a source and a load. This is achieved using two controlled switches (e.g., MOSFETs) and two diodes or with full-bridge topologies.

The chopper is a versatile and essential component in reversible static converters, particularly in systems that involve DC power conversion and bidirectional energy management. With the ability to regulate voltage and control power flow direction, reversible choppers are crucial in applications like electric vehicles, battery systems, and DC motor drives. When integrated with modern control strategies and efficient semiconductor technologies such as MOSFETs, they offer a compact, high-performance solution for next-generation energy systems.

2.6.2 Types of Choppers

Choppers can be classified based on the direction of voltage and current flow, especially in the context of reversible power conversion:

Class A (One Quadrant Chopper)

- Power flows from source to load.
- Used for motoring mode only.
- Unidirectional voltage and current.

. Class B (Second Quadrant Chopper)

- Current flows from load to source (regenerative braking).
- Voltage is positive, but current is negative.

. Class C (Two Quadrant Chopper - Motoring and Regenerative Braking)

- Combines Class A and Class B.
- Bidirectional current flow with positive voltage.
- Suitable for DC motor drives requiring regeneration.

. Class D and E (Four Quadrant Choppers)

- Enable full bidirectional control of both voltage and current.
- Allow forward/reverse motoring and regenerative braking.
- Common in advanced electric drives and battery systems.

2.6.3 Control Techniques for Choppers

Controlling a chopper requires precise modulation of its switching signals. Common techniques include:

- PWM (Pulse Width Modulation): Varying the duty cycle to control output voltage.
- Hysteresis control: Maintains output within a narrow band.
- Current mode control: Used when current needs to be tightly regulated, especially in motor drives.

Advanced reversible systems also implement:

- Digital control with microcontrollers or DSPs.
- Closed-loop feedback for voltage and current.
- Protection algorithms against overcurrent, overvoltage, and short circuits.

2.6.4 Advantages and Challenges of Reversible Choppers

Advantages of Reversible Choppers

- Bidirectional power flow
- High efficiency due to low switching and conduction losses
- Compact design
- Fast dynamic response to load changes
- Precise control of voltage and current

Challenges and Design Considerations

- Switching losses and thermal management
- EMI (Electromagnetic Interference) filtering
- Safe commutation to avoid voltage spikes
- Device protection against fault conditions
- Inductor and capacitor sizing for ripple suppression and energy storage

2.6.5 Applications of Choppers in Reversible Static Converters

Choppers are widely used in various modern electronic systems, particularly when high-efficiency DC power control is required:

- Electric vehicles (EVs): For motor control and battery energy management.
- DC motor drives: To control speed and torque with regenerative capability.
- Battery management systems (BMS): Bidirectional choppers control charging/discharging.
- Solar PV systems: Choppers match panel voltage to load or battery.
- Hybrid energy systems: Coordinate energy flow between multiple sources and storage.

2.7 AC-AC Converter (Dimmer)

AC-AC converters are those converters that convert AC to another magnitude of voltage and frequency. It is used in air conditioners.

AC-AC converters function by modifying the waveform of the AC input to achieve the desired output characteristics. They often use semiconductor switches (e.g., TRIACs, SCRs, IGBTs, or MOSFETs) controlled through modulation strategies to shape the voltage and frequency. Depending on the type of converter, intermediate stages (like DC links) may be used.

2.7.1 Types of AC-AC Converters

They are classified into two groups:

1) Cycloconverter

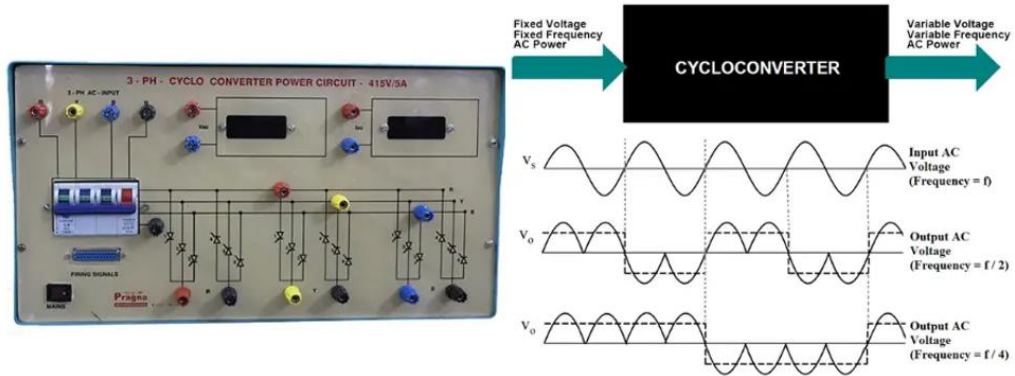


Figure 2.6 Cycloconverter

A Cycloconverter is a device that converts AC (alternating current) from one voltage and frequency to another voltage with a lower frequency. It is used in a straightforward, one-step process. Typically, these converters use a method called line commutation, but sometimes some applications require other methods such as forced or load commutation.

Cycloconverters are very useful for large, slow-moving electric motors and machines, such as in large motors driving large industrial fans or rotary kilns.

2) AC Voltage Controllers (AC voltage regulators):

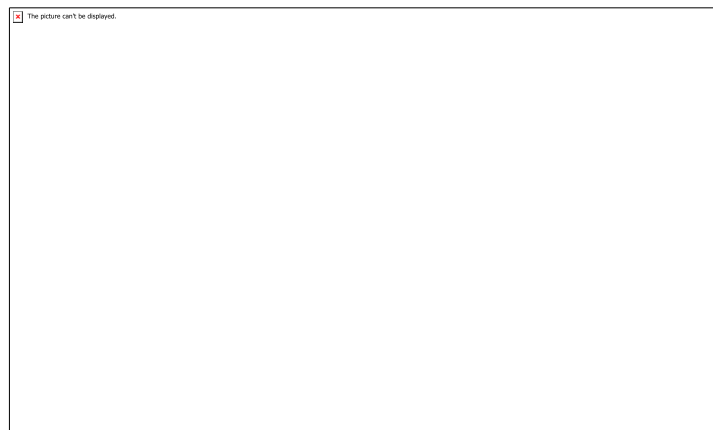


Figure 2.7 AC voltage controllers

AC voltage controllers are devices that adjust the voltage of an AC power supply to a

different level while keeping the same frequency as the original power supply. They use a setup with two components called thyristors, which are arranged to work against each other. These thyristors are turned off using the natural cycle of AC current, a method known as line commutation.[22]

The main feature of these controllers is that they can change the output voltage by adjusting when the thyristors turn on. This configuration makes these controllers very useful in many applications.

They are commonly used to control the brightness of lights, adjust transformers in power lines, and manage the speed of large fans and pumps. This control helps save energy and extends the life of these devices, making operations more efficient in places like factories and large buildings.[27]

2.7.3 AC-AC Converters in Reversible Static Converters

An AC-AC converter is a type of power electronic device used to convert alternating current (AC) from one form to another—either changing its voltage, frequency, or both. In the context of reversible static converters, AC-AC converters are capable of managing bidirectional power flow, making them suitable for systems where both input and output are AC, and reversibility is required for energy recovery or multi-directional control.

AC-AC converters represent a crucial category within reversible static power conversion systems. They enable dynamic, bidirectional control of AC power, supporting a range of applications from motor drives to renewable integration. With advances in semiconductor devices and control algorithms, modern reversible AC-AC converters such as matrix converters and back-to-back systems offer compact, reliable, and highly efficient solutions for today's energy systems.

2.7.4 Reversibility in AC-AC Converters

In reversible static systems, bidirectional AC-AC converters allow energy to flow in both directions between the source and the load. This is particularly important in systems like:

- Motor drives with braking/regeneration

- Renewable energy systems interacting with the grid
- Uninterruptible power supplies (UPS)

Matrix Converters are the best-known **reversible AC-AC converters**:

- Use a matrix of bidirectional switches (typically 9 in 3-phase systems).
- Do not require bulky DC link capacitors.
- Allow full control of amplitude, frequency, and phase.
- Capable of 4-quadrant operation (voltage and current in both directions).

2.7.5 Control Techniques

Control strategies for AC-AC converters depend on the topology:

- Phase angle control: Used in voltage controllers.
- Selective harmonic elimination (SHE): For cycloconverters.
- Space Vector Modulation (SVM): For matrix converters.
- PWM strategies: Used in DC-link-based AC-AC systems to shape output waveform and reduce harmonics.

Feedback control may also be integrated for:

- Voltage and frequency regulation.
- Power factor correction.
- Load compensation and fault handling.

2.7.6 Advantages and Challenges of Reversible AC-AC Converters

Advantages of Reversible AC-AC Converters

- Bidirectional energy transfer

- High efficiency, especially with matrix and PWM-controlled converters
- Precise control of output voltage and frequency
- Elimination of mechanical components (compared to motor-generator sets)
- Compact size and solid-state reliability

Challenges and Design Considerations

- Commutation of current between switches without short-circuits.
- Harmonic distortion and EMI (requires filtering).
- Thermal management due to switching losses.
- Control synchronization with input/output phases.
- Safety and isolation, especially in grid-tied systems.

2.7.7 Applications of Reversible AC-AC Converters

Reversible AC-AC converters are used in a wide range of industrial and power systems:

- Industrial motor control: Variable speed drives (VSDs) for induction and synchronous motors.
- Regenerative drives: Recover energy during deceleration.
- Aircraft and shipboard power systems: Where frequency and voltage differ from standard grids.
- Solid-state transformers (SSTs): High-frequency AC-AC conversion for modern power grids.
- HVAC systems: With variable frequency compressors.

2.8 Other Topologies

Besides the three basic topologies discussed above, other multilevel converter topologies

have been proposed, but most of them are based on hybrid circuits.[28] Some of these topologies are:

- A. L The hybrid asymmetrical converter,
- B. The converter with cascaded bridges and isolated DC/DC sources,
- C. The converter with cascaded multilevel topologies,
- D. The soft-switching converter,
- E. Transformer-connected converters,
- F. The Diode/Capacitor-Clamped converter: a variant of the NPC inverter,
- G. The New Diode-Clamped converter: another variant of the NPC inverter,
- H. The generalized multilevel converter.
- I. The symmetrical converter

2.9- Reversible Converter Modulation Techniques

The different modulation methods implemented in multilevel converters are classified according to the switching frequency used. Three different groups are distinguished (see Figure 2.8).

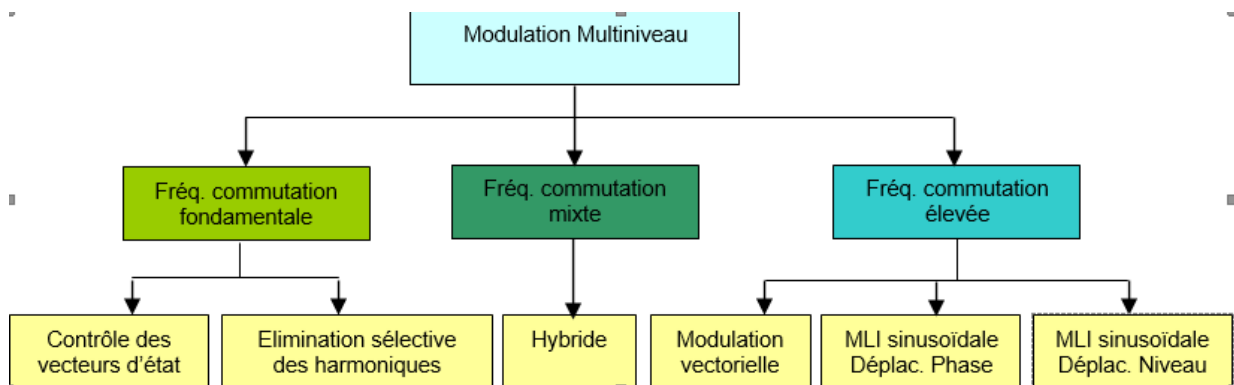


Figure 2.8 Classification of different Multilevel modulation methods

On the one hand, there are techniques that work with a high switching frequency, with many switchings of the semiconductors in a period of the fundamental of the output voltage: sinusoidal PWM (with phase or level shift) and vector PWM. These systems work with switching frequencies at the component level between 275Hz-5000Hz. On the other hand, there

are methods that work with a low switching frequency, one or two switchings per period. Finally, we distinguish the technique that works with a mixed switching frequency: hybrid modulation. This technique is limited to the cascade converter where the different cells work with different frequencies (low or high) in order to limit losses.

One of the most studied methods in the literature is pulse width modulation (Figure 2.9). In addition to adjusting the amplitude, this method controls the harmonic content of the inverter output voltage by pushing lower order harmonics to higher frequencies, which makes filtering easier and less expensive, because the size of the filter components is quite small. However, it should be noted that the PWM technique has limitations with respect to the operating frequency of the inverters. The higher this frequency, the higher the losses due to the switching of the semiconductor switches. In addition, the operating frequency of PWM inverters is also limited by the inherent switching speed of the semiconductor switches.

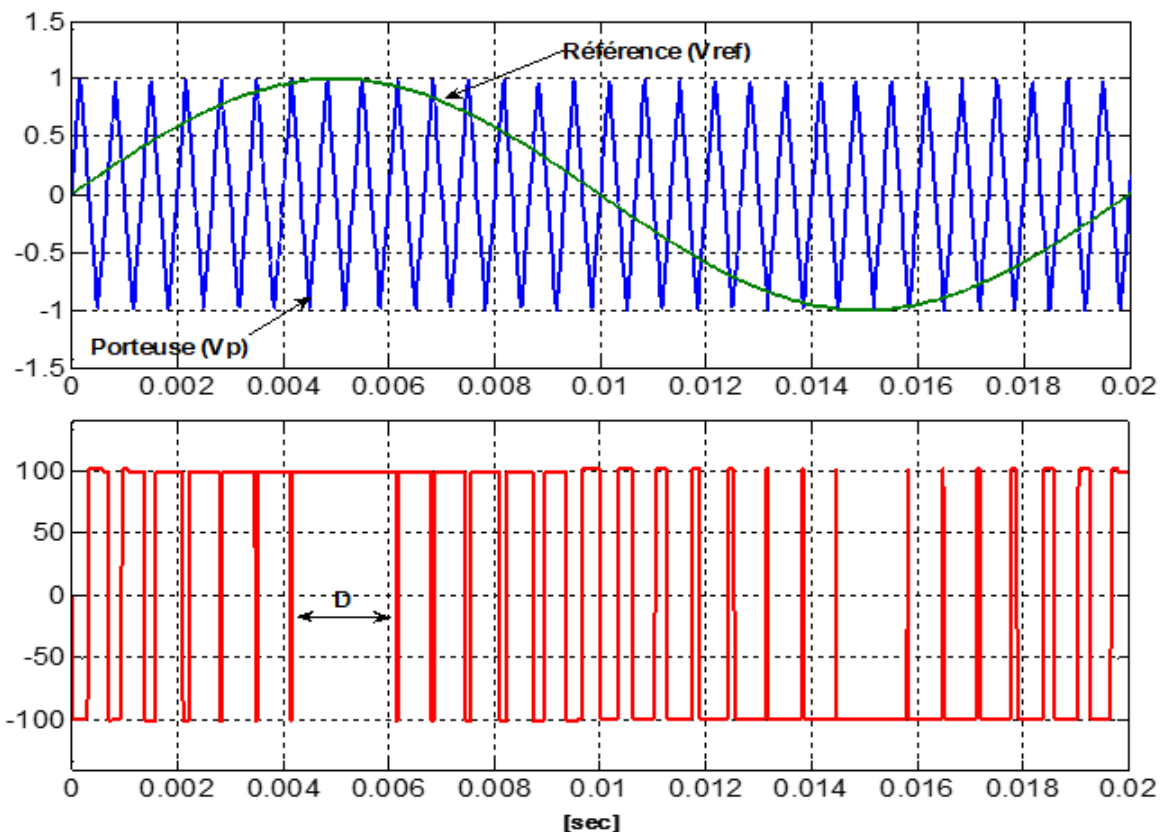


Figure 2.9 Example of PWM (Pulse Width Modulation) voltage. D represents the duty cycle.

Two parameters characterize this command:

- The modulation index (m) which defines the ratio between the frequency of the carrier signal (f_p) and the frequency of the reference signal (f_{ref}).

$$m = \frac{f_p}{f_{ref}}$$

- The modulation rate which gives the ratio of the amplitude of the modulating signal (V_{ref}) and the peak value of the carrier signal (V_p).

$$r = \frac{V_{ref}}{V_p}$$

This technique allows us to reduce the distortion factor. Thus, it eliminates all harmonics less than or equal to $(2N_p-1)$. With N_p being the number of modulations per half cycle.

$$N_p = \frac{m}{2} = \frac{f_p}{2 \cdot f_{ref}}$$

However, the output voltage contains harmonics. This modulation pushes these harmonics into the high frequency range around the switching frequency f , and its multiples.

The fundamental of the output voltage can be increased by choosing (r) greater than unity. This mode of operation is called overmodulation. However, overmodulation is not recommended in applications where minimization of distortion is required, such as in the case of UPS (Uninterruptible Power Supplies).

Several MLI control techniques have been developed. The most used are:

- Single PWM.
- Multiple PWM.
- Sinusoidal PWM.
- Modified Sinusoidal PWM.
- Trapezoidal Modulation.
- Step Modulation.
- Ladder Modulation.
- Delta Modulation.
- Harmonic Injection Modulation.

- Deadband Modulation.
- Modified Sinusoidal Modulation.
- Vector Modulation.

2.10 How a reversible converter works:

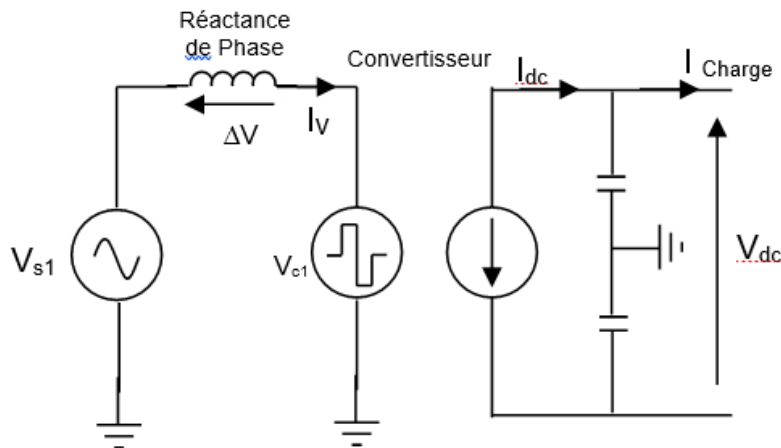


Figure 2.10 Equivalent circuit of a VSC connected to an AC system.

Figure. 2.10 shows the Fresnel diagram of a V_{SC} connected to an AC network. The voltage V_{C1} is phase-lagging (δ) with respect to the voltage V_{S1} , so active power is transferred from the AC system to the V_{SC} .

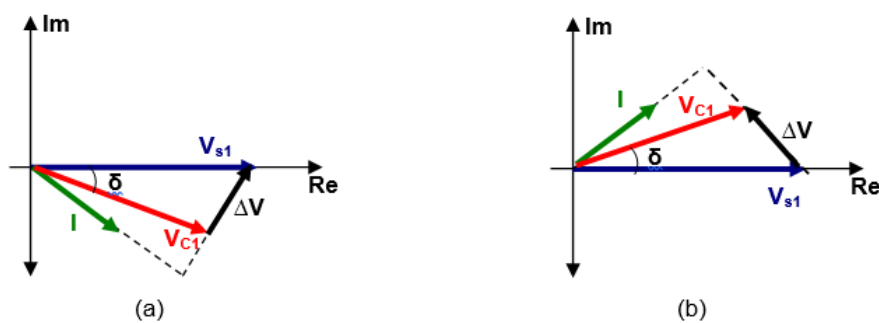


Figure 2.11 Phase diagram of a V_{SC} connected to an AC system

By varying the amplitude and phase shift of the V_{SC} output voltage, it is therefore possible to control the active and reactive powers. The V_{SC} is capable of operating within the circle of the P-Q diagram in Figure 2.11. When the V_{SC} operates in ($P=0, Q>0$) mode, it behaves like a capacitor, supplying only reactive power to the network. This is the operating mode that is used

in the static synchronous compensators (STATCOM).[26]

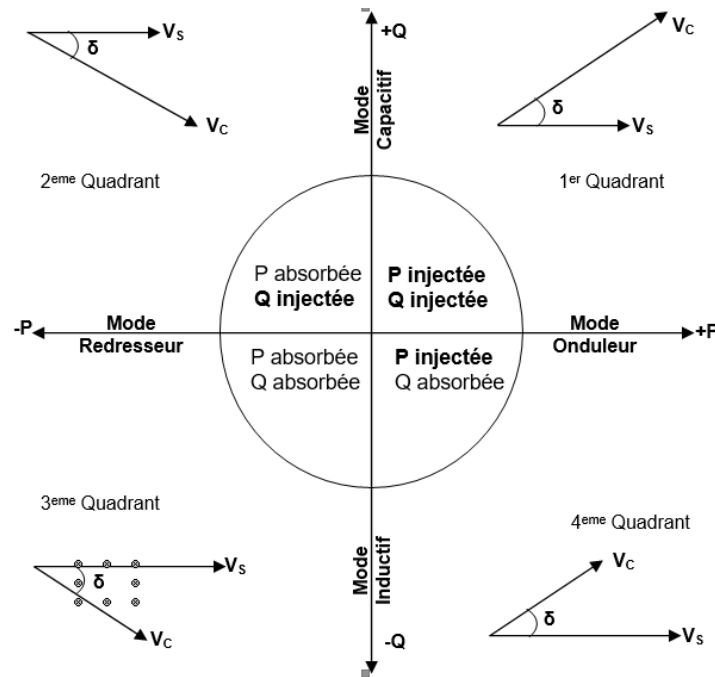


Figure 2.12 P-Q diagram of a VSC.

2.11 DC Voltage Adjustment

The DC voltage is regulated by active power control. If the power supplied to the cable (rectifier side) becomes greater than the power drawn (inverter side), the DC capacitors charge, causing the V_{dc} voltage to increase. This anomaly is immediately detected by the rectifier, which immediately reduces the active power supplied (by adjusting the angle δ) so that the powers balance out. The same procedure is followed when the power drawn is greater than the power supplied. The two V_{SC} converters therefore do not need to communicate with each other for power control (which is not the case with LCC converters).

V_{SC} converters are of course reversible. Unlike the thyristor-based system (LCC system), power inversion does not require cable polarity inversion. It is the direction of current flow in the cable that is reversed, which is made possible by the use of bidirectional current valves (transistor + diode). The absence of polarity inversion can be a beneficial aspect of V_{SC} systems compared to the LCC system, especially when using synthetically insulated cables (known to be sensitive to polarity inversions).

2.12 MOSFET

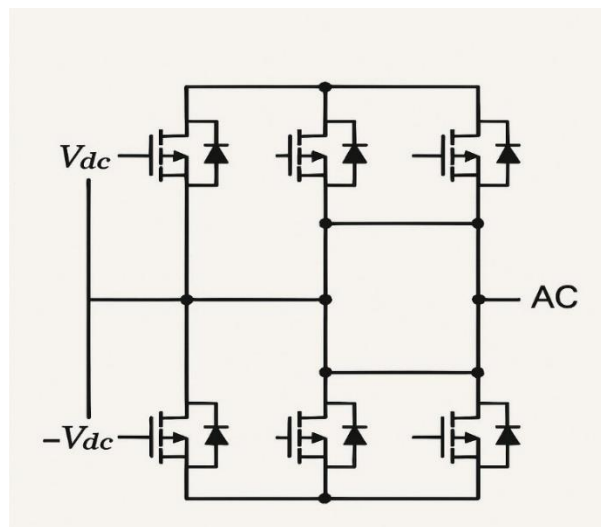


Figure 2.13 A simplified diagram of the model

A MOSFET is a type of transistor used to electrically switch or amplify electronic signals in circuits controlling the amount of electricity that can flow between the source and drain terminals based on the voltage applied to the gate terminal.[29]

It is one of the most fundamental building blocks in modern electronics.

A MOSFET consists of four terminals: the *source*, the *drain*, the *gate* and the *base*. Commonly the base is connected to the source terminal. The substrate, source and drain consist of either positive or negative doped semiconductors. The metal (or conductive silicon) gate terminal is separated from these by a nonconductive oxide layer. By applying voltage to the gate, it changes the electrical properties of the semiconductor underlying, either allowing or inhibiting the flow of electricity between the source and drain.

Why Choose MOSFET Over BJT?[30]

MOSFETs are particularly useful in amplifiers due to their input impedance being nearly infinite which allows the amplifier to capture almost all the incoming signal. The main advantage is that it requires almost no input current to control the load current and that's why we choose MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) over BJT (Bipolar Junction Transistor).

2.12.1 History of MOSFET

The basic principle of the field-effect transistor was first patented by Julius Edgar Lilienfeld in 1925. In 1934, inventor Oskar Heil independently patented a similar device in Europe.

In the 1940s, Bell Labs scientists William Shockley, John Bardeen and Walter Houser Brattain attempted to build a field-effect device, which led to their discovery of the transistor effect. However, the structure failed to show the anticipated effects, due to the problem of surface states: traps on the semiconductor surface that hold electrons immobile. With no surface passivation, they were only able to build the BJT and thyristor transistors.

In 1955, Carl Frosch and Lincoln Derick accidentally grew a layer of silicon dioxide over the silicon wafer, for which they observed surface passivation effects. By 1957 Frosch and Derick, using masking and predisposition, were able to manufacture silicon dioxide field effect transistors; the first planar transistors, in which drain and source were adjacent at the same surface. They showed that silicon dioxide insulated, protected silicon wafers and prevented dopants from diffusing into the wafer. At Bell Labs, the importance of Frosch and Derick technique and transistors was immediately realized. Results of their work circulated around Bell Labs in the form of BTL memos before being published in 1957. At Shockley Semiconductor, Shockley had circulated the preprint of their article in December 1956 to all his senior staff, including Jean Hoerni, who would later invent the planar process in 1959 while at Fairchild Semiconductor.[31][15]

After this, J.R. Ligenza and W.G. Spitzer studied the mechanism of thermally grown oxides, fabricated a high-quality Si/SiO₂ stack and published their results in 1960. Following this research, Mohamed Atalla and Dawon Kahng proposed a silicon MOS transistor in 1959 and successfully demonstrated a working MOS device with their Bell Labs team in 1960. Their team included E. E. LaBate and E. I. Povolonis who fabricated the device; M. O. Thurston, L. A. D'Asaro, and J. R. Ligenza who developed the diffusion processes, and H. K. Gummel and R. Lindner who characterized the device. This was a culmination of decades of field-effect research that began with Lilienfeld.[32]

The first MOS transistor at Bell Labs was about 100 times slower than contemporary bipolar transistors and was initially seen as inferior. Nevertheless, Kahng pointed out several advantages of the device, notably ease of fabrication and its application in integrated circuits

2.12.2 Designing of a MOSFET reversible electrical converter

Design Factor	Consideration
MOSFET Selection	Voltage & current ratings; fast switching; low $R_{ds(on)}$
Gate Drivers	Bootstrap high-side drivers (IR2110, IRS2186, etc.)
Cooling	Use heatsinks or thermal pads as 6 switches can dissipate significant heat
Snubber Circuits	Optional, helps reduce voltage spikes
Control Hardware	STM32, TI C2000, DSPs, FPGAs depending on complexity
Safety	Isolation (opto, digital isolators), fuses, protection circuits

Table 2.1 Designing a MOSFET reversible electrical converter

2.12.3 Characteristics of Power MOSFETs[33]

The general characteristics of power MOSFETs are listed below.

- Basically, MOSFETs are majority-carrier devices and operationally different from bipolar transistors that are minority-carrier devices.
- While bipolar transistors are current-controlled devices, MOSFETs are voltage-controlled devices that are controlled by gate-source voltage.
- Since MOSFETs are majority-carrier devices, they do not suffer delay due to the carrier storage effect, making high frequency switching possible.
- In bipolar transistors, current concentrates in the high voltage region, making them vulnerable to junction destruction due to secondary breakdown. Operating conditions are de-rated as necessary to prevent junction destruction. In contrast, power MOSFETs are

much more immune to secondary breakdown and therefore more rugged. However, the electrical characteristics of recent MOSFET devices should be carefully examined as some of them are vulnerable to secondary breakdown.

- Since power MOSFETs have a positive temperature coefficient of on-state resistance, $R_{DS(ON)}$ at high temperatures should be considered during thermal design.

Key features:

- Voltage-controlled device: current between the *source* and *drain* is controlled by the voltage applied to the *gate*.
- High input impedance (very low gate current).
- Fast switching capability — ideal for digital and power electronics.

Two main types:

- N-channel MOSFET (NMOS)
- P-channel MOSFET (PMOS)

Modes of operation:

- 1) Cutoff (off state) — no current flows.
- 2) Linear (ohmic region) — acts like a variable resistor.
- 3) Saturation (active region) — constant current; used for amplification.

Applications:

- Switching regulators (DC-DC converters).
- Power supplies and motor drives.
- Digital circuits (CMOS technology).
- RF amplifiers.

2.12.4 Structure of MOSFET

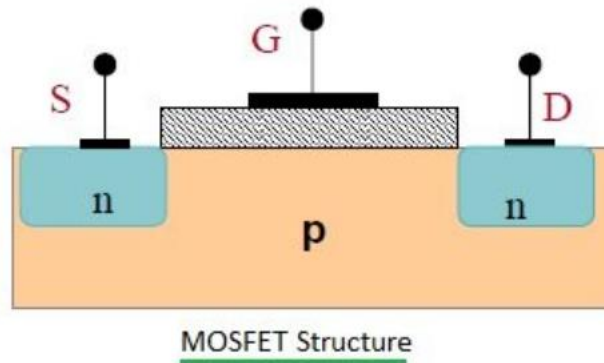


Figure 2.14 Structure of MOSFET[30]

It is a four-terminal device with *Source* (S), *Drain* (D), *Gate* (G), and *Body* (B) terminals. The body (B) is frequently connected to the source terminal, reducing the terminals to three. It works by varying the width of a channel along which charge carriers flow (electrons or holes).

The charge carriers enter the channel at the source and exit via the drain. The width of the channel is controlled by the voltage on an electrode called Gate which is located between the source and the drain. It is insulated from the channel near an extremely thin layer of metal oxide.[34]

A Metal-Insulator-Semiconductor Field-Effect Transistor, MISFET is a term almost synonymous with MOSFET. Another synonym is IGFET for the Insulated-Gate Field-Effect Transistor.[30]

2.12.5 Modes of Operation

1. Inverter Mode (Motoring)

- DC input → generates 3-phase AC
- Used to drive motors or supply AC loads

2. Rectifier Mode (Generating / Regenerative Braking)

- 3-phase AC input → rectified into DC
- Current flows in reverse direction
- Controller changes PWM logic to allow energy to return to the DC side (e.g., charging a battery)

2.13 Different types of MOSFETS

MOSFET works in two modes that we use to classify them

- Depletion Mode: The transistor requires the Gate-Source voltage (V_{GS}) to switch the device “OFF”. The depletion-mode MOSFET is equivalent to a “Normally Closed” switch.
- Enhancement Mode: The transistor requires a Gate-Source voltage (V_{GS}) to switch the device “ON”. The enhancement mode MOSFET is equivalent to a “Normally Open” switch

2.13.1 P channel Depletion MOSFET

A 3-terminal device similar to P-channel enhancement MOSFET. The only difference between the two is the existence of a P-channel. In P-channel depletion MOSFET, P-channel is already present. All other things are the same, as you can see in the figure below.

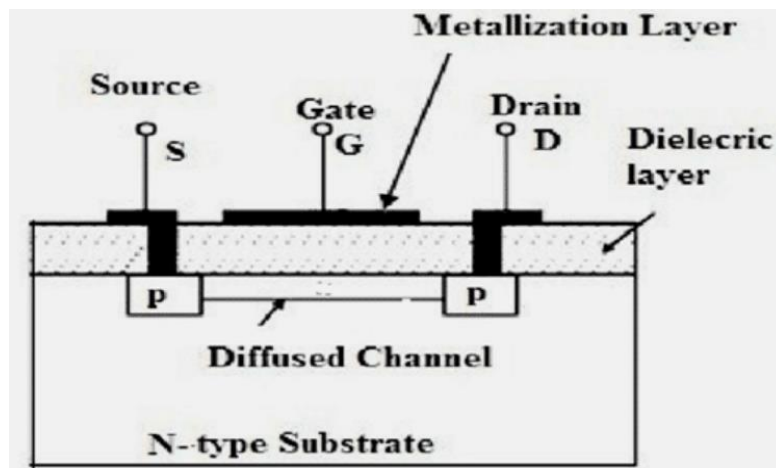


Figure 2.15.a P-channel depletion MOSFET

P-channel depletion MOSFET is similar to N-channel enhancement depletion, the only difference is in the polarities of applied voltages. On applying negative V_{DS} , the holes in the P-channel will move towards the negative drain terminal, and the drain current or I_D will start flowing. On increasing the negative value of V_{DS} further, keeping V_{GS} at 0, a time will come where I_D will become constant, and that value of drain current is called saturation current.

We can conclude from this discussion that when $V_{GS} = 0$ and $V_{DS} < 0$, current I_D flows from and on increasing the negative value of V_{DS} further, $I_D = I_S = I_{DSS}$, as shown in the figure below.

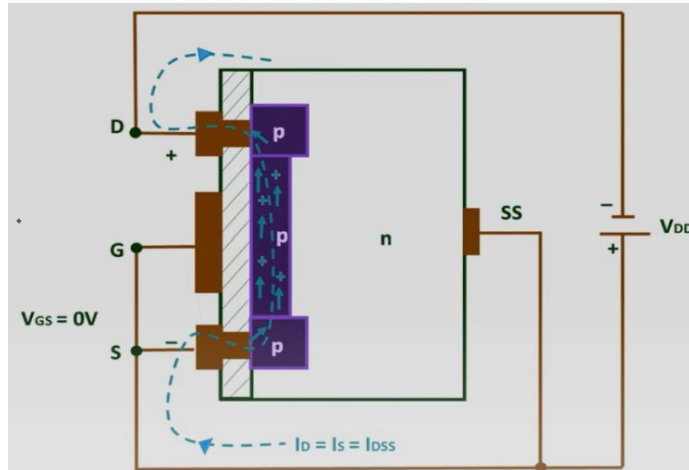


Figure 2.15.b The effect of gate voltage on P-channel depletion MOSFET

Apply $V_{GS} > 0$. Electrons from the N-type substrate will attract towards the positive gate terminal and recombine with holes in the P-channel, forming electron-hole pairs. On increasing positive potential at the gate, more electron-hole combinations will occur, decreasing the number of free holes in the P-channel.

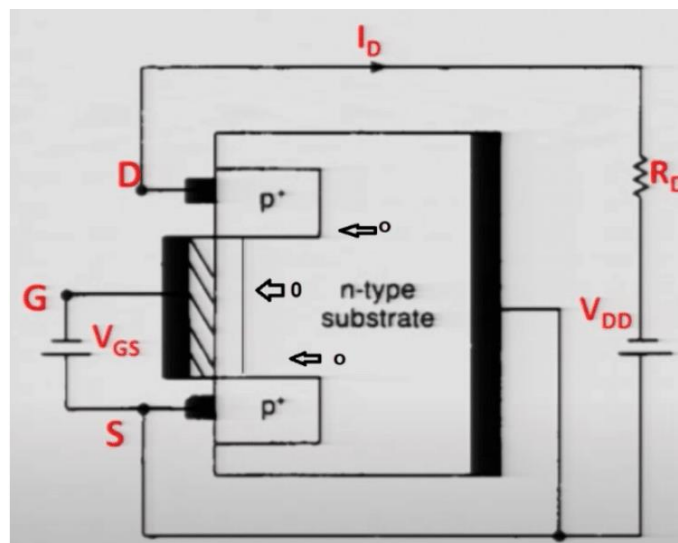


Figure 2.15.c Decreasing the number of free holes in the P channel.

As a result, I_D decreases. A time will come when the drain current will become zero. The positive gate voltage at which the drain current is zero is called pinch-off voltage or V_P . We can conclude that at pinch-off, $V_{GS} = V_P$, $V_{DS} < 0$, and $I_D = 0$.

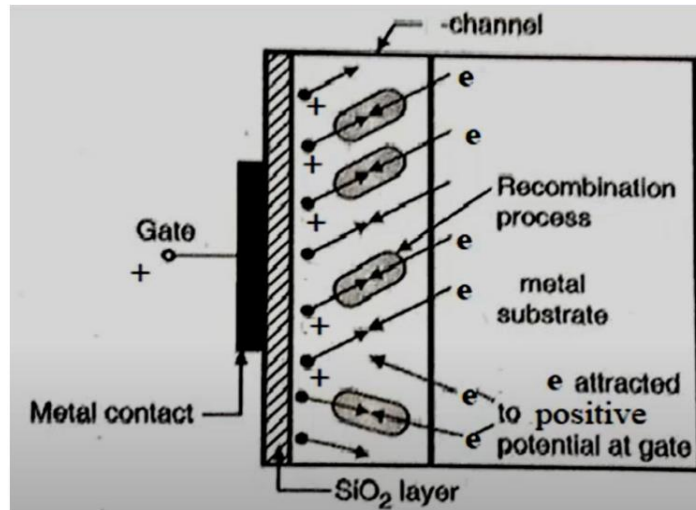


Figure 2.15.d The effect of negative gate voltage on the drain current

On applying $V_{GS} < 0$, the minority carriers in the N-type substrate, i.e. holes, will attract towards the gate terminal, thereby increasing the concentration of holes in the P-channel. As a result, the drain current will increase and exceed the saturation current.[35]

We can conclude, when $V_{GS} < 0$ and $V_{DS} < 0$, then $I_D > IDSS$.

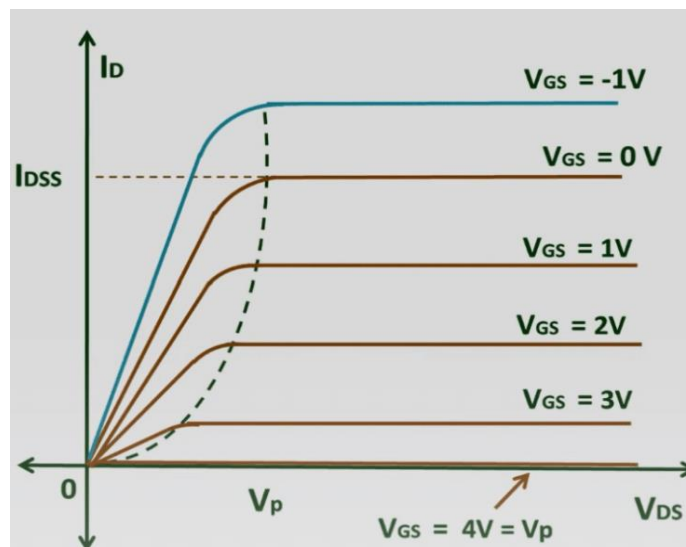


Figure 2.15.e The current I_D flow for both +ve and -ve values of V_{GS}

The graph shows that the current I_D will flow for both positive and negative values of V_{GS} . The drain current is less than the saturation current for the positive value of gate voltage, whereas, for the negative value of gate voltage, the drain current exceeds the saturation current. $V_{GS} = V_P$ is also represented in this graph for which drain current is zero irrespective of drain to source voltage.

2.13.2 P channel Enhancement MOSFET

A 3-terminal device. The body of any P-channel MOSFET is made up of N-type material. 2 P-type materials are diffused at the top. A depletion region will be formed in the PN-junction. A metal contact is made at the bottom of the N-type substrate and a terminal is taken out called the body or substrate.

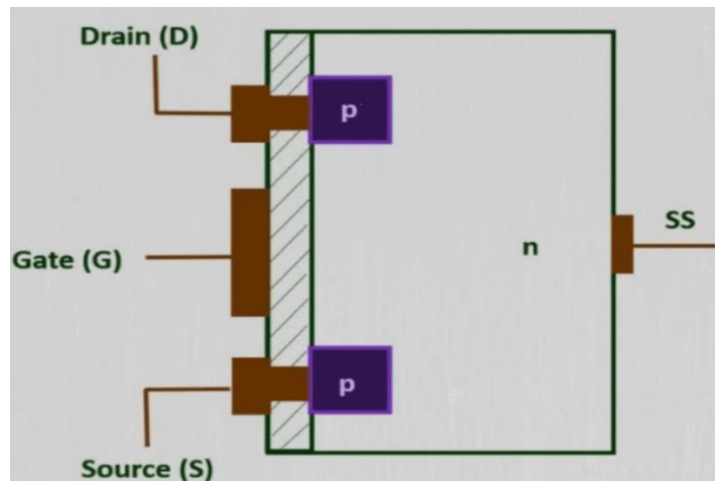


Figure 2.16.a P-channel enhancement MOSFET

Similarly, a metal contact is made at the top of both the P-type materials, and two terminals are taken out as Drain and source. A Silicon dioxide layer is drawn in between the two P-type wells at the top. A metal contact is made at the top of it and a terminal is taken out called a Gate terminal. You can see it is a 4-terminal device yet it is a 3-terminal device. Now, what happens is generally the body terminal and source terminal are internally shorted and connected to the ground. Hence now only three terminals are visible namely Source, Drain, and Gate.

P-channel enhancement MOSFET is similar to N-channel enhancement MOSFET, the only difference is in the polarities of applied voltages. To get the drain current first we have to create a channel for the free movement of holes. To create a channel we have to apply a voltage between the gate and source terminal keeping Gate at a lower potential. This voltage is called V_{GS} . Now the gate is at a lower potential. The free holes will move toward the gate terminal. As discussed earlier we have a Silicon Dioxide layer at the top. Hence these free holes will accumulate near the Gate region and will not escape. The silicon dioxide layer also acts as a dielectric. It will allow more free holes to accumulate near the gate terminal in less applied voltage at the gate terminal.

Now on increasing the negative value of V_{GS} further, a high electric field is developed forcing atoms inside the N substrate to break. The free electrons generated will fill the electrons near the gate region. This way electrons are pushed away from the gate terminal increasing P-type behavior near the gate terminal. A time will come when a P-channel is created between the two P wells. The V_{GS} voltage at which the channel is created is called the threshold voltage or V_T .

We can conclude, when $|V_{GS}| > |V_T|$ a P-channel is induced near the gate terminal as shown in the figure below.

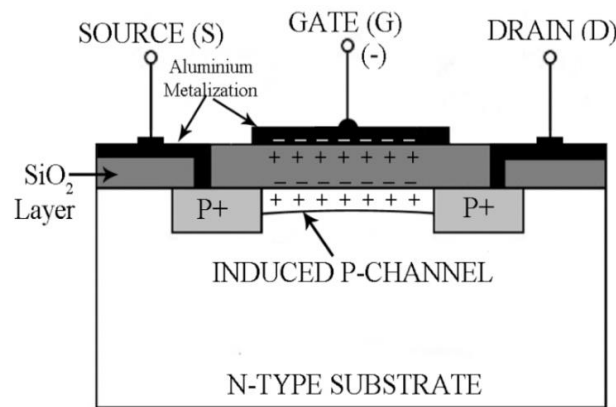


Figure 2.16.b P-channel induced

A channel is created still we are not getting any current. To get the drain current, apply a voltage source between the drain and the source keeping the drain at a lower potential. This voltage is called V_{DS} . On applying this voltage, the drain current or I_D will start flowing.

We can conclude, when $|V_{GS}| > |V_T|$ and $V_{DS} < 0$, the current I_D flows from drain to source as shown in the figure below.

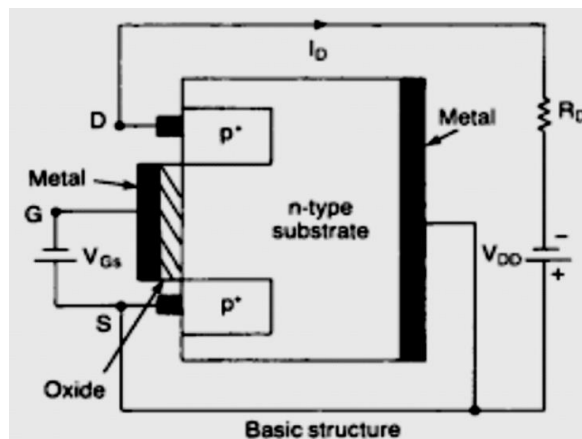


Figure 2.16.c The current I_D flows from drain to source

On increasing the negative value of V_{DS} further I_D will increase. But this I_D will not keep on increasing with V_{DS} . On increasing the negative voltage at the drain terminal, a reverse bias is formed at the PN-junction near the drain terminal. This will result in a thick depletion region near the PN-junction. Hence on increasing the negative value of V_{DS} further you will see the channel near the drain terminal is becoming narrow. The drain current will face more resistance near the drain terminal. A situation will reach when the drain current becomes constant and will not increase further.

This situation is called the pinch-off situation and the drain current is called the saturation current. The voltage at which we will get saturation current is called saturation voltage.

We can conclude that pinch-off is reached when $V_{GS} < 0$ (constant) and $V_{DS} = V_{DS(SAT)}$, $I_D = I_{D(SAT)}$ as shown in the figure below.

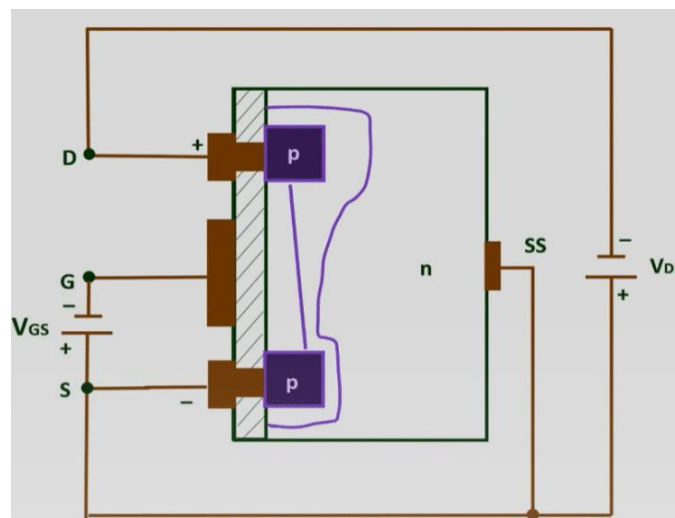


Figure 2.16.d The Pinch-Off

Increasing I_D further increases the negative value of V_{GS} . This will increase the width of the complete P-channel. Hence V_{GS} is controlling voltage. Now we can plot V_1 characteristics very easily.

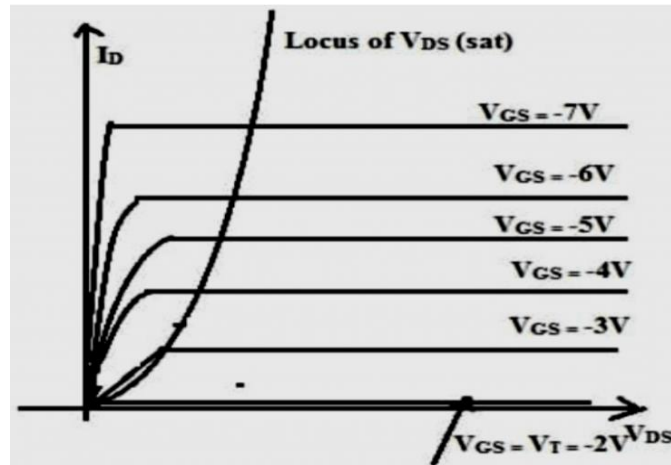


Figure 2.16.e V_1 characteristics

2.13.3 N channel Depletion MOSFET

A 3 terminal device similar to N-channel enhancement MOSFET. The only difference between the two is the existence of an N-channel. In N-channel depletion MOSFET, N-channel is already present. All other things are the same, as you can see in the figure below.

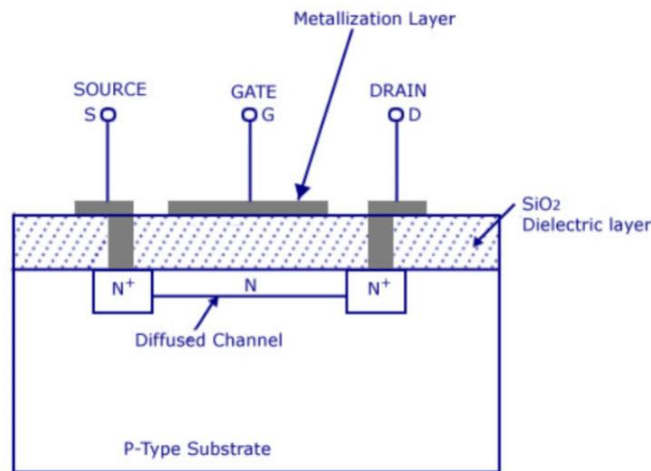


Figure 2.17.a N-channel depletion

On applying positive V_{DS} , the electrons in the N-channel will move towards the positive drain terminal, and the drain current will start flowing from drain to source. On increasing V_{DS} further, keeping V_{GS} 0, a time will come where I_D will become constant, and that value of drain current is called saturation current.

We can conclude that when $V_{GS} = 0$ and $V_{DS} > 0$, current I_D flows from drain to source, and on increasing V_{DS} further, $I_D = I_S = I_{DSS}$, as shown in the figure below.

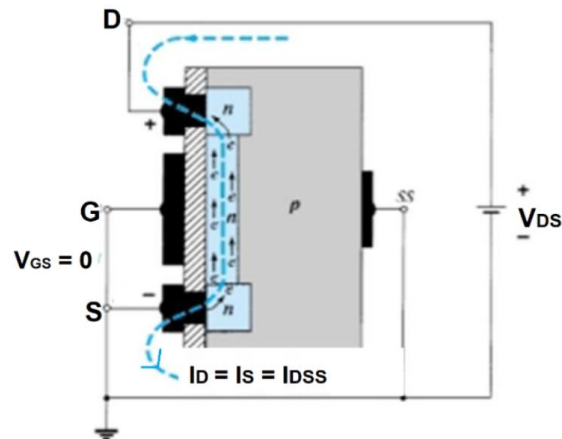


Figure 2.17.b The effect of gate voltage on N-channel depletion MOSFET

Apply $V_{GS} < 0$. Holes from the P-type substrate will attract towards the negative gate terminal and recombine with electrons in the N-channel, forming electron-hole pairs. On increasing negative potential at the gate, more electron-hole combinations will occur, decreasing the number of free electrons in the N-channel. As a result, I_D decreases. A time will come when the drain current will become zero. The negative gate voltage at which the drain current is zero is called pinch-off voltage or V_P .

We can conclude that at pinch-off, $V_{GS} = V_P$, $V_{DS} > 0$, and $I_D = 0$

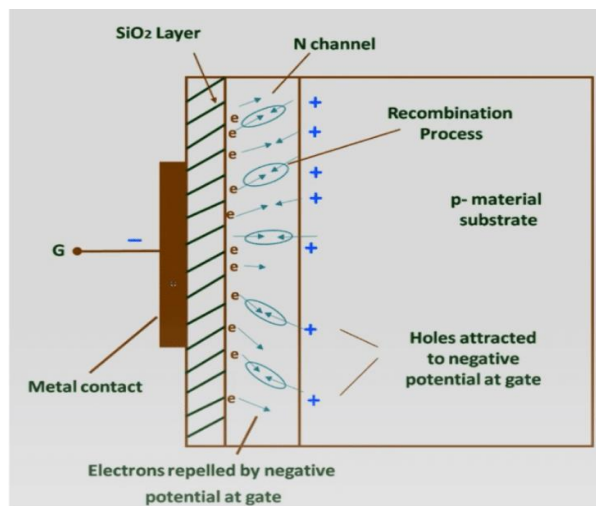


Figure 2.17.c The effect of positive gate voltage on the drain current.

On applying $V_{GS} > 0$, the minority carriers in the P-type substrate, i.e. electrons, will get attracted towards the gate terminal, thereby increasing the concentration of electrons in the N-channel. As a result, the drain current will increase and exceed the saturation current. We, when $V_{GS} > 0$ and $V_{DS} > 0$, then $I_D > I_{DS}$, as shown in the figure 2.17.e.

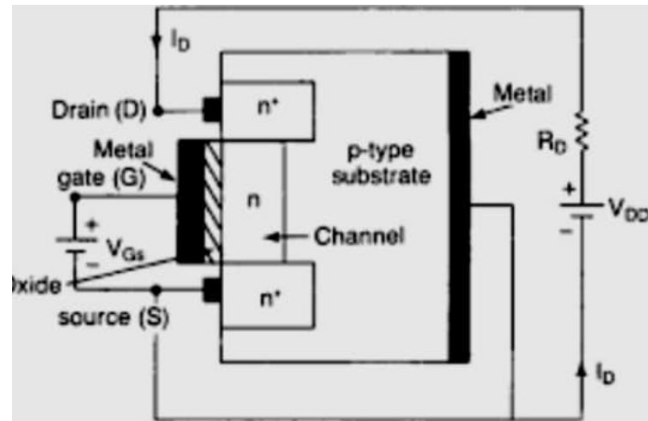


Figure 2.17.d Drain current

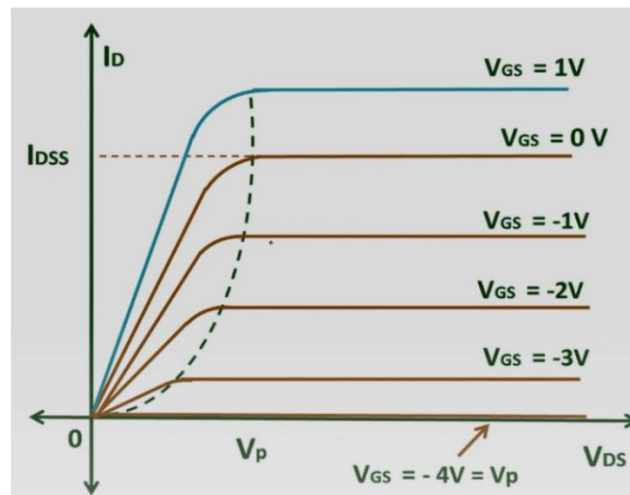


Figure 2.17e The drain current increase and exceed the saturation current

The graph shows that the current I_D will flow for both positive and negative values of V_{GS} . You can see from the graph that the drain current is less than the saturation current for the negative value of gate voltage, whereas for the positive value of gate voltage, the drain current exceeds the saturation current. $V_{GS} = V_P$ is also represented in this graph for which drain current is zero irrespective of drain to source voltage.

2.13.4 N Channel Enhancement MOSFET

The body of any N-channel MOSFET is made up of P-type material. 2 N-type materials are diffused at the top. A depletion region will be formed in the PN-junction. A metal contact is made at the bottom of the P-type substrate and a terminal is taken out called the body or substrate.

Similarly, a metal contact is made at the top of both the N-type materials, and two terminals are taken out as Drain and source. A Silicon dioxide layer is drawn in between the two N-type wells at the top. A metal contact is made at the top of it and a terminal is taken out called a Gate terminal as shown in Figure 2.18.a.

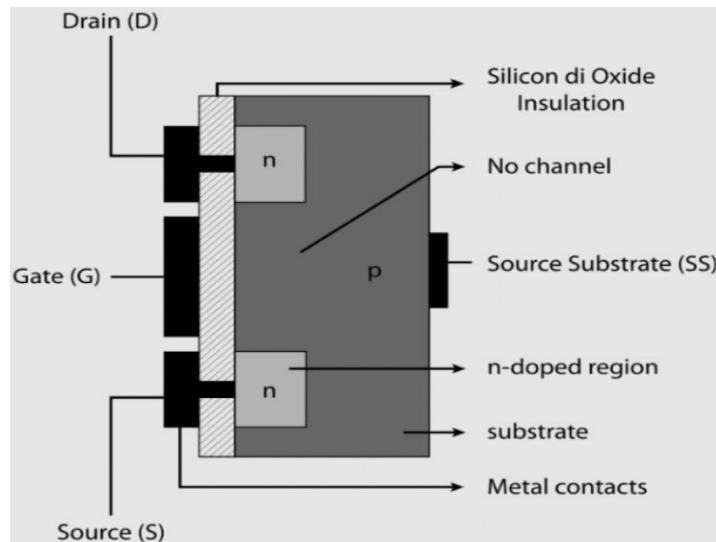


Figure 2.18.a N-channel enhancement

Now, what happens is generally the body terminal and source terminal are internally shorted and connected to the ground. Hence now only three terminals are visible namely Source, Drain, and Gate.

To get the drain current first we have to create a channel for the free movement of electrons. To create a channel we have to apply a voltage between the gate and the source terminal keeping the Gate at a higher potential. This voltage is called V_{GS} . Now the gate is at higher potential. The free electrons will move toward the gate terminal. These free electrons will accumulate near the Gate region and will not escape. The silicon dioxide layer also acts as a dielectric. It will allow more free electrons to accumulate near the gate terminal in less applied voltage at the gate terminal.

Now on increasing V_{GS} further, a high electric field is developed forcing atoms inside the P-substrate to break. The free electrons generated will fill the holes near the gate region. This way holes are pushed away from the gate terminal increasing N-type behavior near the gate terminal. A time will come when an N-channel is created between the two N-cells. The V_{GS} voltage at which the channel is created is called the threshold voltage or V_T . We can conclude that when $V_{GS} > V_T$ an N-channel is induced near the gate terminal as shown in the figure below.

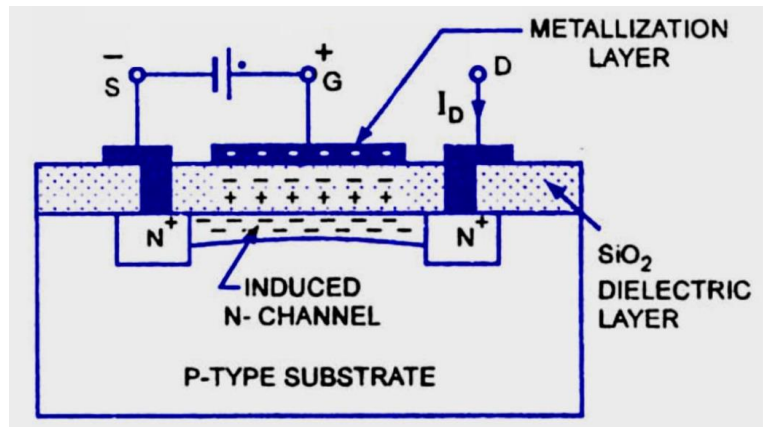


Figure 2.18.b Induced N-channel

A channel is created still we are not getting any current. To get the drain current, apply a voltage source between the drain and the source keeping the drain at a higher potential. On applying V_{DS} voltage, current will start flowing from drain to source. This current is called drain current or I_D .

We can conclude, when $V_{GS} > V_T$ and $V_{DS} > 0$, the current I_D flows from drain to source as shown in the figure below.

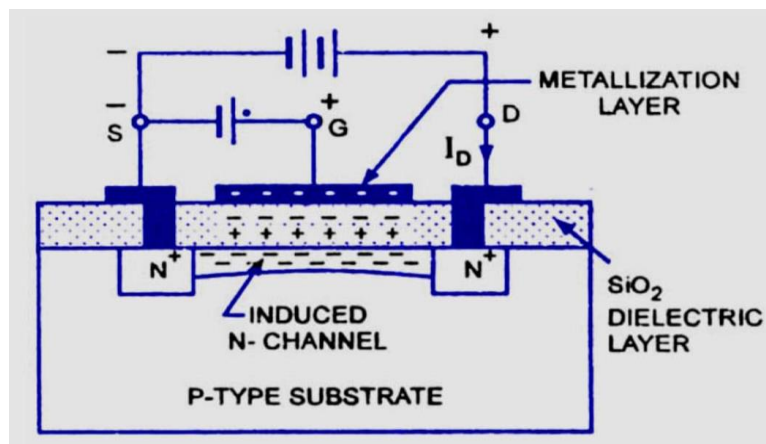


Figure 2.18.c The current I_D flows from drain to source

On increasing V_{DS} further I_D will increase. But will this I_D will not keep on increasing. On increasing the positive voltage at the drain terminal a reverse bias is formed at the PN-junction near the drain terminal. This will result in a thick depletion region near the PN-junction. Hence on increasing V_{DS} further, you will see the channel near the drain terminal is becoming narrow. The drain current will face more resistance near the drain terminal. A situation will reach when the drain current becomes constant and will not increase further.

This situation is called the pinch-off situation and the drain current is called the saturation current. The voltage at which we will get saturation current is called saturation voltage. We can conclude from this discussion, that pinch-off is reached when $V_{GS} > 0$ (constant) and $V_{DS} = V_{DS(SAT)}$, $I_D = I_{D(SAT)}$ as shown in the Figure 2.18.d.

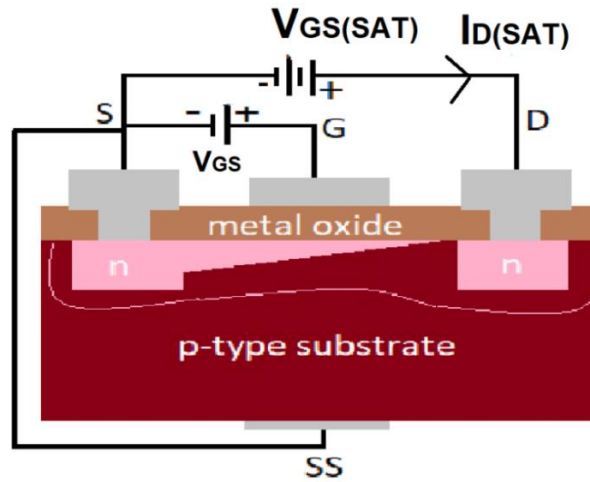


Figure 2.18.d The pinch-off is reached

Increasing I_D further increases the value of V_{GS} . This will increase the width of the complete N-channel. Hence V_{GS} is controlling voltage.

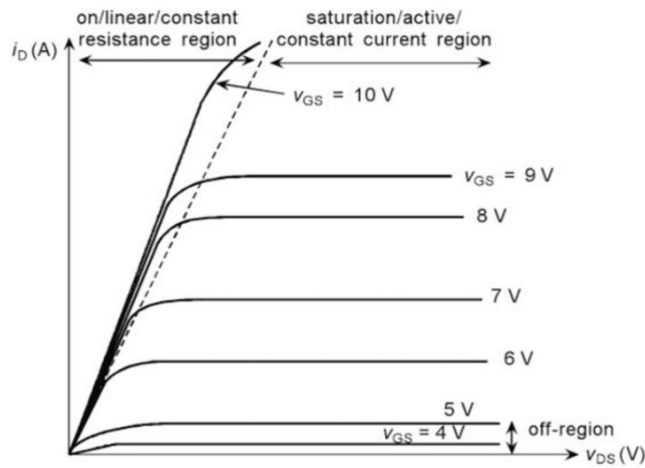


Figure 2.18.e I_D further increases the value of V_{GS}

From the graph, it is clear that the current I_D will become constant at a specific value of V_{DS} . current I_D increases only when the value of V_{GS} is increased.

Applications

- Amplifiers
- Regulation for DC Motors
- Constructions of Chopper Amplifiers
- Switching and Amplifying Signals

Control Requirements

- Bidirectional current sensing
- High frequency
- Current and voltage feedback loops
- PWM strategies like:
 - Sinusoidal PWM (SPWM)
 - Space Vector PWM (SVPWM)
- Dead-time insertion to avoid shoot-through
- Optional: Overcurrent, overvoltage, and temperature protection

CHAPTER III:
**SIMULATION AND CONTROL OF A
REVERSIBLE STATIC CONVERTER**

3.1 Introduction

The control principles of a semiconductor-based converter are explained in the first chapter. To better understand the compensation mechanism, we will present, in this chapter, the adjustment of a static reactive power compensator. This compensator is a multi-level converter. We will specifically monitor the evolution and control of its currents in the dq reference frame as well as its DC voltage.[15]

3.2 Principle of Operation

The principle of operation of the converter is illustrated by the vector diagram (Figure 3.1). We will therefore assume that the converter can generate, from a direct voltage, the voltages V_1 , V_2 , V_3 which will be assimilated to a network of perfectly sinusoidal voltages. [36]

Noting φ as the phase shift between the simple network voltage and the line current of the same phase, we obtain (Figure 3.1):

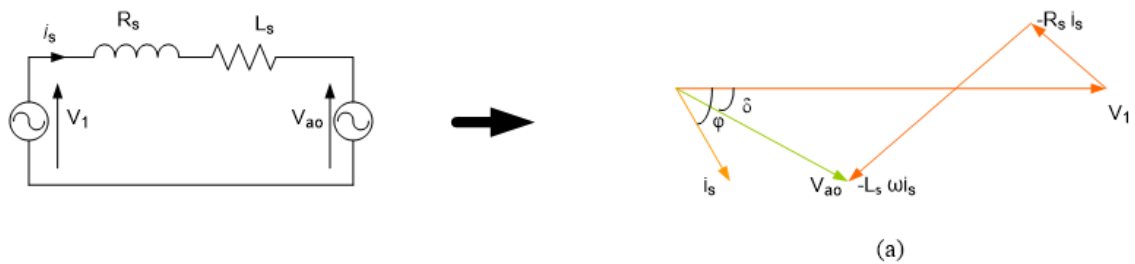


Figure 3.1 Converter phase vector diagram

$$\begin{cases} V_{ao}(t) = V_1 \sqrt{2} \sin(\omega t) - R_s i_s \sin(\omega t - \varphi) - L_s \omega i_s \cos(\omega t - \varphi) \\ V_{bo}(t) = V_1 \sqrt{2} \sin(\omega t - \frac{2\pi}{3}) - R_s i_s \sin(\omega t - \varphi - \frac{2\pi}{3}) - L_s \omega i_s \cos(\omega t - \varphi - \frac{2\pi}{3}) \\ V_{co}(t) = V_1 \sqrt{2} \sin(\omega t - \frac{4\pi}{3}) - R_s i_s \sin(\omega t - \varphi - \frac{4\pi}{3}) - L_s \omega i_s \cos(\omega t - \varphi - \frac{4\pi}{3}) \end{cases} \quad (3.1)$$

3.2.1 Case where the converter absorbs reactive power :

$$(\varphi = -\frac{\pi}{2})$$

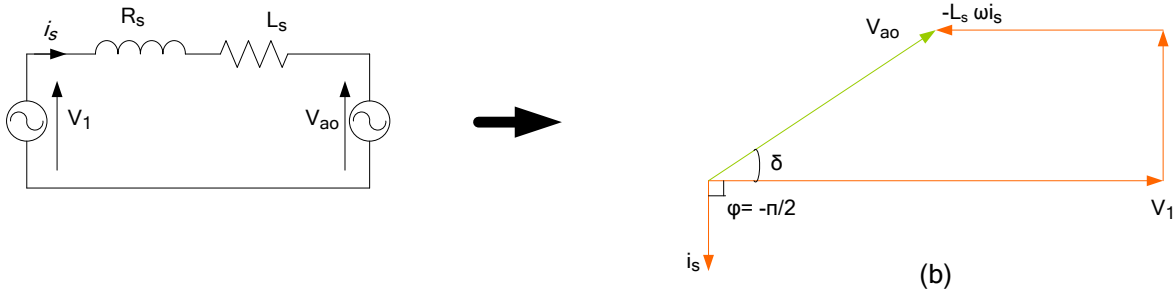


Figure 3.2 Converter phase vector diagram ($\varphi = -\pi/2$)

$$\begin{cases} V_{co}(t) = V_1\sqrt{2} \sin(\omega t) - R_s i_s \sin(\omega t + \frac{\pi}{2}) - L_s \omega i_s \cos(\omega t + \frac{\pi}{2}) \\ V_{bo}(t) = V_1\sqrt{2} \sin(\omega t - \frac{2\pi}{3}) - R_s i_s \sin(\omega t - \frac{\pi}{6}) - L_s \omega i_s \cos(\omega t - \frac{\pi}{6}) \\ V_{co}(t) = V_1\sqrt{2} \sin(\omega t - \frac{4\pi}{3}) - R_s i_s \sin(\omega t - \frac{5\pi}{6}) - L_s \omega i_s \cos(\omega t - \frac{5\pi}{6}) \end{cases} \quad (3.2)$$

3.2.2 Case where the converter injects reactive power :

$$(\varphi = +\frac{\pi}{2})$$

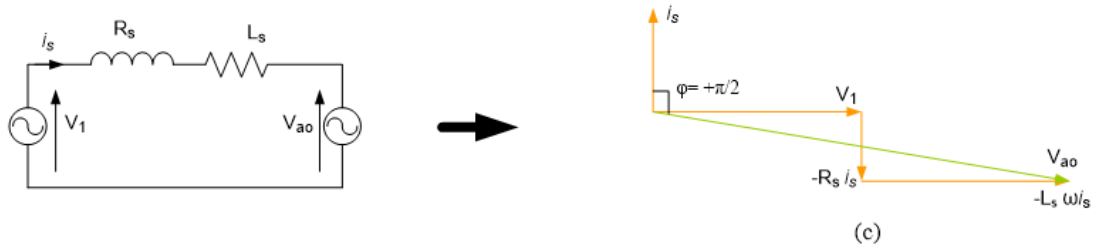


Figure 3.3 Phase vector diagram of the converter ($\varphi = +\pi/2$)

$$\left\{ \begin{array}{l} V_{co}(t) = V_1 \sqrt{2} \sin(\omega t) - R_s i_s \sin(\omega t - \frac{\pi}{2}) - L_s \omega i_s \cos(\omega t - \frac{\pi}{2}) \\ V_{bo}(t) = V_1 \sqrt{2} \sin(\omega t - \frac{2\pi}{3}) - R_s i_s \sin(\omega t - \frac{5\pi}{6}) - L_s \omega i_s \cos(\omega t - \frac{5\pi}{6}) \\ V_{co}(t) = V_1 \sqrt{2} \sin(\omega t - \frac{4\pi}{3}) - R_s i_s \sin(\omega t + \frac{\pi}{6}) - L_s \omega i_s \cos(\omega t + \frac{\pi}{6}) \end{array} \right. \quad (3.3)$$

3.3 Three-Phase Voltage Modeling

The proposed technique makes it possible to take into account a large part of the disturbances of low-frequency networks (distortions, voltage dips, phase variation, amplitude variation)

The analytical study of our system's behavior is complex. It is therefore essential to use mathematical transformations that allow us to describe the system's behavior using differential equations with constant coefficients. The *Concordia* or *Park* transformations allow us to obtain an equivalent system consisting of three orthogonal vectors. Two of these vectors are located in the same plane as vectors a, b, and c. The third vector is located in the plane orthogonal to the plane formed by the phase axes a, b, and c and represents the zero-sequence component. The *Park* transformation allows us to move from a representation in the three-phase frame (a, b, c) to a representation in a so-called *Park* frame with orthogonal axes (d, q, o).

In our study, we are interested in the *Concordia* transformation because it preserves the instantaneous power and is therefore power invariant. The initial hypothesis is to consider that the system is balanced, which means that the homopolar component is zero. This transformation of a three-phase system into a two-phase system can be broken down into two stages (Figure 3.4).

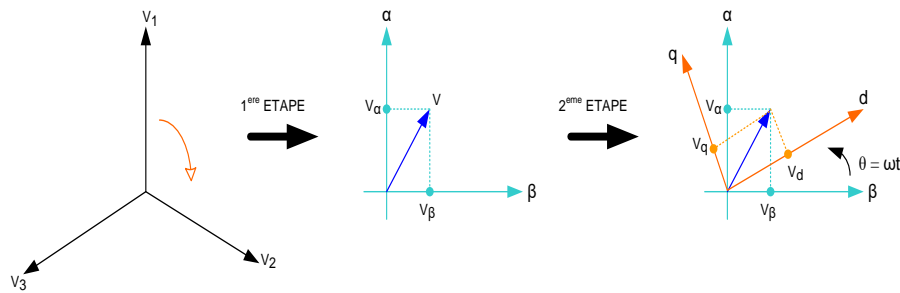


Figure 3.4 Transition from three-phase to two-phase.

The first step is to move from a three-phase system to a two-phase system. The coordinates in the CLARKE frame are denoted by V_α , V_β along the " α " and " β " axes. Formula (3.4) provides the direct balanced three-phase system from the coordinates V_α , V_β in the CLARKE frame.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = M_{32} \cdot \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{\sqrt{3}}{2} & \frac{-1}{2} \\ \frac{-\sqrt{3}}{2} & \frac{-1}{2} \end{bmatrix} \cdot V \cdot \begin{bmatrix} \cos(\omega t) \\ \sin(\omega t) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{\sqrt{3}}{2} & \frac{-1}{2} \\ \frac{-\sqrt{3}}{2} & \frac{-1}{2} \end{bmatrix} \cdot \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (3.4)$$

We can then express V_α , V_β from a direct balanced three-phase system, which gives:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = M_{32}^{-1} \cdot V = \frac{2}{3} \begin{bmatrix} 1 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ 0 & \frac{2}{2} & \frac{-1}{2} \end{bmatrix} \cdot V \quad (3.5)$$

$$M_{32}^{-1} = \frac{2}{3} M_{32}^t \quad (\text{By CLARKE}).$$

In the second step, we go through a rotation of $(-\theta = -\omega t)$ from the two-phase system in the CLARKE frame to the two-phase system in the rotating PARK frame, in which the coordinates of the direct balanced component have the property of being constant:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R(-\theta) \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = R(-\theta) \cdot \frac{2}{3} \cdot M_{32}^t \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (3.6)$$

Thus :

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = [R(\theta)]^{-1} \cdot \frac{2}{3} \cdot M_{32}^t \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (3.7)$$

With :

$$R(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \Rightarrow R(-\theta) = [R(\theta)]^{-1} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \quad (3.8)$$

Where :

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \frac{2}{3} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (3.9)$$

3.4 Converter Control

Generally speaking, the control part of the converter consists of two inner loops and one outer loop.

The objective of the internal loops is to regulate the network currents in order to minimize their harmonic contents and to exchange a certain reactive power with the network, while the objective of the external loop is to regulate the output voltage of the converter. Figure (3.5) shows a block diagram of the principle of the regulation of a converter.

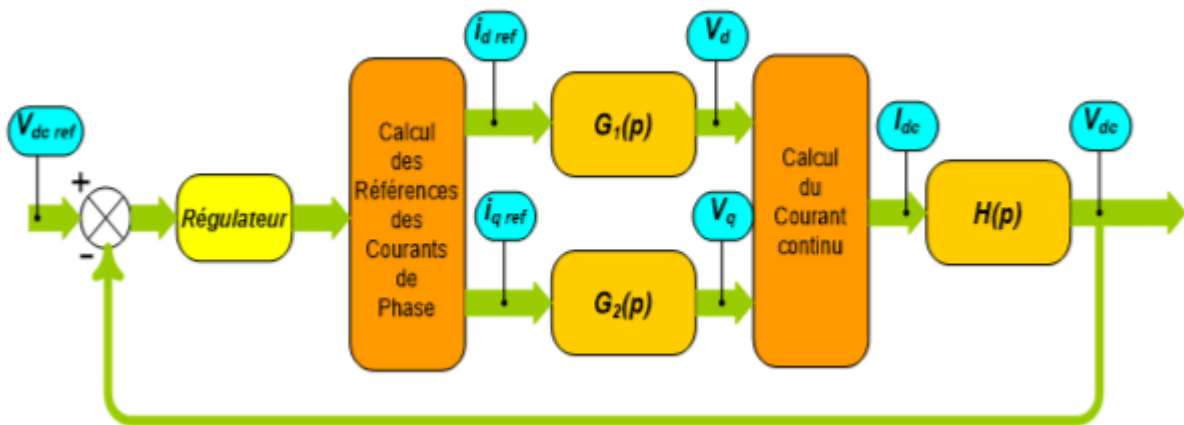


Figure 3.5 Block diagrams of the converter regulation principle.

$G_1(p)$: current regulation loop I_d

$G_2(p)$: current regulation loop I_q

$H(p)$: voltage regulation loop on the direct current side V_{dc}

3.4.1 Modeling the Inner Loop

As illustrated in figure (3.6), the modeling of the internal loop is represented by a mesh composed of an alternating voltage (V_{s1}) in series with an impedance consisting of a resistance (R_s) and an inductance (L_s). The output of this mesh is the voltage V_{ao} provided by the converter.

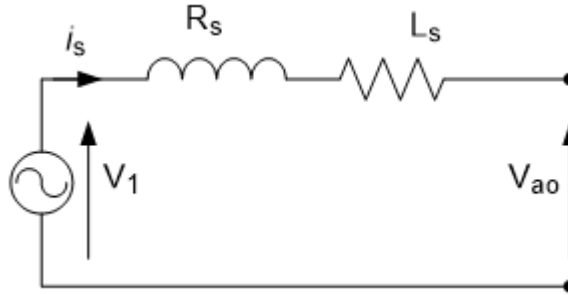


Figure 3.6 Inner loop modeling.

For this mesh, we can write :

$$V_1(t) = R_s i_s(t) + L_s \frac{di_s(t)}{dt} + V_{ao}(t) \quad (3.10)$$

So its Laplace transform is of the form :

$$V_1(p) = R_s i_s(p) + L_s p i_s(p) + V_{ao}(p) \quad (3.11)$$

Thus :

$$V(p) - V_{ao}(p) = (R_s + L_s p) i_s(p) \quad (3.12)$$

Thus :

$$G_1(p) = \frac{i_s(p)}{V(p) - V_{ao}(p)} = \frac{1}{R_s(1 + \tau p)} \quad ; \tau = \frac{L_s}{R_s} \quad (3.13)$$

3.4.2 Modeling the External Loop:

Figure (3.7) gives us a representation of the external loop which maintains the capacitance voltage " V_{dc} " at a reference voltage $V_{dc \text{ ref}}$.

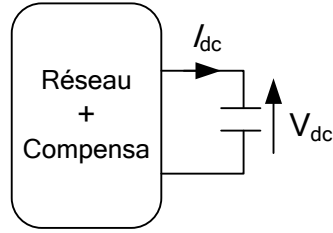


Figure 3.7 Modeling of the outer loop.

To calculate the transfer function of this loop, we have :

$$V_{dc}(t) = \frac{1}{C} \int I_{dc}(t) \cdot dt \quad (3.14)$$

Which gives :

$$I_{dc}(t) = C \frac{dV_{dc}(t)}{dt} \quad (3.15)$$

The Laplace transform gives us :

$$I_{dc}(p) = C \cdot p \cdot V_{dc}(p) \quad (3.16)$$

Where :

$$\frac{V_{dc}}{I_{dc}} = \frac{1}{Cp} \quad (3.17)$$

Thus :

$$H(p) = \frac{1}{Cp} \quad (3.18)$$

3.4.3 Calculation of Active Power

The active power in a three-phase network is obtained by the relationship :

$$P = V_1 i_1 + V_2 i_2 + V_3 i_3 \quad (3.19)$$

In matrices form:

$$P = [V_1 \quad V_2 \quad V_3] \cdot \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix}$$

In the dq frame the active power becomes:

$$P = \left[M_{32} \cdot R(\theta) \begin{bmatrix} V_q \\ V_d \end{bmatrix} \right]^t \cdot \left[M_{32} \cdot R(\theta) \begin{bmatrix} i_q \\ i_d \end{bmatrix} \right] \quad (3.20)$$

$$P = \left[\begin{bmatrix} V_q \\ V_d \end{bmatrix}^t \cdot R(\theta)^t \cdot M_{32}^t \right] \cdot \left[M_{32} \cdot R(\theta) \begin{bmatrix} i_q \\ i_d \end{bmatrix} \right] \quad (3.21)$$

$$P = \left[\begin{bmatrix} V_d & V_q \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} 1 & -1 & -1 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ -1 & \frac{\sqrt{3}}{2} \\ -1 & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} \right]$$

Thus :

$$P = \frac{3}{2} (V_d i_d + V_q i_q) \quad (3.22)$$

3.4.4 Calculation of Reactive Power

This power is only defined in sinusoidal mode. It is associated with the reactive component of the current. Here we present two definitions of reactive power "Q" which is obtained by two calculation techniques:

- From the active power formula written using PARK components: reactive power is deduced by replacing the network current with the quadrature current (-90°) in the dq reference frame (Figure 3.8).

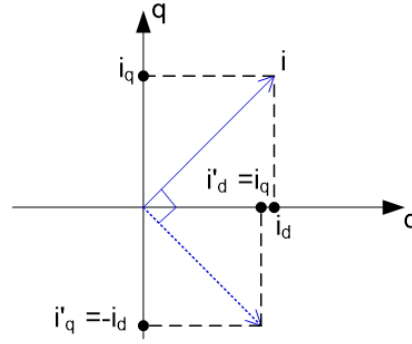


Figure 3.8 Calculation of quadrature currents in the dq frame

So the reactive power Q seen in the dq frame can be expressed by:

$$Q = \frac{3}{2}(V_d i'_d + V_q i'_q) = \frac{3}{2}(V_d i_q - V_q i_d) \quad (3.23)$$

- A second possibility is to use the quadrature voltage (90°). The power obtained is then equivalent to the reactive power for a balanced three-phase system. To calculate the quadrature voltage, the line-to-line voltages of the network are used.

$$Q = \left(\frac{V_3 - V_2}{\sqrt{3}}\right) i_1 + \left(\frac{V_2 - V_1}{\sqrt{3}}\right) i_3 + \left(\frac{V_1 - V_3}{\sqrt{3}}\right) i_2 \quad (3.24)$$

In matrices form :

$$Q = \frac{1}{\sqrt{3}} \cdot [i_1 \quad i_2 \quad i_3] \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \cdot \begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix}$$

$$Q = \frac{1}{\sqrt{3}} \begin{bmatrix} i_d \\ i_q \end{bmatrix}^t \cdot R(\theta)^t \cdot M_{32}^t \begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix} \cdot M_{32} \cdot R(\theta) \cdot \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (3.25)$$

$$Q = \frac{1}{\sqrt{3}} \begin{bmatrix} i_d & i_q \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$

After calculations, we find :

$$Q = \frac{3}{2}(V_d i_q - V_q i_d) \quad (3.26)$$

3.4.5 Regulation :

e.1 Current regulation instructions in the dq reference :

The active and reactive power setpoints being fixed, the components along the d and q axes of the setpoint currents are calculated after measuring the PARK components of the network voltage. We can write :

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \frac{3}{2} \begin{bmatrix} V_d & V_q \\ -V_q & V_d \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (3.27)$$

The shapes of the currents along the direct axis and in quadrature are given by :

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} V_d & V_q \\ -V_q & V_d \end{bmatrix}^{-1} \begin{bmatrix} P \\ Q \end{bmatrix} = \frac{2}{3} \cdot \frac{1}{V_d^2 + V_q^2} \cdot \begin{bmatrix} V_d & -V_q \\ V_q & V_d \end{bmatrix} \cdot \begin{bmatrix} P \\ Q \end{bmatrix} \quad (3.28)$$

Which implies:

$$\begin{cases} i_{d \text{ ref}} = \frac{2}{3} \cdot \frac{1}{V_d^2 + V_q^2} (P \cdot V_d + Q \cdot V_q) \\ i_{q \text{ ref}} = \frac{2}{3} \cdot \frac{1}{V_d^2 + V_q^2} (P \cdot V_q - Q \cdot V_d) \end{cases} \quad (3.29)$$

System (3.28) provides the PARK components of the setpoint currents to be imposed in open loop. Figure (3.9) describes this principle:

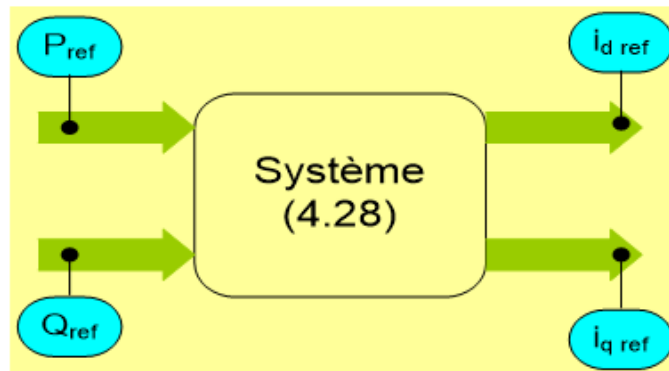


Figure 3.9 Calculation of reference currents in the dq frame

Decoupling ,

Equation (3.28) shows that the currents I_d and I_q depend on both the currents on the "d" and "q" axes; We will then briefly present two methods for decoupling our system. These two methods both have advantages and disadvantages that we will highlight.

Decoupling by decoupling network :

Figure (3.10) represents one of these methods which uses a decoupling network placed upstream of the system to be controlled. We subtract from the control quantities V_d and V_q the value necessary to perfectly decouple our system. Figure (3.10) represents the principle diagram for obtaining decoupling.[37]

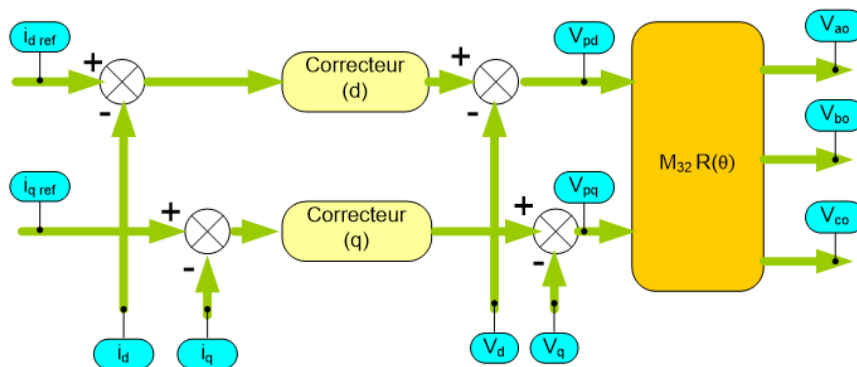


Figure 3.10 Network current regulation with network voltage compensation

This method produces very good results. However, it has a definite drawback: it requires very precise knowledge of all the system parameters. If this is not the case, this decoupling can become an additional coupling and further degrade the adjustment.

Approximate decoupling :

The second method is based directly on the structural diagram of the system (fig (3.11)). It consists of subtracting from the control quantities the current responsible for the coupling multiplied by a transfer function.

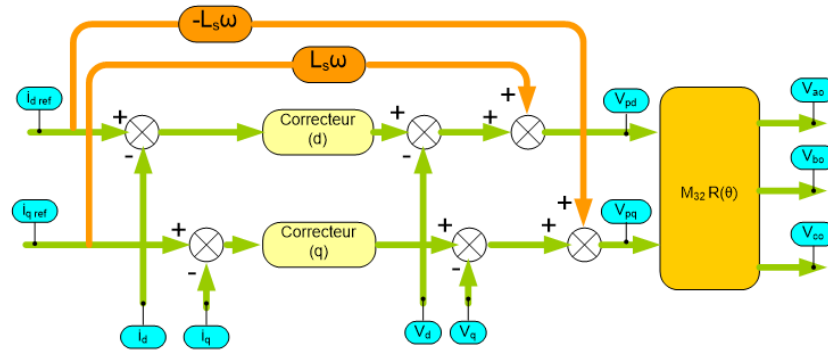


Figure 3.11 Network current regulation with approximate decoupling.

This method gives very good results for small values of " t_m ", which corresponds to a high pulse frequency. It has the advantage of not requiring knowledge of all the system parameters.

3.4.6 Study of regulators

Once the transfer function is identified and its approximate model is known, the loop must be closed so that there can be control. Eventually, the whole system must also be corrected to improve its performance; then different types of regulators can be used for the regulation of the internal and external loops. [32]

The choice of corrector will depend on the expected performance of the closed loop system. These criteria are:

- **Stability:** The system is unstable if its output changes indefinitely without changing the input (infinite transient state).
- **Speed:** This is the time it takes for the system to react and reach its final value.
- **Accuracy:** This is defined by the error between the desired final value and the one actually reached.

We will now present two types of correctors:

f.1 Using the "PI" regulator :

The transfer function of the PI regulator is:

$$F_{PI}(P) = K_p + \frac{K_i}{p} \quad (3.30)$$

The inner loop transfer function associated with the open loop PI regulator transfer function will be :[38]

$$FTBO [G_1(p), F_{PI}(p)] = \left(K_p + \frac{K_i}{p} \right) \cdot \left(\frac{1}{R_s(1 + \tau p)} \right) \quad (3.31)$$

We can write formula (3.31) in the following form :

$$FTBO [G_1(p), F_{PI}(p)] = \left(\frac{1 + \frac{K_p}{K_i} p}{\frac{R_s}{K_i} p + \frac{R_s \tau}{K_i} p^2} \right) \quad (3.32)$$

The closed-loop transfer function is illustrated by:

$$FTBF [G_1(p), F_{PI}(p)] = \left(\frac{1 + \frac{K_p}{K_i} p}{1 + \frac{R_s + K_p}{K_i} p + \frac{R_s \tau}{K_i} p^2} \right) \quad (3.33)$$

The external loop transfer function associated with the open loop PI regulator transfer function will be :

$$FTBO [H(p), F_{PI}(p)] = \left(K_p + \frac{K_i}{p} \right) \cdot \left(\frac{1}{Cp} \right) \quad (3.34)$$

$$FTBO [H(p), F_{PI}(p)] = \frac{P \cdot K_p + K_i}{C p^2} \quad (3.35)$$

The deduced closed-loop transfer function is :

$$FTBF [H(p), F_{PI}(p)] = \left(\frac{1 + \frac{K_p}{K_i} p}{1 + \frac{K_p}{K_i} p + \frac{C}{K_i} p^2} \right) \quad (3.36)$$

Furthermore, a second-order system is characterized by

$$D(p) = \frac{1}{1 + \frac{2\zeta}{\omega_n} p + \frac{1}{\omega_n^2} p^2} \quad (3.37)$$

Comparing characteristic equation 4.36 with that of a second-order system, we obtain:

$$\begin{cases} \frac{R_s + K_p}{K_i} = \frac{2\zeta}{\omega_n} \\ \frac{R_s \tau}{K_i} = \frac{1}{\omega_n^2} \end{cases}$$

Thus :

$$\begin{cases} K_p = R_s (2 \cdot \zeta \cdot \tau - 1) \\ K_i = R_s \cdot \tau \cdot \omega_n \end{cases} \quad (3.38)$$

Similarly, for equation 4.36, we will have:

$$\begin{cases} \frac{K_p}{K_i} = \frac{2\zeta}{\omega_n} \\ \frac{C}{K_i} = \frac{1}{\omega_n^2} \end{cases} \quad (3.39)$$

From the system (4.37), we obtain the parameters of the PI regulator (K_p and K_i).

These are obtained by:

$$\begin{cases} K_p = C \cdot \omega_n \cdot 2\zeta \\ K_i = C \cdot \omega_n^2 \end{cases} \quad (3.40)$$

Figure (3.12) shows the control block diagram of our system.

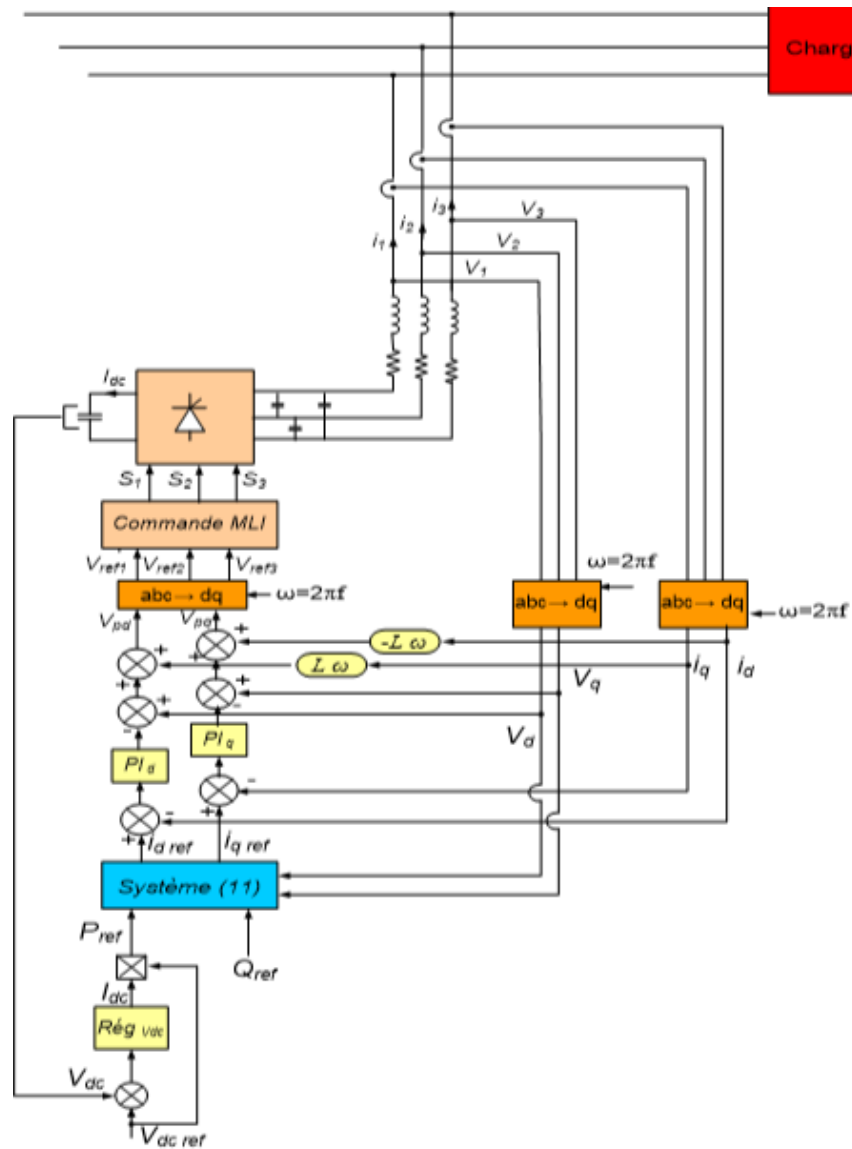


Figure 3.12 Converter block diagram.[39]

In order to carry out the simulation study on MATLAB/Simulink, we use these parameters

Network voltage (V_s)		80V
Network frequency (f_s)		50Hz
The impedance of the network	R_s	0.1Ω
	L_s	0.5mH
The voltage across the capacitor ($V_{dc \text{ ref}}$)		160V
Capacitance		1000μF

Table 3.1 Electrical parameters of the system to be simulated

3.5 SIMULATION

In our work, we used two types of regulators ("PI" and "IP") to control a converter.

To analyze the performance of this type of converter control, we will perform several simulations.[40], [41]

3.5.1 Converter via an IP regulator controlled by the sinusoidal PWM:

Firstly, figure (3.13.a) shows the quasi-sinusoidal voltage produced by a 3-level converter, as well as its harmonic spectrum in figure (3.13.b),

Then, figure (3.13.c) shows the simulation of the control voltage V_{ref1} for the first phase.

Figure (3.13.d) shows the converter phase current I_1 with respect to the network voltage. For a first reference change of the quadrature current ($I_{q \text{ inductive}}$), the current lags behind the voltage (V_1) by $\frac{\pi}{2}$. From $t=0.2s$, the mode is resistive. There is no power exchange. From $t=0.3s$, and for a second reference change ($I_{q \text{ capacitive}}$), the current leads the voltage (V_1) by $\frac{\pi}{2}$.

To see the influence of the main regulation quantities, Figure (3.13.e) illustrates the evolution of the direct current I_d which, after the voltage V_{dc} reaches its steady state, is canceled because its main role is to charge or discharge the capacitor. It remains zero regardless of the mode. In the same Figure (3.13.e), we show the evolution of the current I_q of the inductive mode (+10.20 A). At $t=0.2s$, during the resistive mode, the current is canceled. At $t=0.3 s$, the mode is capacitive and the current changes value (-10.20 A).[42]

Figure (3.13.f) illustrates the dynamic response of the active power, which always remains zero in the three operating modes of the converter. It has the same shape as the current I_d because they are linked to each other. The dynamic response of the reactive power is also simulated. It goes from (+1000 Var) in the case where it is absorbed by the converter, to zero (from $t = 0.2s$), then to a value of (-1000 Var) from $t = 0.3s$ when the converter supplies reactive power. It has the same shape as the current in quadrature.[40], [43]

Figure (3.13.g) shows the V_{dc} voltage on the DC side which is maintained, more or less, at a stable value (+160v), whatever the variation of the operating modes.[42]

Finally, figure (3.13.h) simulates the DC current I_{dc} flowing through the capacitor during inductive mode up to $t=0.2s$. Then, after a very short transient, it tends towards zero during resistive mode. Finally, at $t=0.3s$, we switch to capacitive mode after a negligible transient.

Simulation Results of a Three-Level Converter Used for Reactive Energy Compensation ($Q=\pm 1000$ Var) (using an IP regulator).

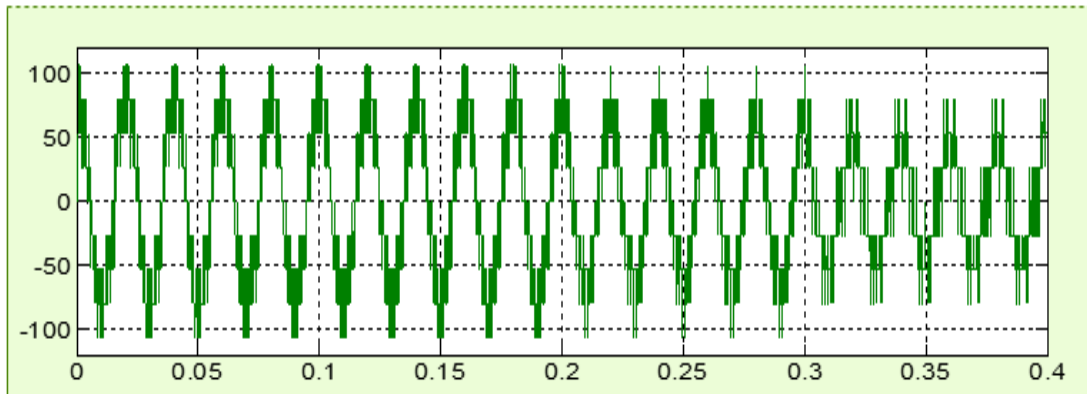


Figure 3.13.a Output voltage of the first phase converter

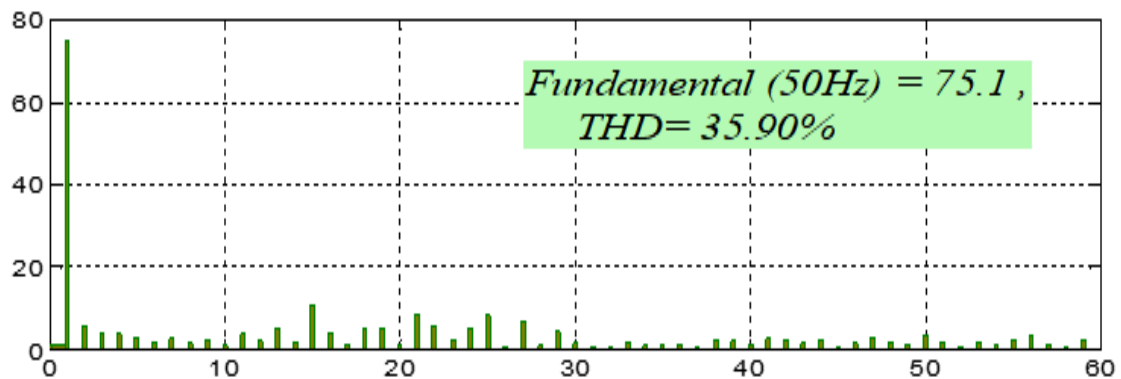


Figure 3.13.b Harmonic spectrum of the first phase voltage of the converter.

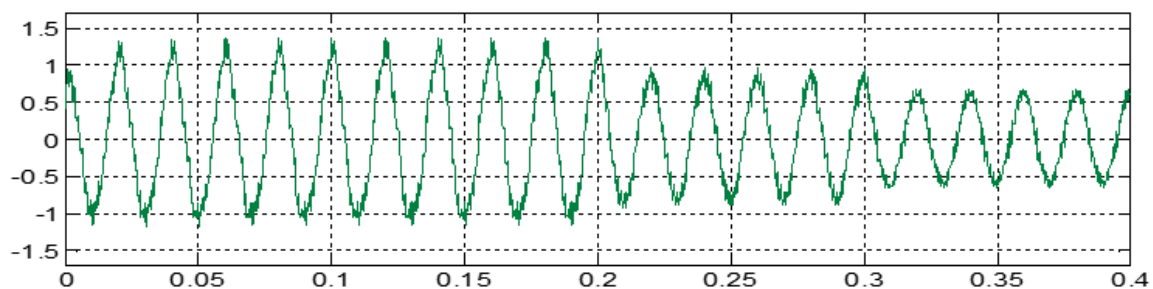


Figure 3.13.c Reference voltage (V_{ref1}) of the first phase.

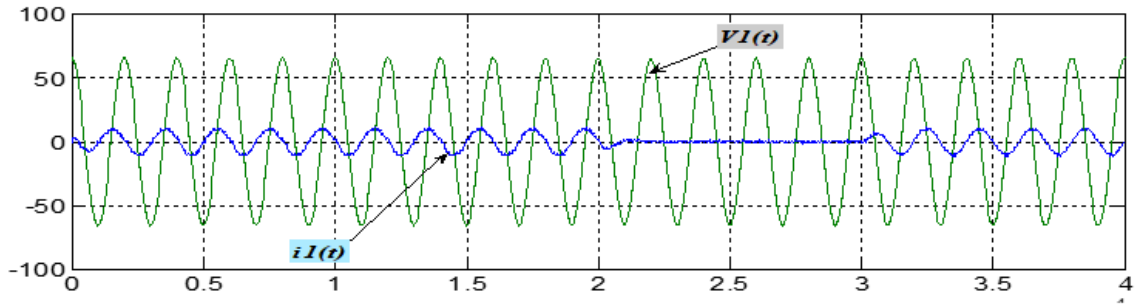


Figure 3.13.d Voltage (V_1) and current (I_1): transition from inductive mode to capacitive mode

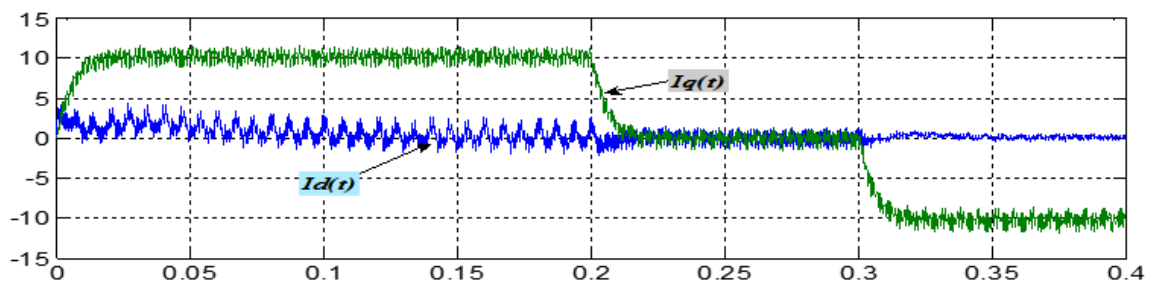


Figure 3.13.e Current I_q and Current I_d in the dq frame

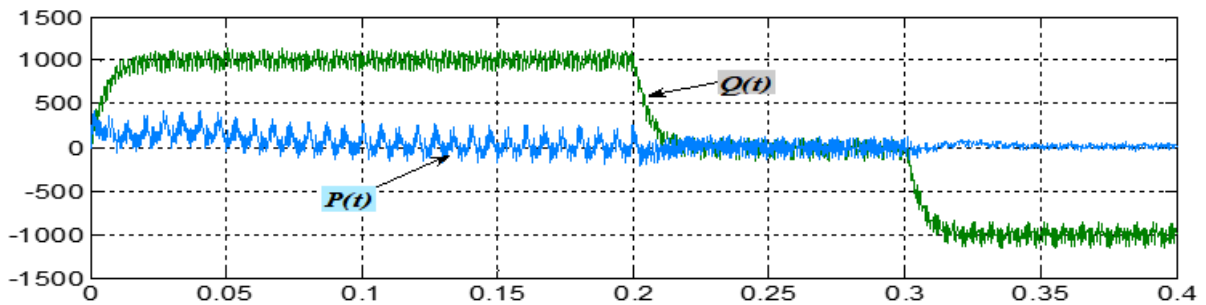


Figure 3.13.f Active power and reactive power exchanged between the converter and the network.

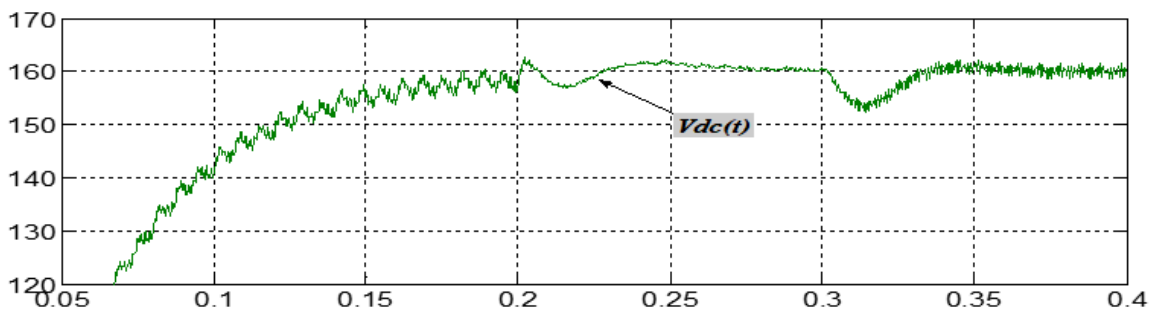


Figure 3.13.g Converter output voltage V_{dc}

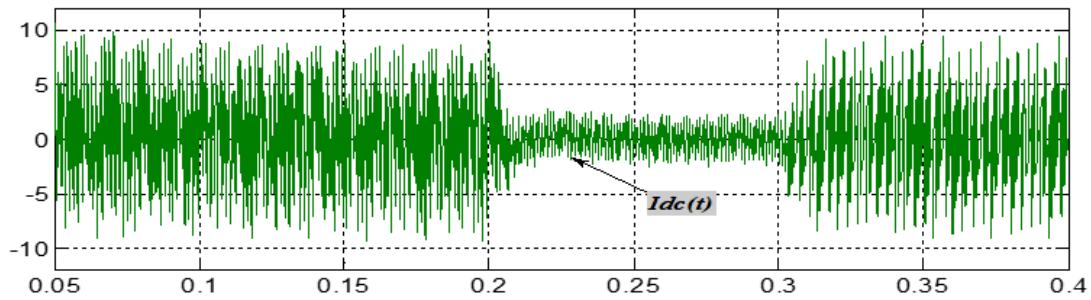


Figure 3.13.h Output current I_{dc} of the converter

3.5.2 Interpretation Of Simulation Results

As we described in the first chapter, if we increase the value of the alternating voltage produced by the converter and if the modulus of this voltage is higher than that of the AC system, the amount of reactive power supplied by the converter will also increase. If we decrease the value of the voltage produced by the converter below that of the AC system, the converter will absorb reactive power. In order to reduce transient regimes, zero-free IP regulators were introduced; the results obtained with these show an improvement in the transient regime.

3.6 Conclusion :

This chapter has shown the principle of controlling a converter based on the orientation of the two-phase currents: one on the direct axis "d", the other in quadrature "q". It is necessary to keep " I_d " zero and ensure the control of the reactive power by the " I_q " component. The input voltage of the converter is kept constant via a regulator.

Different control techniques were developed to analyze their closed-loop behavior. Finally, two regulators were used, and it was concluded that with the zero-free IP corrector, very fast responses and an acceptable transient regime are obtained.

GENERAL CONCLUSION

The design of a reversible electric converter based on MOSFET technology demonstrates the versatility and efficiency of modern power electronics in achieving bidirectional energy flow. Through the integration of MOSFETs, the converter achieves high switching speeds, low conduction losses, and excellent control over power conversion, which are critical factors for applications such as electric drives, renewable energy systems, and advanced industrial automation.

Throughout this work, we explored the theoretical principles, design methodologies, and practical considerations necessary to implement a reversible converter. Simulations and analysis confirmed that MOSFET-based designs offer significant advantages in terms of efficiency, thermal management, and dynamic response compared to traditional switching devices.

Moreover, the adaptability of MOSFETs to various control techniques, such as PWM (Pulse Width Modulation), further enhances the converter's performance and operational flexibility. As energy systems increasingly demand smarter, more efficient, and bidirectional power management, the role of MOSFET-based converters will continue to grow.

In conclusion, the project not only validates the effectiveness of MOSFET-based reversible converters but also opens pathways for further innovations in power electronics, aimed at supporting the transition to more sustainable and intelligent energy infrastructures.

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