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THEME

Energy management of a standalone PV-Battery hybrid system

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Dedication

I dedicate this modest work

To my dear grandma, to my dear mother,

To my esteemed father,

To my great aunt,

And to my lovely sister.

To all my friends who I shard the best moment of my life,

And to all those who have helped me near or far.

Mahdjoubi Sadjida belkis

Table of contents

CHAPTRE I Generalities On Renewable Energy Sources

CHAPTRE II Modeling and Simulation of PV-Battery hybrid system

CHAPTRE III Control and Energy management of PV/battery hybrid system

List of figures and tables

List of figures

List of tables

General introduction

General Introduction

Renewable energy sources such as biomass, wind, solar, hydropower, and geothermal can provide sustainable energy services. Switching over to renewable-based energy systems is being increasingly considered by various countries globally. With refinements in technology the feasibility and cost of solar and wind power systems have become affordable. Also with the policy interventions and technology refinements, market systems are rapidly evolving in favor of renewable energy systems. [1]

The sector studied in this work is photovoltaic solar energy, storage systems and control methods.

The purpose of this work is to simulate and to use a hybrid control method to improve the management and exploit energy. Matlab/Simulink is used to simulate and analyze the systems, and step by step guide is illustrated in order to understand the well-functioning of PV-Battery systems.

The writing of our dissertations consists of three chapters:

In the **first chapter**, a general description of renewable energy such as solar energy, wind energy and photovoltaic systems including the energy storage systems as Fuel cells, batteries and supercapacitors .

The **second chapter,** describes a preliminary study of the mathematical modeling of PV cells PV panels, batteries and DC-DC converters and simulation of hybrid system PV-Battery.

The **third chapter** is devoted to describe a preliminary study of the maximum peak power tracking control method. We also presented the Fuzzy logic control and its steps as well as its order. And the simulation results of our hybrid system with different controllers PI, FLC and hybrid controller PI-FLC are presented. Finally, the obtained results are discussed.

At the end of this work, a general conclusion is then given as well as some recommendations for the present work for its future development.

Chapter I

Generalities on renewable energy sources

I.1.Introduction

Renewable Energy sources are not depleted and it is distributed over a wide geographical area, these resources are quickly renewed through natural process. It won't create any environmental pollution problems. The main advantage of using renewable resource is its availability throughout the year. By an one time investment we can drew energy for many decades without affecting the environment [2].

Energy storage is the capture of energy produced at one time for use at a later time. Energy comes in multiple forms including radiation, chemical, gravitational potential, electrical potential electricity, elevated temperature, latent heat and kinetic. Energy storage involves converting energy from forms that are difficult to store to more conveniently or economically storable forms. A device that stores energy is generally called an accumulator or battery.

Our objective from this first chapter is to present firstly the different Renewable Energy sources such as solar energy, wind energy and other ones. While the second part is dedicated to the presentation of the energy storage systems namely batteries, fuel cell and supercapacitors.

I.2.Solar Energy

Solar Energy has the greatest potential for providing clean, safe, and reliable power. The solar energy falling on the Earths continents is more than 200 times the total annual commercial energy currently being used by humans [3,2]. The government started solar power adoption with subsidies. A consumer who installs a solar panel array on a house can sell surplus energy to the local utilities. The solar panel cost, reduced to 50%, which would make solar Powered Electricity cost comparable with other types of fuel, is possible within the next decade [4,2]. Solar Energy can be classified as two types 1. Passive solar and 2. Active solar. Passive solar energy is making direct and indirect use of thermal energies from the sun. Indirect use of Energy is possible only in building (or) structures (as shown in Fig. I.1).

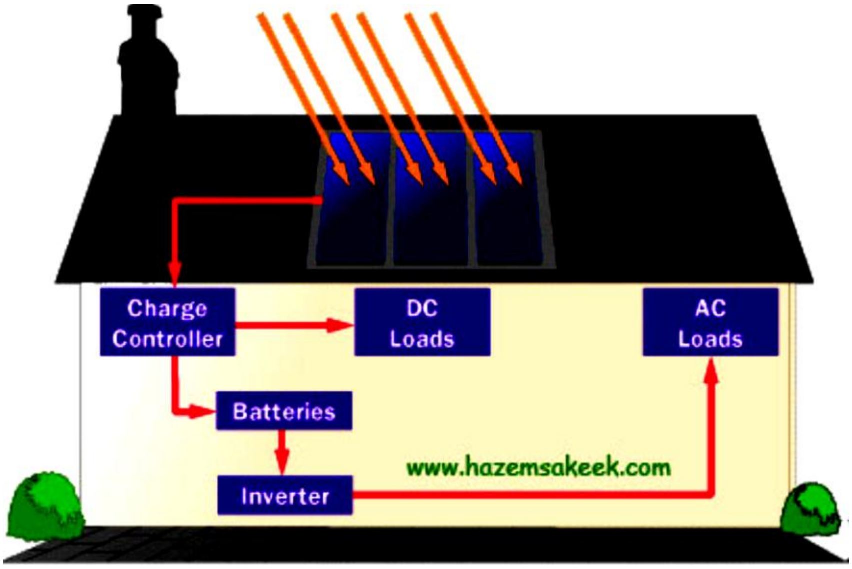


Fig. I.1. Solar energy mechanism at the unıt

A southern exposure of a building guarantees the maximum exposure of the sun's rays. Special metal leaf covering over windows and roofs can block out the sun during the summer months. Special thermal solar collectors can circulate water through the collection unit that collect the sun's thermal energy for the purpose of heating the water for use [5,2].

Active Solar Energy is the use of the sun's Electro magnetic radiation in generating Electrical Energy. Generally semiconductor silicon Boron solar chips are used for this. The problem of these chips one that they have low Efficiency ratio and can only be used in supplying Energy needs of small devices (i.e. calculators, watches, radio etc.)as shown in Fıg. I.2 .

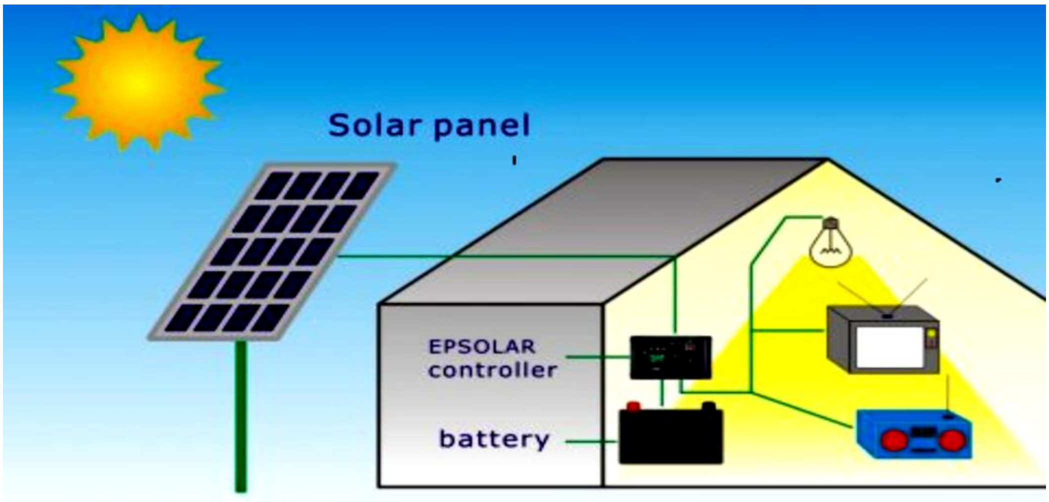


Fig.I.2. Solar energy at small unit

I.3. Photovoltaic

Photovoltaic is a method to convert solar radiation into electricity using semiconductors that exhibit the photovoltaic effect. The first solar cell was constructed by Charles Fritts in 1880.

There are at least fourteen types of photovoltaic cells such as thin film, mono crystalline silicon, polycrystalline silicon and amorphous cells, as well as multiple types of concentrating solar power. Photovoltaic (PV) technologies are based on the use of solar cells aligned and installed into what is called a PV module. These modules are commonly called Solar Panels. The suns radiation hits the semiconductor material within the PV cell and excites electrons resulting in electric power. These electrons are carried through the PV cell to an electrical circuit. Each PV solar cell is protected by a layer of plastic or glass. A collection of solar panels is called an array. Each array is designed to produce a certain voltage and current. Each is then attached to an inverter that converts the Direct Current (DC) of the array to Alternating Current (AC). This new electricity is connected to the electrical power grid enabling our customers to access energy from their utility company when the solar system isn’t supplying all the necessary power to their facility. [6]

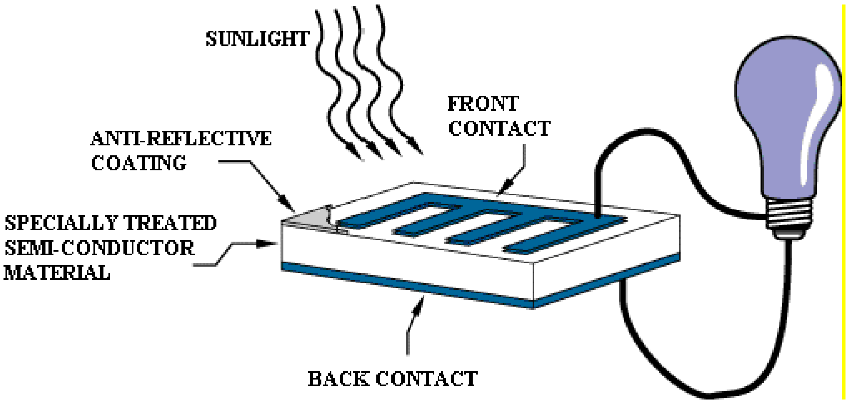


Fig.I.3. Principle of the Photovoltaic conversion.

I.3.1 PV cells

PV cells are devices that convert solar energy to electric energy. They are invented in 1839 by a French physicist, Alexander Edmund Becquerel. However, the first solar cell has been developed with an efficiency of 6% at the late 1940s. The first use of the PV cell was to power a satellite in 1958 and they are still used to power some spacecraft and satellites [7,54].

a) Structure of a solar cell

A typical solar cell is a multi-layered unit consisting as shown in Fig. I.4 of:

- **Cover:** a clear glass or plastic layer that provides outer protection from the elements. Transparent Adhesive - holds the glass to the rest of the solar cell;
- **Anti-reflective Coating**: this substance is designed to prevent the light that strikes the cell from bouncing off so that the maximum energy is absorbed into the cell;
- **Front Contact**: transmits the electric current;
- **Back Contact**: transmits the electric current;
- **N-Type Semiconductor Layer**: is often formed from Silicon and a small amount of Phosphorus. Phosphorus gives the layer an excess of electrons and therefore has a negative character. The n-layer is not a charged layer, it has an equal number of protons and electrons, but some of the electrons are not held tightly to the atoms and are free to move;
- **P-Type Semiconductor Layer**: is formed from Silicon and Boron and gives the layer a positive character because it has a tendency to attract electrons. The p-layer is not a charged layer and it has an equal number of protons and electrons;
- **P-N Junction-** when the two layers are placed together, the free electrons from the n-layer are attracted to the p-layer. At the moment of contact between the two wafers, free electrons from the n-layer flow into the p-layer for a split second, then form a barrier to prevent more electrons from moving from one layer to the other. This contact point and barrier are called the p-n junction [7,54].

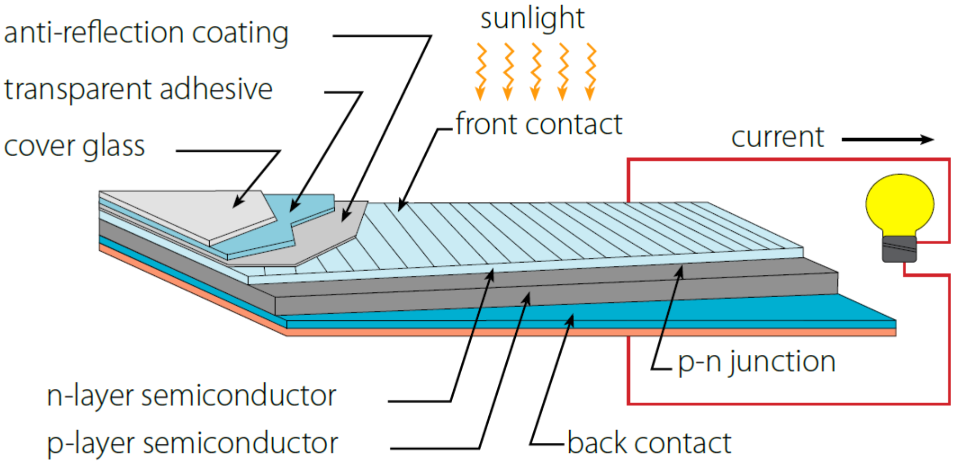


Fig.I.4. Structure of solar cells.

b) Types of solar photovoltaic cells

There are three types of solar cells commonly used. Mono and polycrystalline Silicon solar cells as well as amorphous Silicon. The efficiency of the photovoltaic cell is dependent on the cell structure as expressed in Table I.1.

Material	**Level of efficiency in laboratories %**	**Level of the efficiency in production %**
Monocrystalline silicon	Approx. 24	14 to 17
Polycrystalline silicon	Approx. 18	13 to 15
Amorphous silicon	Approx. 13	5 to 7

Table I.1 Types of solar cells and its efficiency **[8,54].**

Moreover, other solar cells technologies can be found known as Organic cells. A summary of all the types of cells are shown in Fig.I.5.

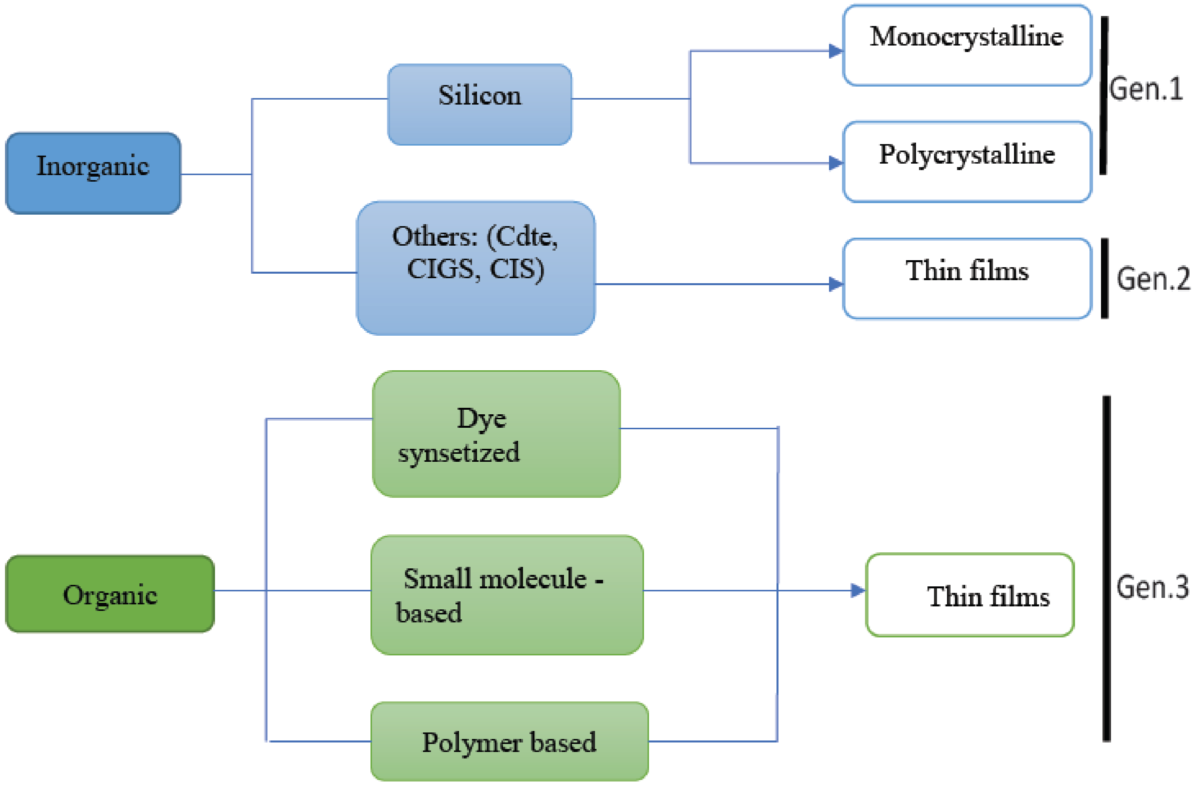


Fig.I.5. Scheme of types of solar photovoltaic cells Generation

I.4.Wind energy

Wind, ultimately driven by atmospheric air, is just another way of collecting Energy. Sun also heats the atmosphere, which produces wind. It works on cloudy days and Rainy season also. The location of wind turbines is a very important factor, which influences the performance of the machine. The windmills are generally located at the top of a tower to heights approximately 30 m. To avoid turbulence from one turbine affecting the wind flow at others it is located at 5-15 times blades diameter. Windmills are working both in horizontal axis and vertical axis. The basic mechanics of the two systems are similar.

Wind passing over the blades is converted in to mechanical power, which is fed through transmission to an electrical generator. Wind turbines will not work in winds below 13 km an hour. They work best where the wind speed averages 22 km an hour. The majority of wind turbines produced at the present time are horizontal axis turbine with three blades, 15-30 m diameter, producing 50-350 Kw of Electricity.

Wind energy produces no air or water pollution, involves no toxic or hazardous substances, and poses no threat to public safety.[2]

Wind turbines are divided into three categories according to their nominal power [9]:

- Small power wind turbines: less than 40 kw;
- Medium power wind turbines: from 40 to few hundred kilowatts;
- High power wind turbines : great than 1MW.

I.4.1.Typs of wind turbines

There are two basic types of wind turbines[10]:

- Horizontal-axis turbines
- Vertical-axis turbines

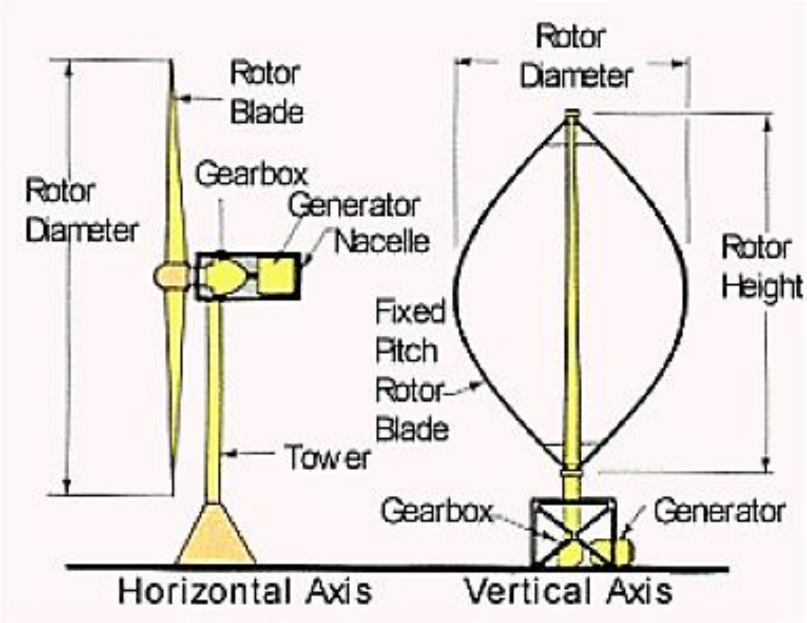


Fig.I.6. Wind turbine configurations

The size of wind turbines varies widely. The length of the blades is the biggest factor in determining the amount of electricity a wind turbine can generate. Small wind turbines that can power a single home may have an electricity generating capacity of 10 kilowatts (kW). The largest wind turbines in operation have electricity generating capacities of up to 10,000 kW, and larger turbines are in development. Large turbines are often grouped together to create wind power plants, or wind farms, that provide power to electricity grids.

a) Horizontal-axis turbines are similar to propeller airplane engines

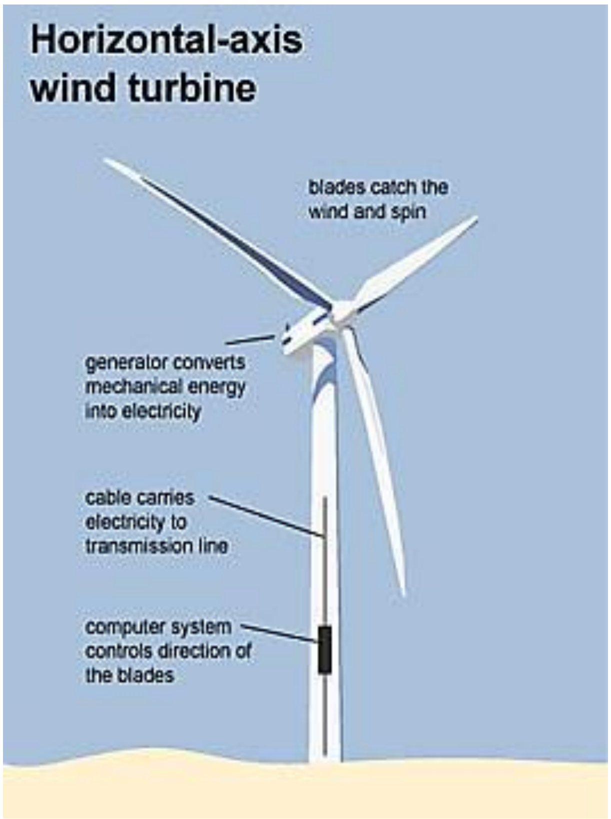


Fig.I.7. Horizontal-axis wind turbines

Horizontal-axis turbines have blades like airplane propellers, and they commonly have three blades. The largest horizontal-axis turbines are as tall as 20-story buildings and have blades more than 100 feet long. Taller turbines with longer blades generate more electricity. Nearly all of the wind turbines currently in use are horizontal-axis turbines.

b) Vertical-axis turbines look like egg beaters

Vertical-axis turbines have blades that are attached to the top and the bottom of a vertical rotor. The most common type of vertical-axis turbine—the Darrieus wind turbine, named after the French engineer Georges Darrieus who patented the design in 1931—looks like a giant, two-bladed egg beater. Some versions of the vertical-axis turbine are 100 feet tall and 50 feet wide. Very few vertical-axis wind turbines are in use today because they do not perform as well as horizontal-axis turbines.

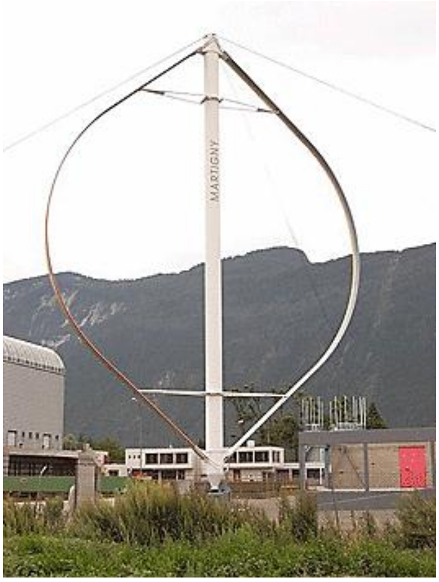


Fig.I.8. Darrieus vertical-axis wind turbine in Martigny, Switzerland

c) Wind power plants (or wind farms)

Wind power plants, or wind farms, are clusters of wind turbines that produce large amounts of electricity. A wind farm usually has many turbines scattered over a large area. One of the world's largest wind farms, the Horse Hollow Wind Energy Center in Texas, has about 430 wind turbines spread over about 47,000 acres. The project has a combined electricity generating capacity of about 735 megawatts (or 735,000 kW). [10]

Fig. I.9. Horizontal-axis wind turbines on a wind farm

There are many forms of other renewables energies. Other renewable energies that do not depend on sunlight are geothermal energy, which is a result of radioactive decay in the crust combined with the original heat of accreting the Earth, and tidal energy, which is a conversion of gravitational energy.

Hydroelectric energy

This form uses the gravitational potential of elevated water that was lifted from the oceans by sunlight. It is not strictly speaking renewable since all reservoirs eventually fill up and require very expensive excavation to become useful again. At this time, most of the available locations for hydroelectric dams are already used in the developed world.

Biomass is the term for energy from plants. Energy in this form is very commonly used throughout the world. Unfortunately the most popular is the burning of trees for cooking and warmth. This process releases copious amounts of carbon dioxide gases into the atmosphere and is a major contributor to unhealthy air in many areas. Some of the more modern forms of biomass energy are methane generation and production of alcohol for automobile fuel and fueling electric power plants. [18]

Geothermal power

Energy left over from the original accretion of the planet and augmented by heat from radioactive decay seeps out slowly everywhere, every day. In certain areas the geothermal gradient (increase in temperature with depth) is high enough to exploit to generate electricity. This possibility is limited to a few locations on Earth and many technical problems exist that limit its utility. Another form of geothermal energy is Earth energy, a result of the heat storage in the Earth's surface. Soil everywhere tends to stay at a relatively constant temperature, the yearly average, and can be used with heat pumps to heat a building in winter and cool a building in summer. This form of energy can lessen the need for other power to maintain comfortable temperatures in buildings, but cannot be used to produce electricity. [18]

I.5. Energy Storage Systems (ESS)

Unfortunately, PV systems and wind ones are limited by the climatic conditions as the sun and wind. This handicaps their electricity production during some periods as night, when there is no wind and other conditions. For this reason it is needed to include Energy Storage Systems to ensure the service continuity during these critical periods. Fuel cells, batteries and supercapacitors are the candidate to check this role.

I.5.1Fuel Cell

A fuel cell is like a battery in that it generates electricity from an electrochemical reaction. Both batteries and fuel cells convert chemical energy into electrical energy and also, as a by-product of this process, into heat. However, a battery holds a closed store of energy within it and once this is depleted the battery must be discarded, or recharged by using an external supply of electricity to drive the electrochemical reaction in the reverse direction.

A fuel cell, on the other hand, uses an external supply of chemical energy and can run indefinitely, as long as it is supplied with a source of hydrogen and a source of oxygen (usually air). The source of hydrogen is generally referred to as the fuel and this gives the fuel cell its name, although there is no combustion involved. Oxidation of the hydrogen instead takes place electrochemically in a very efficient way. During oxidation, hydrogen atoms react with oxygen atoms to form water; in the process electrons are released and flow through an external circuit as an electric current.

Fuel cells can vary from tiny devices producing only a few watts of electricity, right up to large power plants producing megawatts. All fuel cells are based around a central design using two electrodes separated by a solid or liquid electrolyte that carries electrically charged particles between them. A catalyst is often used to speed up the reactions at the electrodes. Fuel cell types are generally classified according to the nature of the electrolyte they use. Each type requires particular materials and fuels and is suitable for different applications[11].

I.5.1.1.History

The developments leading to an operational fuel cell can be traced back to the early 1800’s with Sir William Grove recognized as the discoverer in 1839. Throughout the remainder of the century, scientists attempted to develop fuel cells using various fuels and electrolytes. Further work in the first half of the 20th century served as the foundation for systems eventually used in the Gemini and Apollo space flights. How-ever, it was not until 1959 that Francis T. Bacon success-fully demonstrated the first fully operational fuel cell. Proton exchange membrane fuel cells were first used by NASA in the 1960’s as part of the Gemini space program, and were used on seven missions. Those fuel cells used pure oxygen and hydrogen as the reactant gases and were small-scale, expensive and not commercially viable. NASA’s inter-est pushed further development, as did the energy crisis in 1973. Since then, fuel cell research has continued unabated and fuel cells have been used successfully in a wide variety of applications[12].

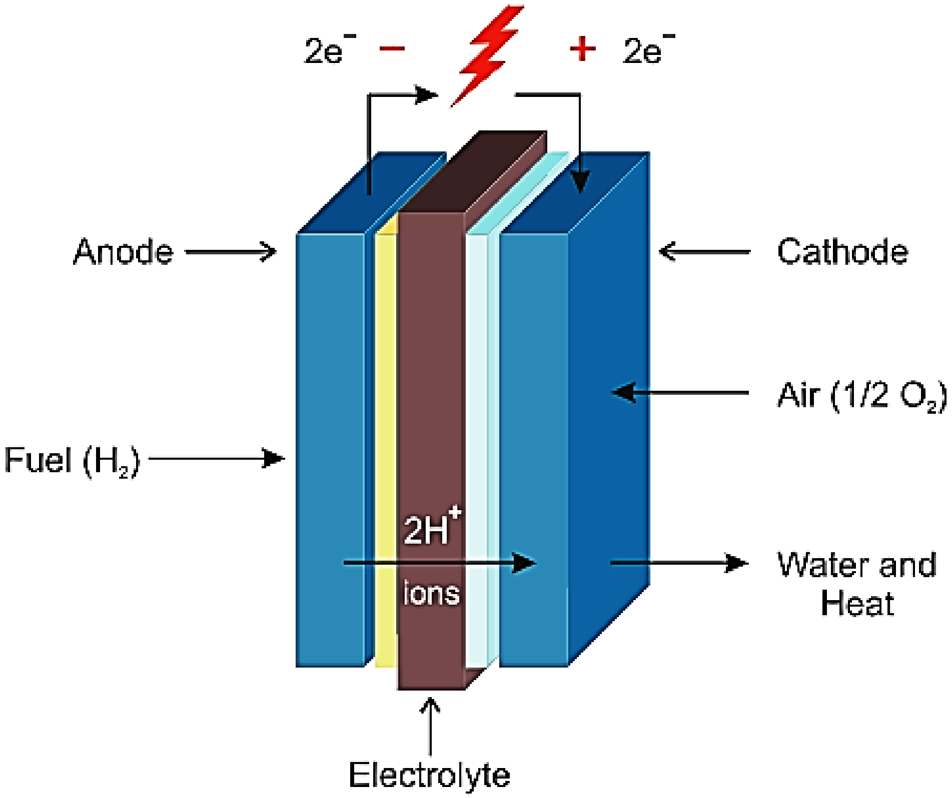


Fig.I.10. Generic Hydrogen Fuel Cell Operation

I.5.1.2.Applications

- *Stationary Power-plants*: Stationary power-plant applications have been demonstrated in a number of pilot projects using a variety of fuel cell technologies over the past decades. The largest power-plant to date is the Ballard Generation Systems 250 kW natural gas fueled proton exchange membrane fuel cell power-plant currently operating at a number of sites worldwide. Although 250 kW is a small amount of power compared to convention-ally powered generating stations, it is adequate to service isolated neighborhoods or to provide emergency backup power to critical facilities, such as hospitals. Stationary power-plants are obvious candidates for operation using conventional fuels, such as natural gas, which can be piped to the power plant and reformed on site. Overall size and warmup time are less critical issues than in smaller, mobile applications. In addition to the high operating efficiency, low emissions and good transient response characteristic of fuel cell systems, stationary applications also pro-duce copious amounts of hot water and waste heat that can be used directly in the surrounding community, further in-creasing the overall system effectiveness [12].

- *Submarines* : Fuel cells systems are attractive for military submarine applications due to their low noise and infrared signatures. In many ways, fuel cells are a logical replacement for the banks of batteries currently used to power many submarines. As with stationary power plants, hot product water can be used for on-board domestic purposes. Prototype systems using pure reactants and on-board reformers have been demonstrated in recent years [12].

- *Buses*: Buses are the most commercially advanced of all fuel cell applications to date. Successful demonstration programs have been carried out by XCELLSiS Fuel Cell Engines, Inc., with the introduction of three buses each in Vancouver, BC and Chicago, IL into revenue service for a period of two years, and a year-long field trial program in Palm Springs, CA. In the near future, additional buses will enter service throughout Europe and in other areas of the world. All of these buses use pure hydrogen stored as a high-pressure gas; other demonstration vehicles have used liquid fuels and incorporate on-board reformer systems. Buses are a logical starting point for the introduction of fuel cell technology into the transportation sector for several rea-sons: they offer a reasonably large platform for system com-ponents and fuel storage, they can be fueled at a central fueling station, and they are regularly maintained by trained personnel [12].

- *Cars* : Cars represent the ultimate market for fuel cell manufacturers due to the quantities involved worldwide. While cars pro-vide the major stimulus for fuel cell development, as they are a major contributor to air pollution, they also pose some of the greatest challenges to commercialization. These challenges include their relatively small size, the vast fueling infrastructure required, and the inconsistent maintenance habits of the public at large. In addition, performance and reliability expectations are high, while cost expectations are low. Many major car companies are engaged in automotive fuel cell programs including Daimler-Chrysler, Ford, General Motors, Nissan, Mazda, Subaru, Toyota, Honda and Hyundai. Some of these companies have built prototype vehicles using fuel cells with or without auxiliary batteries, and fu-eled using either pure (gaseous or liquid) hydrogen or refor-mate. Lack of an existing hydrogen infrastructure is a serious de-terrent to automotive fuel cell use. To this end, many current prototypes use an on-board reformer with methanol as the preferred fuel, although gasoline systems are also under investigation. Although this alleviates some of the fuel avail-ability and storage problems, it increases the amount of hardware that must be installed in the vehicle (thereby in-creasing cost and complexity), and introduces control and performance problems associated with reformers. Of course, use of a reformer does not completely eliminate harmful emissions, and does little or nothing to reduce dependence on fossil fuels. Some automotive manufacturers have made commitments to introduce fuel cell vehicles to the market in the early years of the first decade of this century. It is likely that these vehicles will make their debut within fleet operations so that fueling and maintenance issues can be minimized [12].

- ***Portable Power Systems***: Portable Power Systems Portable fuel cell systems can potentially be used in many applications that currently rely on batteries. Commercial units that provide up to 1.2 kW (4100 Btuh) of electrical power are now available [12].

I.5.1.3. Principle of Operation

A fuel cell is an energy conversion device that converts the chemical energy of a fuel directly into electricity without any intermediate thermal or mechanical processes. Energy is released whenever a fuel reacts chemically with the oxygen in air. In an internal combustion engine, the reaction occurs combustive and the energy is released in the form of heat, some of which can be used to do useful work by pushing a piston. In a fuel cell, the reaction occurs electrochemically and the energy is released as a combination of low-voltage DC electrical energy and heat. The electrical energy can be used to do useful work directly while the heat is either wasted or used for other purposes. In galvanic (or “voltaic”) cells, electrochemical reactions form the basis in which chemical energy is converted into electrical energy. A fuel cell of any type is a galvanic cell, as is a battery. In contrast, in electrolytic cells, electrical energy is converted into chemical energy, such as in an electrolyzer or electroplater. A basic feature of fuel cells is that the electric current load determines the consumption rate of hydrogen and oxygen. In an actual systems application, a variety of electrical loads may be applied to the fuel cell. [12]

I.5.1.4. Advantages of Fuel Cells

- Fuel cell systems are usually compared to internal combustion engines and batteries and offer unique advantages and disadvantages with respect to them. Fuel cell systems offer the following advantages [12]:

- Fuel cell systems operate without pollution when run on pure hydrogen, the only by-products being pure water and heat. When run on hydrogen-rich reformate gas mixtures, some harmful emissions result although they are less than those emitted by an internal combustion engine using conventional fossil fuels. To be fair, internal combustion engines that combust lean mixtures of hydrogen and air also result in extremely low pollution levels that derive mainly from the incidental burning of lubricating oil.

• Fuel cell systems operate at higher thermodynamic efficiency than heat engines. Heat engines, such as internal combustion engines and turbines, convert chemical energy into heat by way of combustion and use that heat to do useful work. The optimum (or "Carnot") thermodynamic efficiency of a heat engine is known to be:

$$Efficiency_{MAX} = 1 - \frac{T_2}{T_1} \tag{I.1}$$

Where:

- T_1= Absolute temperature of inlet (hot) gas (in °R or K);
- T_2= Absolute temperature of outlet (cold) gas (in °R or K).

This formula indicates that the higher the temperature of the hot gas entering the engine and the lower the temperature of the cold outlet gas after expansion, the higher the thermodynamic efficiency. Thus, in theory, the upper temperature can be raised an arbitrary amount in order to achieve any desired efficiency, since the outlet temperature cannot be lower than ambient. However, in a real heat engine the upper temperature is limited by material considerations. Furthermore, in an internal combustion engine, the inlet temperature is the operating temperature of the engine, which is very much lower than the ignition temperature. Since fuel cells do not use combustion, their efficiency is not linked to their maximum operating temperature. As a result, the efficiency of the power conversion step (the ac-tual electrochemical reaction as opposed to the actual combustion reaction) can be significantly higher. The electrochemical reaction efficiency is not the same as overall system efficiency as discussed in Section 4.1.2. The efficiency characteristics of fuel cells compared with other electric power generating systems are shown in Figure I.11.

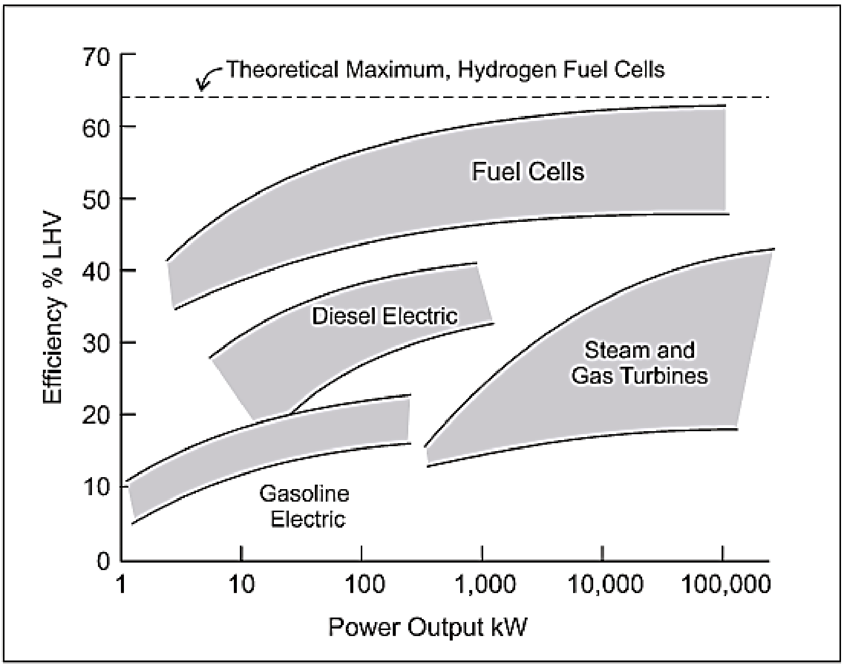


Fig.I.11. Power Generating Systems Efficiency Comparison

- In addition to having higher specific thermal efficiency than heat engines, fuel cells also exhibit higher part-load efficiency and do not display a sharp drop in efficiency as the powerplant size decreases. Heat engines operate with highest efficiency when run at their design speed and ex-hibit a rapid decrease in efficiency at part load. Fuel cells, like batteries, exhibit higher efficiency at part load than at full load and with less variation over the en-tire operating range. Fuel cells are modular in construction with consistent efficiency regardless of size. Reform-ers, however, perform less efficiently at part load so that overall system efficiency suffers when used in conjunction with fuel cells.

- Fuel cells exhibit good load-following characteristics. Fuel cells, like batteries, are solid state devices that react chemically and instantly to changes in load. Fuel cell systems, however, are comprised of predominantly mechanical devices each of which has its own response time to changes in load demand. Nonetheless, fuel cell systems that operate on pure hydrogen tend to have excellent overall response. Fuel cell systems that operate on reformate using an on-board reformer; however, can be sluggish, particularly if steam reforming techniques are used.

- When used as an electrical energy generating device, fuel cells require fewer energy transformations than those associated with a heat engine. When used as a mechanical energy generating device, fuel cells require an equal number of conversions, although the specific transformations are different. Every energy transformation has an associate energy loss so that the fewer transformations there are, the better the efficiency. Thus fuel cells are more ideally suited to applications that require electrical energy as the end product, rather than mechanical energy. Comparative energy transformations for fuel cells, batteries and heat engines are shown in Figure I.12.

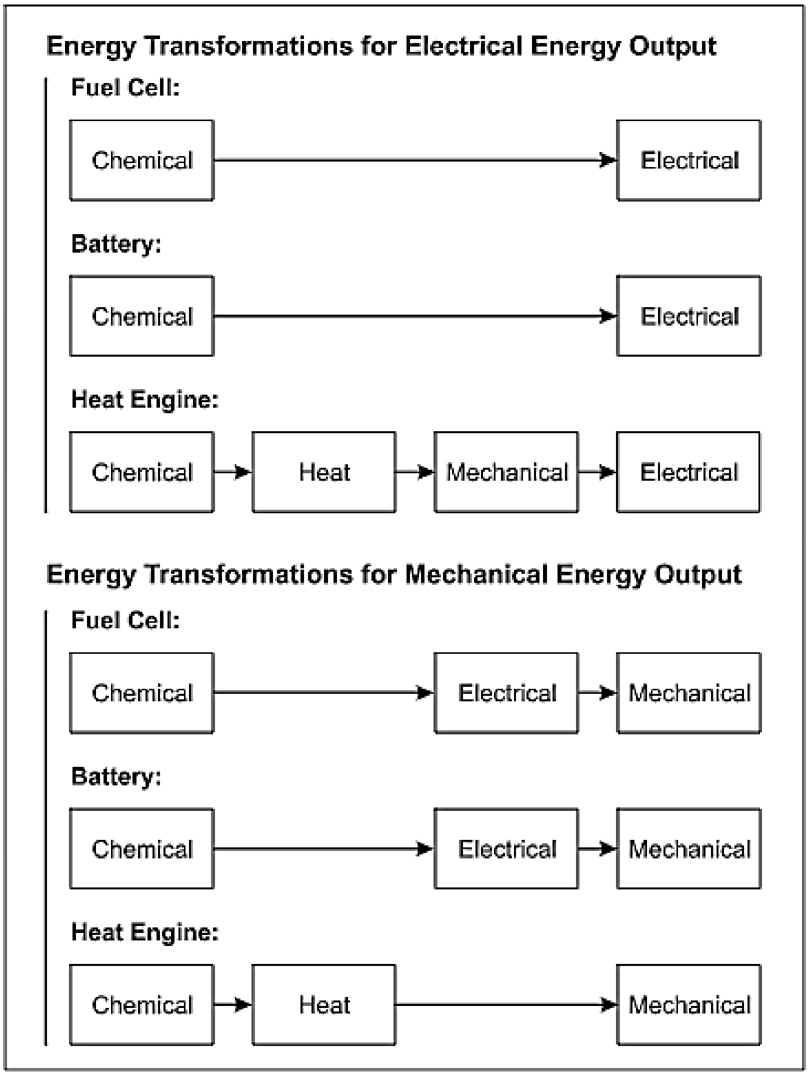


Fig. I.12. Comparative Energy Transformations

• Fuel cell systems suitable for automotive applications operate at low temperatures (typically less than 212 ºF/100 ºC). This is an advantage in that the fuel cells re-quire little warm-up time, high temperature hazards are reduced, and the thermodynamic efficiency of the electro-chemical reaction is inherently better. This is a disadvantage in that medium-grade waste heat is harder to expel (especially in hot climates) so that cooling systems must be larger, and the electrochemical reaction proceeds more slowly than at high temperatures. Reformers used in con-junction with fuel cells operate at high temperatures and therefore may require prolonged warm-up periods.

- Fuel cell systems can be used in co-generation applications. In addition to electrical power, fuel cells generate pure hot water and medium-grade heat, both of which can potentially be used in association with domestic or industrial applications. When this is done, the overall efficiency of the combined systems increases.
- Fuel cell systems do not require tuning.
- Fuel cell systems do not require recharging. Rather, fuel cell systems must be re-fueled, which is faster than charging a battery and can provide greater range depend-ing on the size of the storage tank.

I.5.1.5 Disadvantages of Fuel Cells

Fuel cell systems suffer from the following disadvantages [12]:

- Ironically, hydrogen which is of such benefit environmentally when used in a fuel cell, is also its greatest liability in that it is difficult to manufacture and store. Current manufacturing processes are expensive and energy intensive, and often derive ultimately from fossil fuels. An effective hydrogen infrastructure has yet to be established. Gaseous hydrogen storage systems are large and heavy to accommodate the low volumetric energy density of hydrogen. Liquid hydrogen storage systems are much smaller and lighter, but must operate at cryogenic temperatures. Alternatively, if hydrogen is stored as a hydro-carbon or alcohol and released on demand by way of an on-board reformer, the storage and handling issues simplify, but some of the environmental benefits are lost.
- Fuel cells require relatively pure fuel, free of specific contaminants. These contaminants include sulfur and car-bon compounds, and residual liquid fuels (depending on the type of fuel cell) that can deactivate the fuel cell catalyst effectively destroying its ability to operate. None of these contaminants inhibit combustion in an internal combustion engine.
- Fuel cells suitable for automotive applications typically require the use of a platinum catalyst to promote the power generation reaction. Platinum is a rare metal and is very expensive.
- Fuel cells must not freeze with water inside. Fuel cells generate pure water during the power generating reaction and most fuel cells suitable for automotive applications use wet reactant gases. Any residual water within the fuel cells can cause irreversible expansion damage if permitted to freeze. During operation, fuel cell systems generate sufficient heat to prevent freezing over normal ambient temperatures, but when shut down in cold weather the fuel cells must be kept warm or the residual water must be removed before freezing. This normally en-tails bringing the vehicle into a heated facility or the use of a localized hot air heating device.

• Fuel cells that use proton exchange membranes must not dry out during use and must remain moist during storage. Attempts to start or operate these fuel cells under dry conditions can lead to membrane damage.

• Fuel cells require complex support and control systems. Fuel cells themselves are solid state devices, but the systems required to support fuel cell operation are not. Of particular note is the requirement for compressed air; this necessitates a high-speed compressor that imposes a large parasitic load on the overall system. System complexity increases significantly when the fuel cells are operated in conjunction with an on-board reformer.

• Fuel cell systems are heavy. Fuel cells themselves are not excessively heavy, but the combined weight of the fuel cells, their support systems and their fuel storage is presently greater than for a comparable internal combustion engine system. Systems that include an on-board re-former are heavier still. Fuel cell systems are generally lighter than comparable battery systems even though the battery systems require less support equipment. System weight will likely continue to decrease as the technology develops. Despite their weight, existing fuel cell prototype vehicles have shown that systems can be made sufficiently compact for automotive use.

• Fuel cells are an emerging technology. As with any new technology, reductions in cost, weight and size concurrent with increases in reliability and lifetime remain primary engineering goals.

I.5.1.6. Fuel cell types

There are several types of fuel cell systems as:

a) FC TYPS PEMFC – Proton Exchange Membrane Fuel

b) Direct Methanol Fuel Cells – DMFC
c) PAFC – Phosphoric Acid Fuel Cells
d) Alkaline Fuel Cells – AFC
e) SOFC – Solid Oxide Fuel Cells
f) Molten Carbonate Fuel Cells – MCFC,

In this chapter, we are going to use FC TYPS PEMFC – Proton Exchange Membrane Fue, which features of :

- Electrolyte: water-based, acidic polymer membrane
- Also called polymer electrolyte membrane fuel cells
- Use a platinum-based catalyst on both electrodes

- Generally hydrogen fuelled
- Operate at relatively low temperatures (below 100°C)
- High-temperature variants use a mineral acid-based electrolyte and can operate up to 200°C.
- Electrical output can be varied, ideal for vehicles [11]

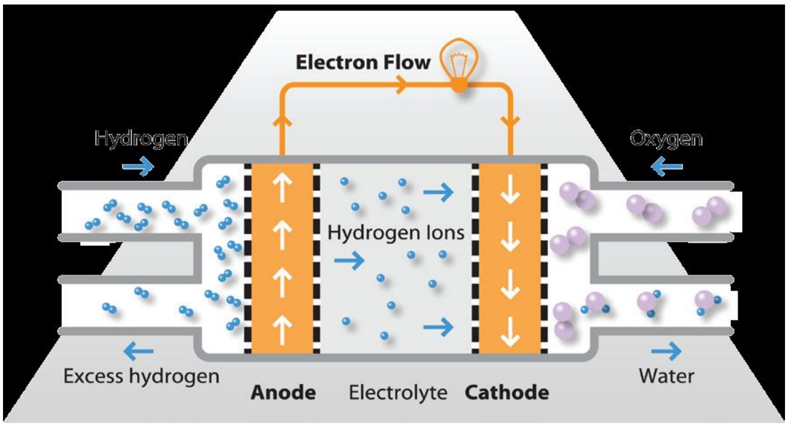


Fig.I.13. PEMFC – Proton Exchange Membrane Fuel Cells

I.5.2. Battery

The mode of storage of electrical energy privileged currently in our everyday life remains the accumulator. Whether mobile phones or cars, batteries are very widespread. The technology is based on the chemical concept of battery: accumulates chemical energy. Basically, the basic element of a battery is consisting of two electrodes, playing the roles of anode and cathode, as well as an electrolyte, in contact with the electrodes, allowing the circulation of the ions, and thus the creation of a current [14,15,55]. Among the many sectors currently developed [14,55]:

- Lead-acid batteries (shown below in Fig.I.14) , commonly used to power installations unable to withstand power cuts (photovoltaic system or hybrids of isolated sites).

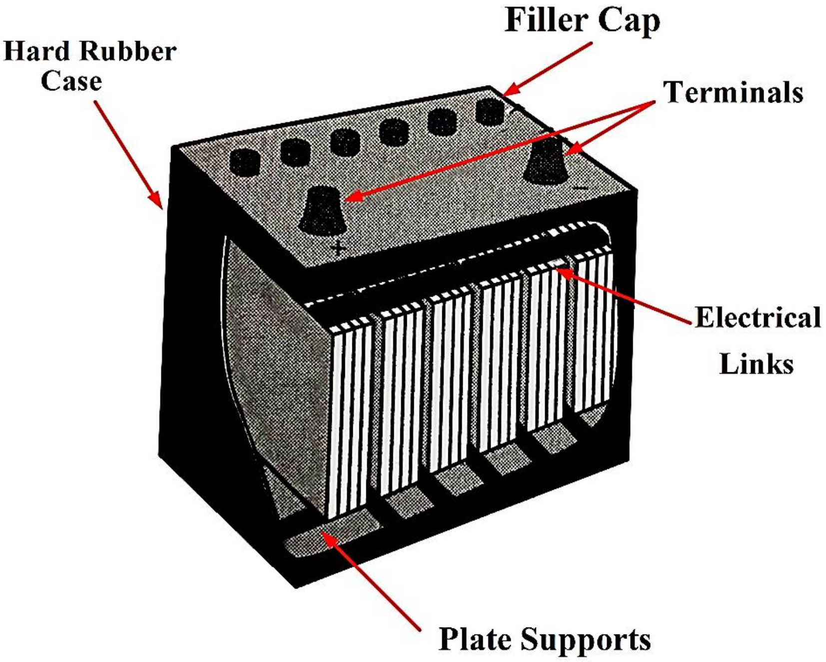


Fig.I.14. Lead-acid battery

- Nickel-cadmium batteries, widely used on all vehicles electric. However, the main flaw of this sector lies in the use of Cadmium, which is a heavy metal.

Fig.I.15. Nickel-cadmium batteries in car uses

- All channels derived from lithium batteries: lithium-ion, lithium polymers, lithium-metal polymers ... etc. this type of technology is widely used in several applications as electric vehicles, mobiles, and this is thanks to their high power density.

I.5.3.Supercapacitor

The basic principle of a supercapacitor is the following: an electrolyte (conductive purely ionic, electronic insulator) is placed between two electrodes conductive to very large surface area that is to say with a very large contact area between the electrode and the electrolyte. When an electric field is applied between the electrodes, positive and negative ions are move in the electrolyte and form on the surface of each electrode a layer of charges called double layer (see figure I.16). As this surface is very large, the amount of accumulated charges is much greater than in the case of capacitors classics. The stored energy density is also between 1 and 10 kWh / m^3 against 0.1 to 1 kWh / m3 for capacitors or ultra-capacitors [16,55]. Since there is no chemical reaction on the surface of the electrodes, longevity (or cycling) is much more high (100,000 to 500,000 charge / discharge cycles) for the electrochemical route studied previously (300 to 1500 cycles). However, to obtain systems exploitable, it is necessary to put in series a large number of cells to arrive at a voltage of high storage [13,17,55]. Figure I.16 showing the charge distribution in an electric double-layer capacitor when it is charged (left) and discharged (right).

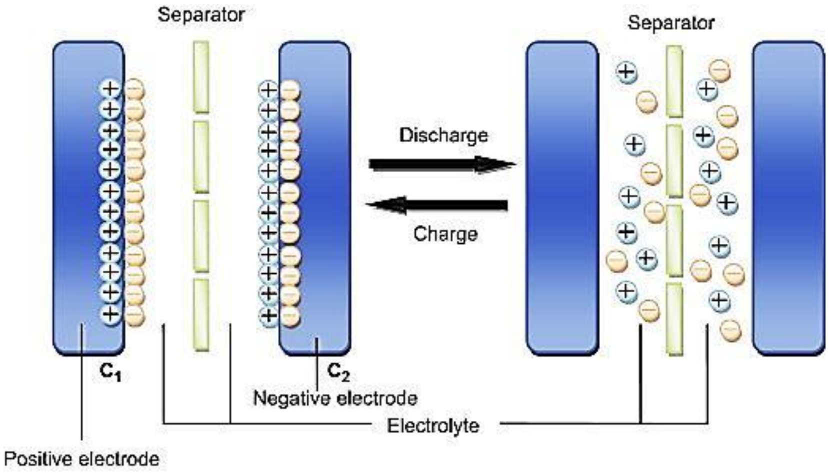


Fig.I.16. Principal of supercapacitor

I.5.4.Flywheel

Flywheels have historically been used in public transport. Their operating principle is as follows: a rotating disk or cylinder is accelerated by an electric motor / generator, when it is desired to store electrical energy and braked by the same engine / generator (operating in this case as a generator), when one wants to recover the stored energy. The friction must be limited as much as possible. The steering wheel is placed in a vacuum chamber and on magnetic suspension bearings.

The system life is almost unlimited (> 10,000 cycles). The absence of lubricant allows also working in quite wide temperature and pressure ranges [13,55].(see figure I.17)

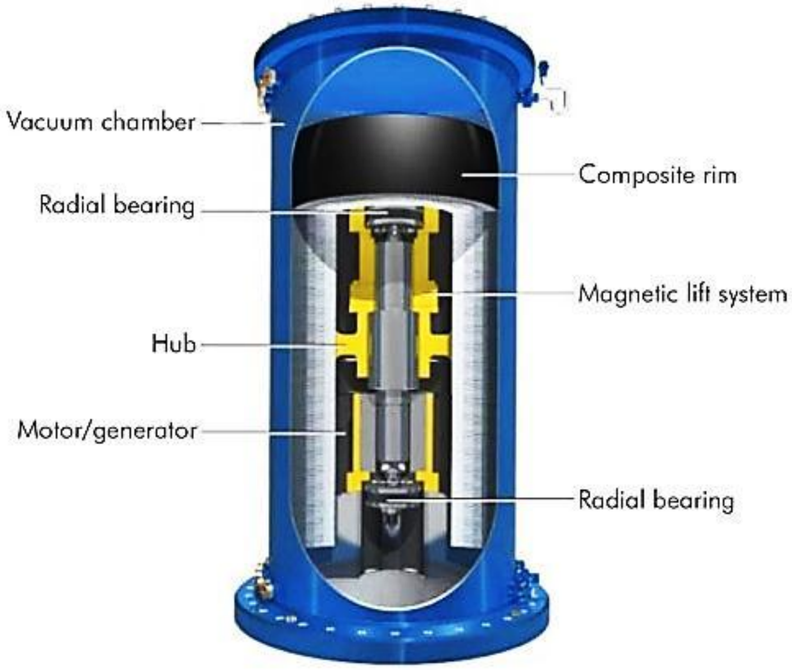


Fig.I.17.flywheele components

1.6 Conclusion

This chapter is dedicated to describe and present the renewable sources namely solar energy and wind energy. It is clear that photovoltaic cells can convert the solar free energy in electric form which can be used to supply electric loads. Furthermore, we have cited that wind farms can use the wind energy via the turbines and electric generator to produce electricity.

These two categories of renewable energy sources are limited by the climatic conditions which can affect the electricity production. For this reason, we have presented the energy storage systems as a solution to complement the renewable source systems. Fuel cells, batteries and supercapacitors or flywheel can be used as an energy storage system.

The next chapter is devoted to study the use of solar energy and a battery as an Energy Storage System for a stand-alone application.

Chapter II

Modeling and simulation of PV-Battery hybrid system

II.1 Introduction

The objective of this chapter is to present firstly the photovoltaic generator (PVG) and the electrochemical batteries as well as their association to compose a hybrid system. The first part is devoted to the photovoltaic system; we will present the modeling of the photovoltaic panel and then presenting the mathematical models. Also, we will then show the influence of the temperature and the illumination on the efficiency of the PVG by numerical simulations.

The second part will be dedicated to the modeling and simulation of the lead-acid battery used as an energy storage system. The important part of this chapter is dedicated to the study of the PVG-battery connection through the DC bus with a DC load and power electronics converters.

II.2.Constitution of a photovoltaic generator

A photovoltaic panel or photovoltaic module is obtained from the association of parallel and / or series of several PV cells as shown in Fig.II.1 below. There are in the market standardized PV modules, we can find 50W power modules, 150W or 200W [19].

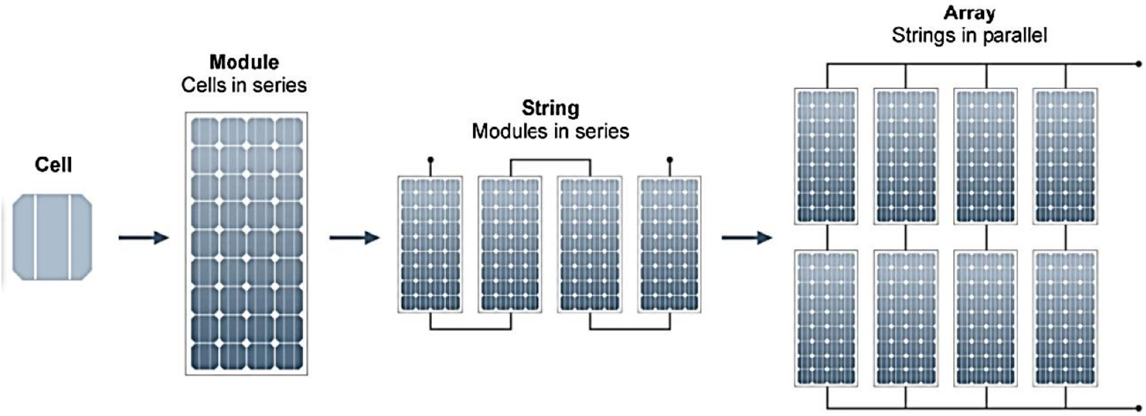


Fig.II.1. Photovoltaic cells, modules, strings and arrays. [50]

The expressions of the current delivered by the PV module and the voltage at its bounds are given by the following equations[19]:

With:

$$\begin{cases} I_{module} = N_p * I_{cell} \\ I_{cc\ module} = N_p * I_{cc\ cell} \\ V_{module} = N_s * V_{cell} \\ V_{co\ module} = N_s * V_{co\ cell} \end{cases} \qquad (II.1)$$

N_s: Number of cells connected in series;

N_p: Number of cells connected in parallel;

I_{cc} : current of short circuit (court-circuit);

V_{co} : voltage of open circuit.

In order to increase the operating voltage, the PV cells are connected in series. The fragility of cells to breakage and corrosion requires protection towards their environment and they are usually encapsulated under glass, the whole is called a photovoltaic module.

The modules can also be connected in series and in parallel to build a PhotoVoltaic Generator (PVG) to increase the voltage and the intensity of use. However, it is important to take some precautions because the existence of less efficient cells or the occlusion of one or more cells (due to shading phenomena, dust, ...) can damage the cells permanently[20,28].

- Association (series and parallel)

This type of association is generally used to derive a significant voltage since the series association of the photocells delivers a voltage equal to the sum of the individual voltages and a current equal to that of a single cell. The characteristic of a grouping of two solar modules can be generalized over a range of Ns solar modules in series. This kind of grouping increases the current.

In order to obtain powers of a few kW, under a suitable voltage, it is necessary to associate the modules in panels and to mount the panels in rows of series and parallel panels to form what is called a photovoltaic generator [21,28].

II.3.Conventional PVG protections

To ensure a long service life of a photovoltaic system intended to produce electrical energy over years, electrical protections must be added to the commercial modules in order to avoid destructive failures related to the association of cells in series and of panels in parallel. For this, two types of conventional protections are used in current installations:

- The anti-return diode preventing a negative current in the PVGs. This phenomenon can occur when multiple modules are connected in parallel, or when a direct connection load can switch from the receiver mode to the generator mode, for example a battery during the night.
- The bypass diodes can isolate a sub-network of cells when the illumination is not homogeneous thus avoiding the appearance of hot spots and the destruction of poorly lit cells. The conduction of these diodes affects the output characteristic of the generator [22,28], the loss of a part of the energy production and the presence of two maximum powers.

II.4. PVG-Load direct connection

Currently, there are still many applications where a direct connection between a PVG and a charge is performed. This choice is mainly related to the simplicity of the operation and the very high degree of reliability, due basically to the absence of electronics, not to mention a low cost. Figure II.3 shows this case. If this load was a battery, when the module is not lit, it could function as a receiver, the battery could therefore be discharged on the PV generator and in addition irreversibly damage it. Thus, to avoid this situation, the connection must be ensured by means of a non-return diode placed between the PVG and the load. The disadvantage of this configuration is that it offers no type of limitation and / or adjustment of the battery voltage. The transfer of available power at the terminals of the PVG to the load is also not guaranteed [23,24,19].

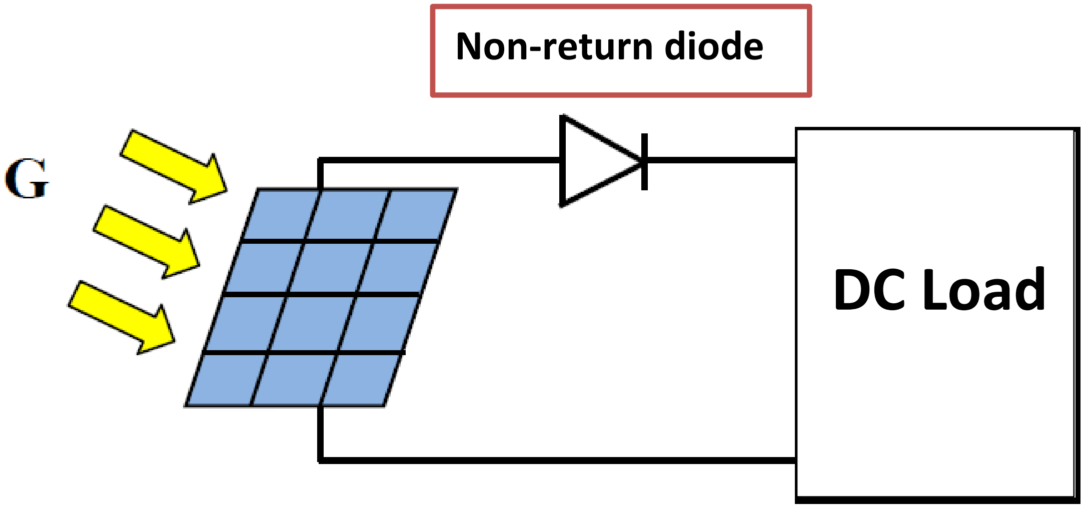


Fig.II.2. Direct PVG-load connection via a non-return diode.

II.5.Definition of the adaptation stage between a PVG and a load

PVG has nonlinear I (V) characteristics with MPPs. These characteristics depend among other things on the level of illumination and the temperature of the cell. In addition, depending on the characteristics of the load on which the PVG is discharging, we can find a very large gap between the potential power of the generator and that actually transferred to the load in direct connect mode.

In order to extract at each moment the maximum power available at the terminals of the GPV and transfer it to the load, the technique used conventionally is to use a floor between the GPV and the load as described in Figure II.4 This floor plays the role interface between the two elements by ensuring through a control action, the transfer of the maximum power supplied by the generator so that it is as close as possible to P_{MAX} available [19,25,26].

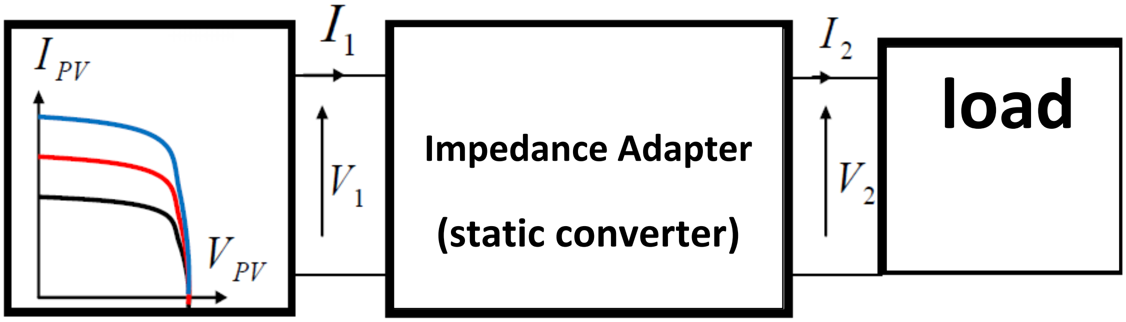


Fig.II.3. Connecting of a PVG to a load through a power converter. [28]

The electronic photovoltaic module (EPVM) is a single (PVG) and an adaptation stage with function (MPPT) which provides the functions of search (MPP) and protection of the whole. Figure (II.4) shows the distribution of functions required for (EPVM). We plan during implementation that the adaptation stage and the control (MPPT) are glued to the back of the module in the box provided for the connections of the (PVG) [23,28].

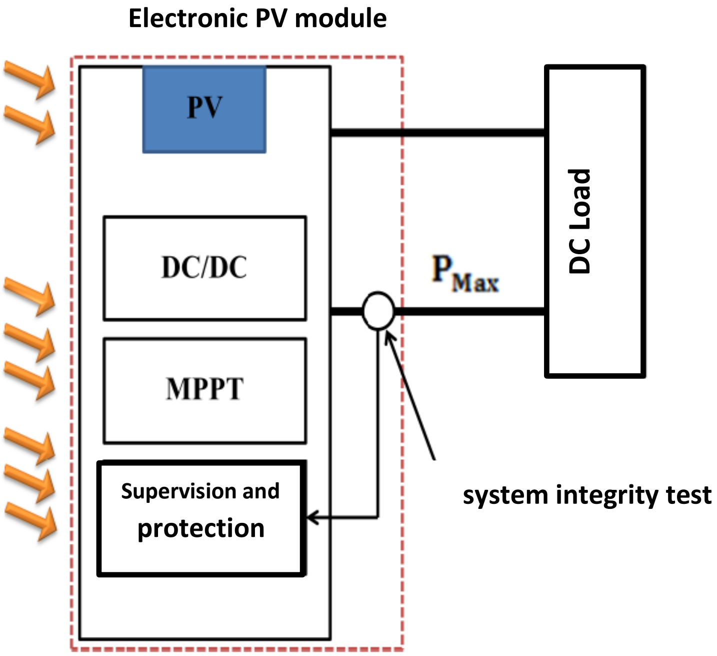


Fig.II.4. Schematic diagram of an EPVM.

The ultimate goal of the EPVM design is the reduction of the kWh price by increasing the energy transmitted from the PVG to the load compared to a conventional connection. An EPVM could also be defined as a source of PV energy that runs continuously at its PPM.[28]

II.6. Modeling of the PV Cell

The mathematical model for the current-voltage characteristic of a PV cell is described as follows :

II.6.1. Ideal PV cell (Simple model)

A photovoltaic cell can be described in a simple way as an ideal source of current that produces a current Icc proportional to the incident light power, in parallel with a diode that corresponds to the transition area (P-N) of the cell (PV). If a resistive load is connected to the terminals of the photovoltaic generator, the latter generates a part of the current I and the rest, the current ID, in the diode. We then have the relationship [19.40] :

$$I = I_{cc} - I_D \tag{II.2}$$

For an ideal PV generator, the voltage across the resistor is equal to that across the diode:

$$V = V_D \tag{II.3}$$

The equivalent electrical circuit is shown in Figure (II.8) [19]

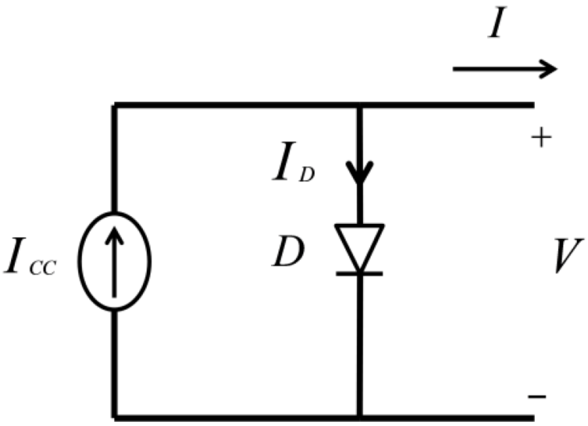


Fig.II.5. Equivalent circuit of an ideal cell.

Since the diode is a nonlinear element, its characteristic (I-V) is given by the relation:

$$I_D = I_S(\exp\left(\frac{qV_D}{KT}\right) - 1) \tag{II.4}$$

With :

- I_S : Saturation current;
- q: Charge of the electron;
- V_D: Voltage of the diode;
- K : Boltzmann constant;
- T: Effective temperature of the cell.

By replacing equation (II.4) in equation (II.2), the load current is giving by:

$$I = I_{CC} - I_D = I_{CC} - I_S(\exp\left(\frac{qV_D}{KT}\right) - 1) \qquad \textit{(II.5)}$$

This model remains theoretical and does not account for the behavior of a photovoltaic cell under real conditions. However, it remains valid under certain assumptions (not taking into account loss of voltage, leakage current ...). There are other models, certainly theoretical, but which more accurately reflect the behavior of a real photovoltaic cell.

II.6.2. Real PV cell

The previous photovoltaic model did not take into account the phenomena present during the conversion of light energy. Indeed, in the real case, there is a loss of voltage output as well as leakage currents. This voltage loss is modeled by a series resistance RS and the leakage currents by a parallel resistance Rp The equivalent electrical circuit is shown in Figure (II.6)

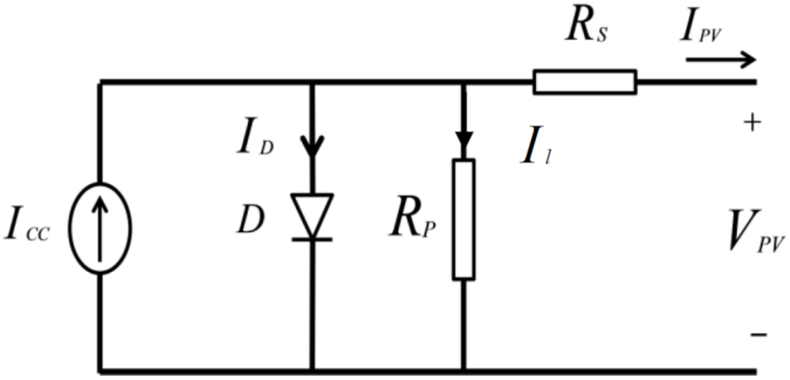


Fig.II.6. Equivalent circuit of an Real cell.

So, the current-voltage relationship of the cell (PV) is given by:

$$I_{pv} = I_{cc} - I_D - I_l = I_{cc} - I_S(\exp q\left(\frac{V_{pv}+R_S I}{R_P}\right) - 1) - \frac{V_{pv}+R_S I_{PV}}{R_P} \qquad \textit{(II.6)}$$

So, we get an implicit equation in I and V that can be solved through a numerical method (the method of Newton-Raphson for example).

II.7.Modeling of a photovoltaic module

The solar panel module bp_sx150s is chosen as the simulation model in this study. It provides photovoltaic power for DC loads characterized by moderate energy requirements. With 72 multi-crystalline cells series-mounted, they effectively charge batteries in virtually any environment. The typical commercial applications of this module, with a maximum power rating of 150 W [19,29]. Table (II.1) summarizes its typical electrical characteristics:

Max power (Pmax)	150W
Voltage at Pmax (Vpmax)	34.5V
Current at Pmax (Ipmax)	4.3 A
Short circuit current (Icc)	4.45 A
Open circuit voltage (Vco)	43.5 V

Table.II.1. Electrical characteristics of the solar panels module.

The electric model shown in Figure (II.7) is also used [27], it includes a current source Icc, a diode D with its ideality coefficient n, and a series resistance RS. The effect of the parallel resistor Rl is very small in a module of 72 cells connected in series, so the model does not include it.

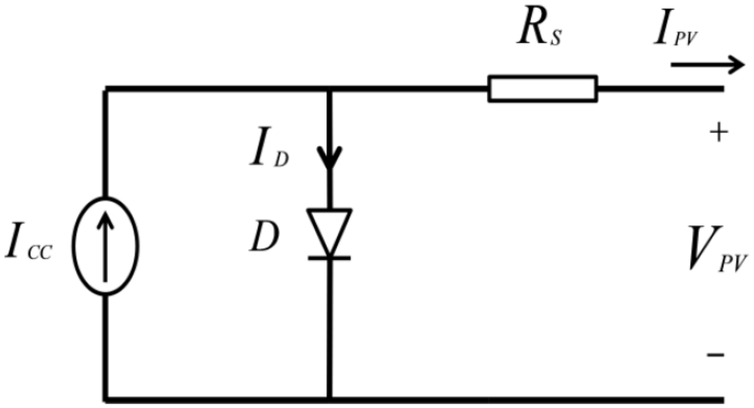


Fig.II.7. Equivalent electrical circuit used.

Since it neglects the effect of resistance, equation (II.6) becomes by posing[28]:

$$I_D = I_S(\exp q\left(\frac{V_{PV}+R_S I}{nKT}\right)) - 1 \qquad (II.7)$$

First, we calculate the short circuit current Icc at a given temperature T

$$I_{cc(T)} = I_{CC(ref)}.[1 + a(T - T_{(ref)})] \qquad (II.8)$$

- where:
  $Icc\ (ref)$: is given in the dataset (measured under a radiation of 1000W / m²
  $T\ (ref)$: is the reference temperature of the PV cell in Kelvin (k) equal to 298k
  a: is the temperature coefficient of Iccen% / ° C given in the dataset.

The short-circuit current is proportional to the intensity of illumination, so at a given illumination G, it is given by:

$$I_{cc\ (G)} = \frac{G}{G_0} I_{cc(\ G_0)} \qquad (II.9)$$

where :

- G_0: is the nominal value of the radiation equal to 1000W / m^2. The saturation current of The diode is at the reference temperature is given in equation (II.3) By introducing the ideality coefficient of the diode, we obtain:

$$I_S = \frac{I_{cc}}{exp\ q\left(\frac{V + R_S I}{nkT}\right) - 1} \qquad (II.10)$$

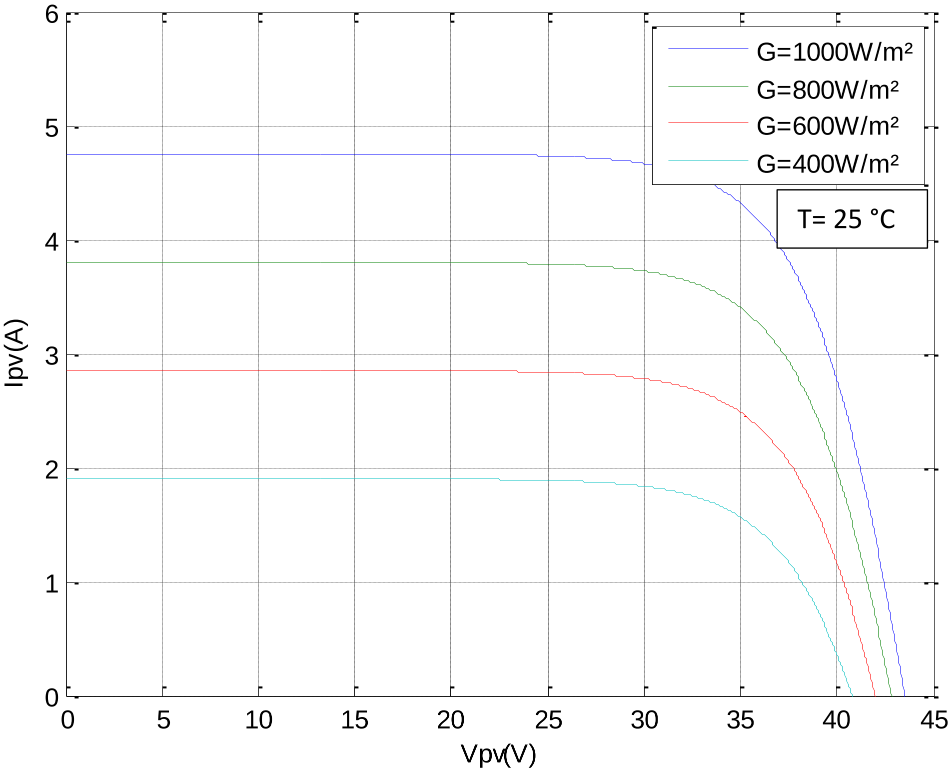
II.7.1. Simulation of PV generator

The photovoltaic generator (PVG) was modeled and simulated in the Matlab / Simulink environment. The simulation was started with the influence of the irradiation and the temperature of the PVG (equivalent of 1 panel) the results are represented respectively as follows:

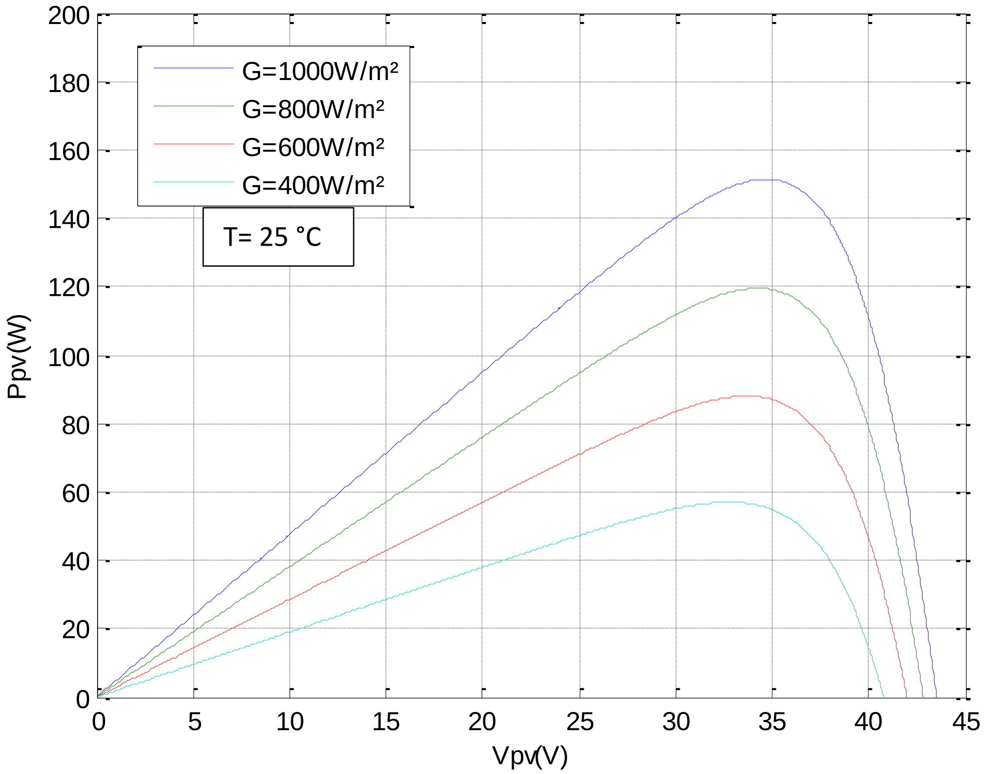
- Influence of irradiation and temperature on curves I = f (V) and P = f (V):

Figure (II.8.a) shows the influence of illumination on the characteristic I = f (V). At a constant temperature, it is found that the current undergoes a significant variation, but on the other hand the voltage varies slightly. Because the short circuit current is a linear function of illumination whiles the open circuit voltage is a logarithmic function [30, 31, 32, 28].

Figure (II.8.b) shows the variation of the delivered power by the generator as a function of the voltage for different illumination values, which allows to deduce the influence of illumination on the characteristic P (V).



(a)

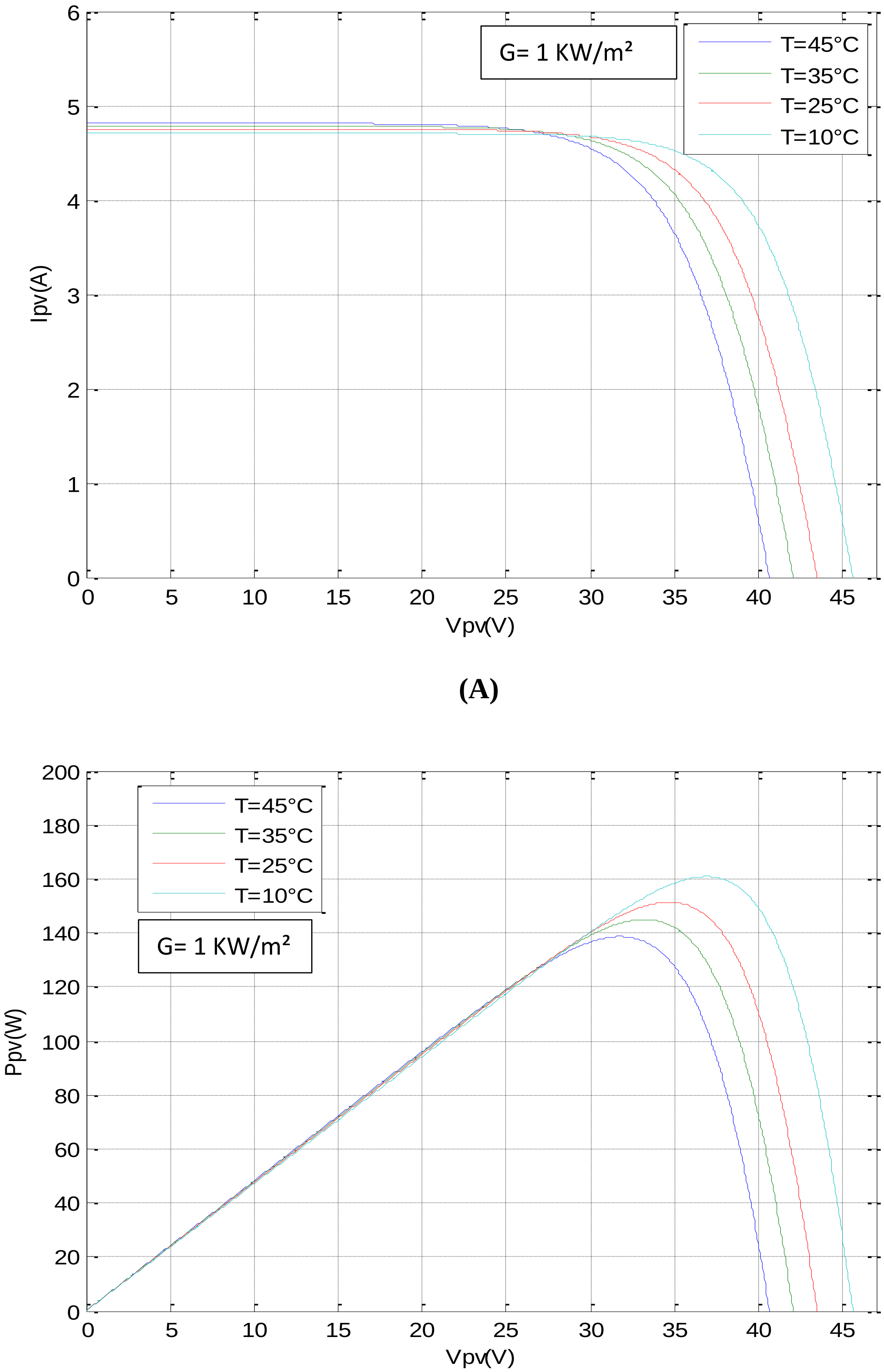


(b)

Fig.II.8. The influence of irradiation on the characteristic I = f (V) and P = f (V) for the GPV.

Figure (II.9.A) shows the influence of temperature on the characteristic I = f (V). It is essential to understand the effect of changing the temperature of a solar cell on the characteristic I = f (V).

The current depends on the temperature since the current increases slightly as the temperature increases, but the temperature has a negative influence on the voltage open circuit. When the temperature increases the open circuit voltage decreases. As a result, the maximum power of the generator is reduced. The figure (II.9.B) illustrates the variation of the power delivered by the generator as a function of the voltage for different values of the temperature, which allows us to deduce the influence of the temperature on the characteristic P = f (V).



(A)

(B)

Fig.II.9. The influence of temperature on the characteristic I = f (V) and P = f (V) for the PVG

II.8. Storage system

Energy storage is the capture of energy produced at one time for a use at a later time. Energy comes in multiple forms including radiation, chemical, gravitational potential, electrical potential electricity, elevated temperature, latent heat and kinetic. Energy storage involves converting energy from forms that are difficult to store to more conveniently or economically storable forms. A device that stores energy is generally called an accumulator or battery. And here we go with modeling of batteries.

II.8.1. Modeling of batteries

This part is dedicated to the modeling of battery accumulator based on lead-acid technology.

- **Simple electric model of the battery**

The simple electric model of the battery includes an e.m.f (E_0) (Modeling the no-load voltage of the battery), a capacitor (C_b) (modeling the internal capacity of the battery) and an internal resistance (R_s), as shown in figure II.10.

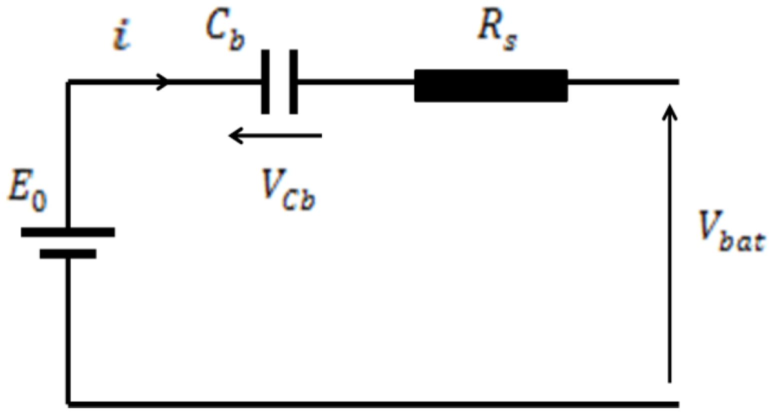


Fig.II.10. Model R-C of the battery.

So we have :

$$V_{bat} = E_0 - R_S * i - V_{cb} \tag{II.11}$$

The State Of Charge (SOC) of the battery is also defined by:

$$SOC = 1 - \frac{Q_d}{C_b} \tag{II.12}$$

With:

- C_b: The nominal capacity (Ah) of the battery;
- Q_d: The amount of missing load in relation to C_b.

In this work, we used the "Battery" block parameters available in the Matlab / Simulink library developed by [33,28]. It models the most popular technologies of rechargeable batteries. The equivalent circuit parameters can be modified to represent a particular type of battery based on its charge / discharge characteristic. When the battery current is negative, the battery will recharge according to the charging characteristic of the corresponding battery type.

- Dump model [19]:

$$V_{bat} = E_0 - R_s\, i - K\left(\frac{Q.it}{Q-it} + \frac{Q.i*}{Q-it}\right) + Aexp\,(-B.it) \qquad (II.13)$$

- load model [19] :

$$V_{bat} = E_0 - R_s\, i - \left(\frac{Q.it}{Q-it} + \frac{Q.i*}{it-0.1Q}\right) + Aexp\,(-B.it) \qquad (II.14)$$

With :

- V_{bat} : Battery voltage (V);
- E_0: The constant voltage of the battery (V);
- K: The constant polarization (V / Ah) or (Ohm);
- Q: The capacity of the battery (Ah);
- it =∫ i dt : The current charge of the battery (Ah);
- A: Amplitude of the exponential area (V);
- B: Constant (Ah^{-1});
- R: The internal resistance (Ohm);
- i: Battery current (A);
- i *: The filtered current (A).

- **Extraction of the parameters**

The particularity of this model is the simplicity of use. Indeed, it is not necessary to make experimental measurements on real batteries to identify their parameters. Only three points on the discharge curve given by the manufacturer, in steady state, are sufficient to obtain these parameters. Battery manufacturers provide a plug that includes the "typical discharge characteristic" (Figure II.11) where it is possible to extract the voltage from the full load (V_{full}), the end of the exponential zone (Q_{exp}, V_{exp}), the end of the nominal zone (Q_{nom}, V_{nom}) (when the voltage begins to fall sharply) and the maximum capacity (Q). In addition, the internal resistance (R_s) is generally given. With these three points, it is possible to solve, using the coming equations.

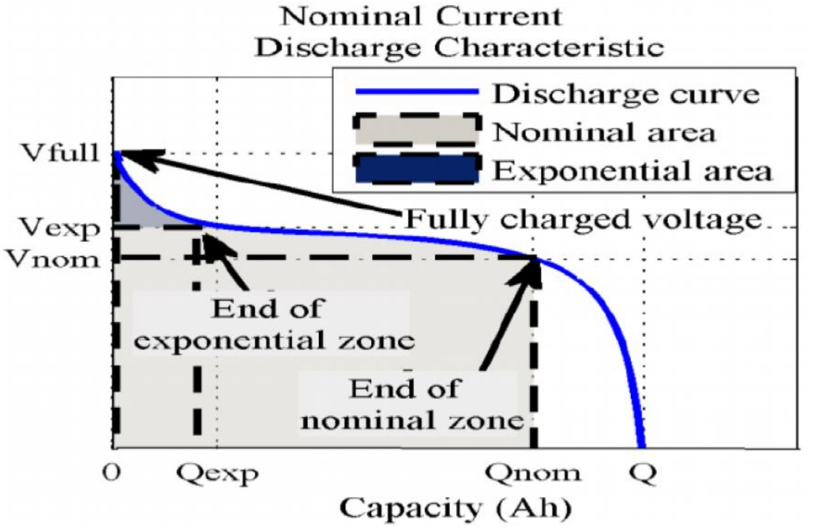


Fig.II.11. Typical characteristic of discharge of a battery.

The discharge curve given by the manufacturer is obtained at constant current (generally equal to 0.2 C). For the full load voltage, the extracted load is $0A$h (it = $0A$h) and the filtered current (i *) is 0, so:

$$V_{full} = E_0 - R_s i + A \tag{II.15}$$

At the end of the exponential zone, the factor B can be approximated 3 / $Qexp$:

$$V_{exp} = E_0 - R_s i - K + \left(\frac{Q.i}{Q-Q_{exp}} + \frac{Q.Q_{exp}}{Q-Q_{exp}}\right) + Aexp\left(-\frac{3}{Q_{exp}}.Q_{exp}\right) \tag{II.16}$$

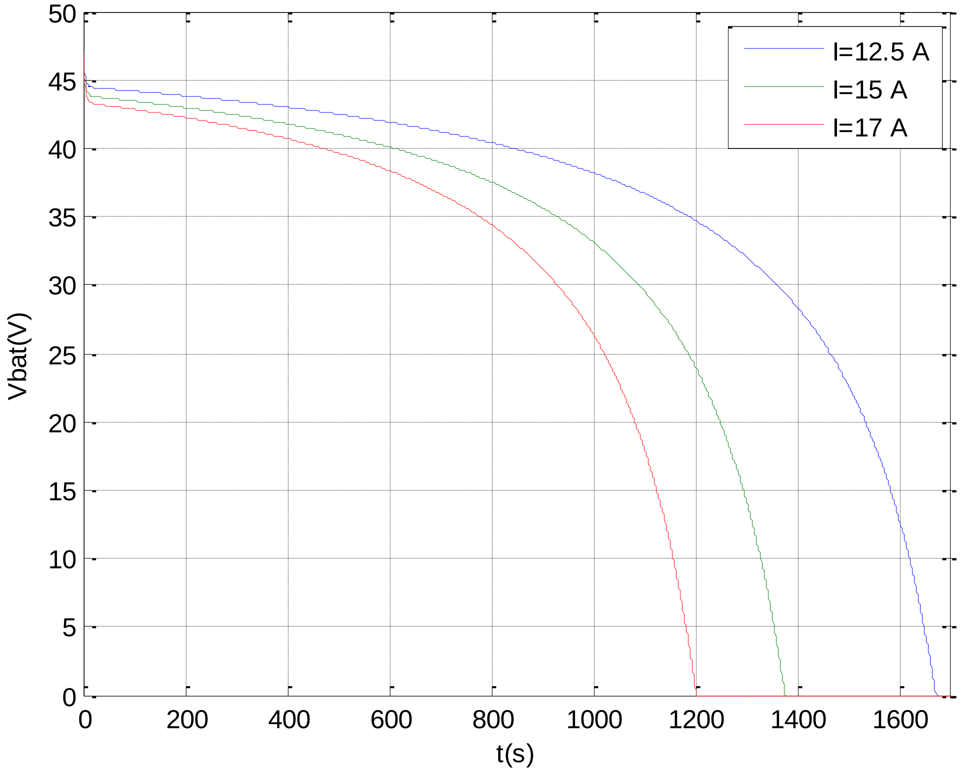
The voltage of the nominal area is given by

$$V_{nom} = E_0 - R_s\, i - \left(\frac{Q.i}{Q-Q_{nom}} + \frac{Q.Q_{nom}}{Q-Q_{nom}}\right) + Aexp\left(-\frac{3}{Q_{nom}}.Q_{nom}\right) \tag{II.17}$$

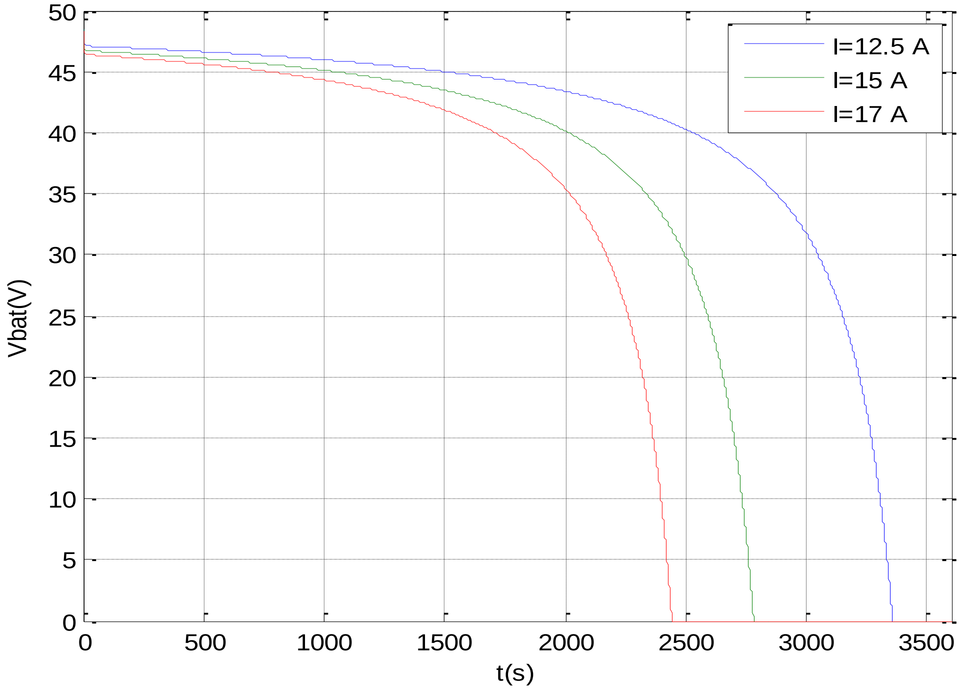
Nominal Voltage	48 V
Rated Capacity	12 Ah
Initial State-Of-Charge	50 %
Maximum Capacity	12.5 Ah
Fully Charged Voltage	52.2632 V
Nominal Discharge Current	2.4 A
Internal Resistance	0.04 Ohms

Table.II.2. Electrical characteristics of the battery.

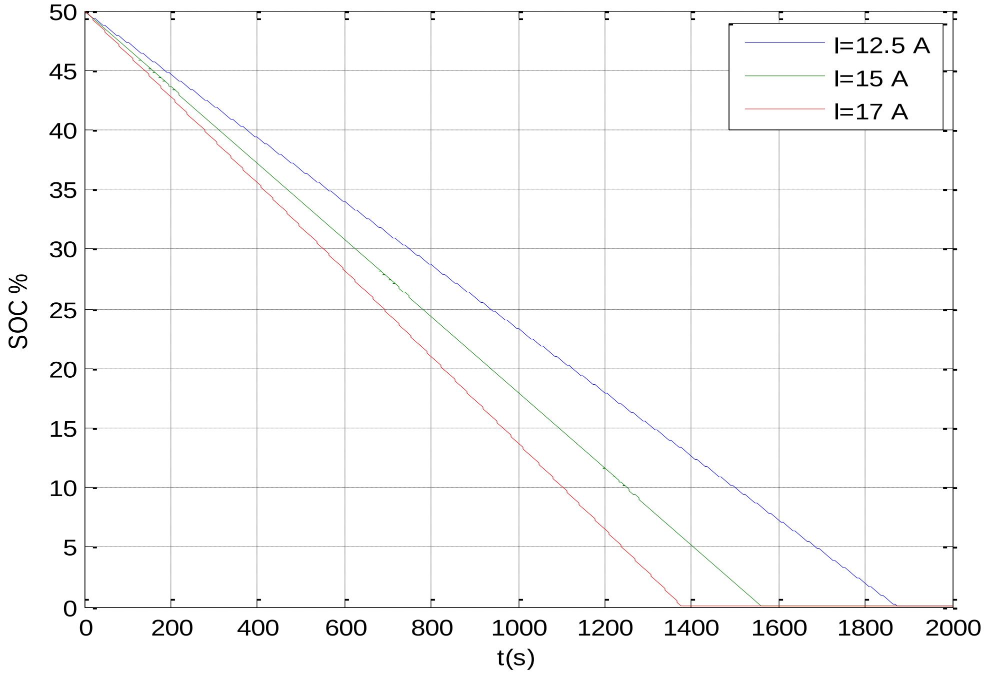
Figure (II.12) shows the simulation results of the evolution of the battery voltage for different discharge currents. We note that each time the discharge current increases the battery is discharged quickly and this comes back to the SOC characteristics of the lead acid battery. On the other hand, each time the charge current decreases, the battery charges rapidly as shown in Figure (II.13).


Vbat(V)
t(s)
0
5
10
15
20
25
30
35
40
45
50
0
200
400
600
800
1000
1200
1400
1600
I=12.5 A
I=15 A
I=17 A

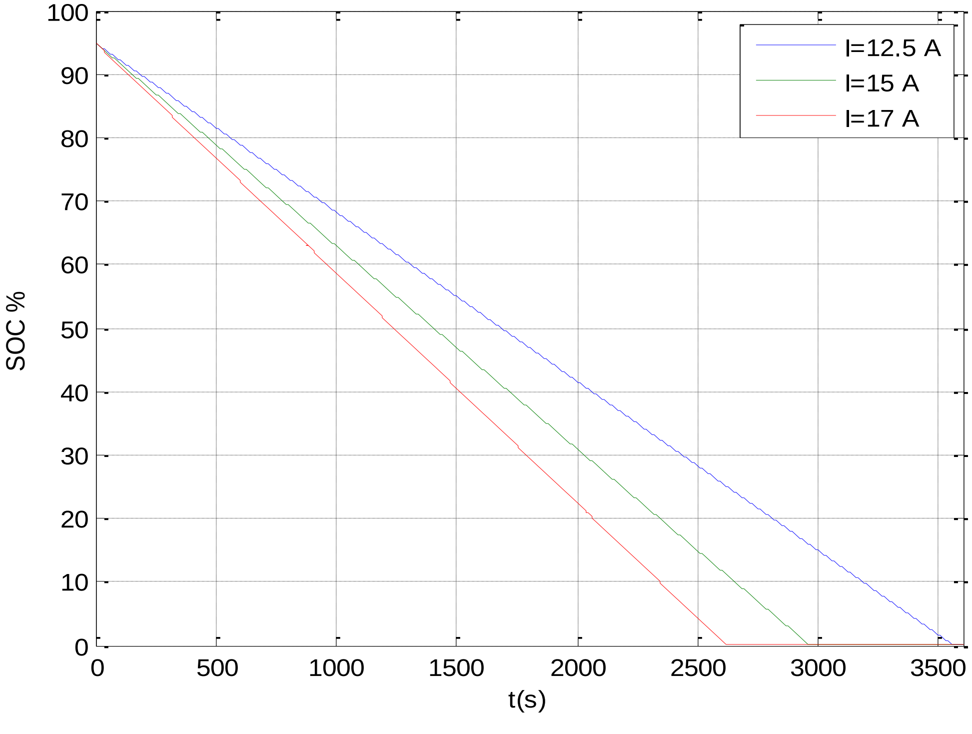
SOC=50%


Vbat(V)
t(s)
0
5
10
15
20
25
30
35
40
45
50
0
500
1000
1500
2000
2500
3000
3500
I=12.5 A
I=15 A
I=17 A

SOC=95%



SOC=50%



SOC=95%

Fig.II.12. Battery voltage and SOC for different discharge currents.

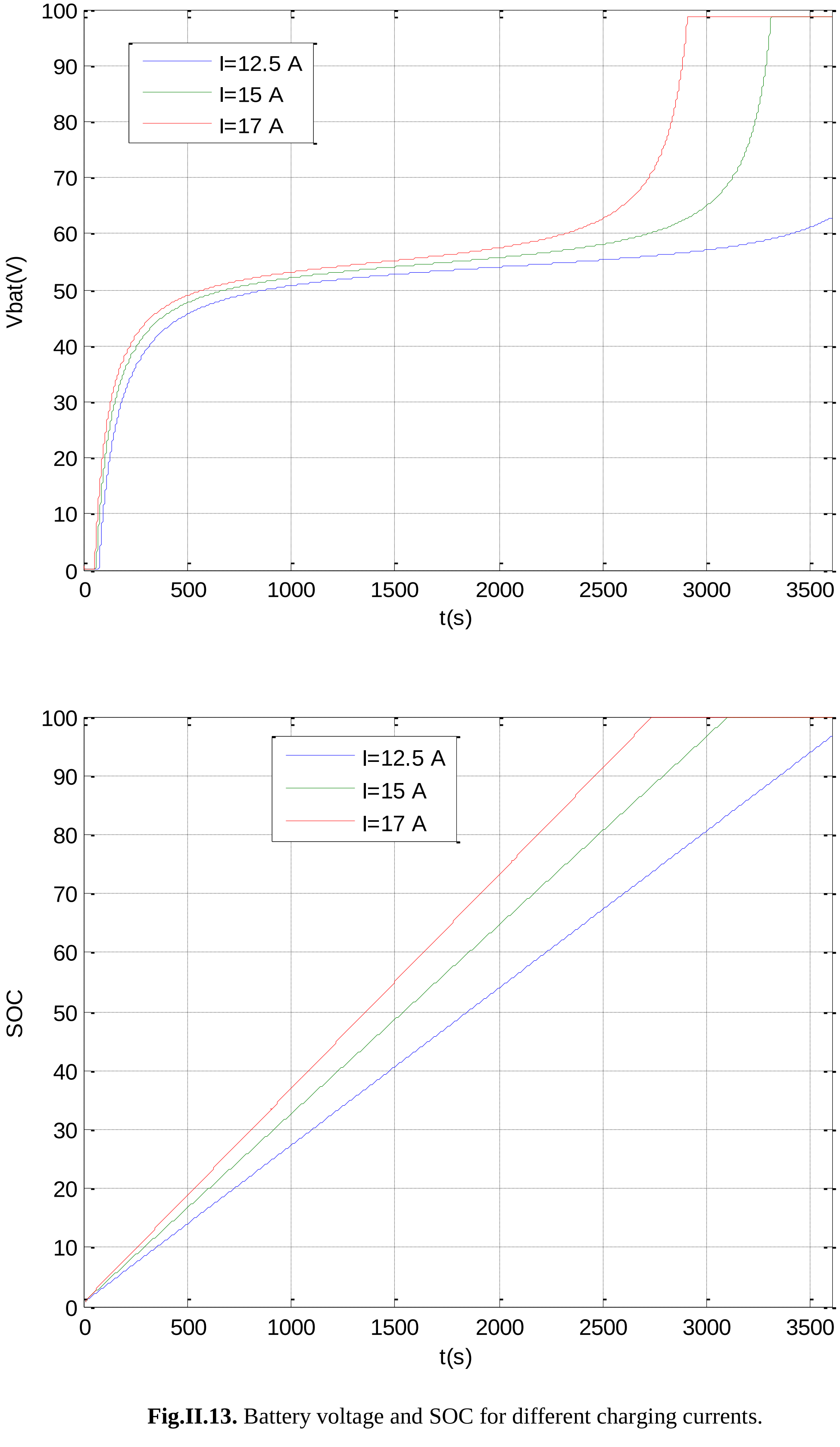


Fig.II.13. Battery voltage and SOC for different charging currents.

II.9. Modeling of DC/DC converters

This part is devoted to the modeling of DC/DC converter used to link the sources with DC load via DC bus.

II.9.1. DC-DC converters

A DC-to-DC converter, also known as DC chopper, is a static device which is used to obtain a variable DC voltage from a constant DC voltage source. Choppers are widely used in trolley cars, battery operated vehicles, traction motor control, control of large number of DC motors, etc..... They are also used as DC voltage regulators.

Choppers are of two types: step-down choppers and step-up choppers. In step-down choppers, the output voltage will be less than the input voltage, where as in step-up choppers output voltage will be more than the input voltage.

The role of the DC / DC converter (in the context of the PV) is to make the adaptation between the PVG source and the load for maximum power transfer. This is done by keeping (P_{pv}) on or close enough to the MPP for any operating conditions (radiation, temperature, charging characteristic, etc.) [34,28].

Unlike the general case where the DC / DC converter is used to regulate the output voltage, here it is rather the input voltage that is regulated. The reference voltage (setpoint) is then constant or imposed by a control algorithm.

II.9.2. DC/DC converter control

The regulation of the output voltage at a constant level is achieved by an action on the "duty cycle", defined as the fraction of the switching period when the switch is on. The switch is a semiconductor device in all-nothing mode (blocked - saturated), usually a transistor (MOSFET) or (IGBT). If the semiconductor device is blocked, its current is zero and therefore its power dissipation is zero. If the device is in the saturated state the voltage drop at its terminals will be almost zero and therefore the power lost will be very small [35,28].

There are several types of DC-DC converters. Among them, we present the principle of the three types of switching converters (voltage, boost and mixed), frequently used in photovoltaic systems to generate the desired voltages and currents and for the adaptation of solar panels with different loads [30, 36, 37,28].

II.9.2.1. Boost converter

This is a boost converter, also known as "Boost" or parallel chopper, its basic electrical circuit is that of Figure (II.14). Its typical application is to convert its input voltage to an upper output voltage [38, 35,28].

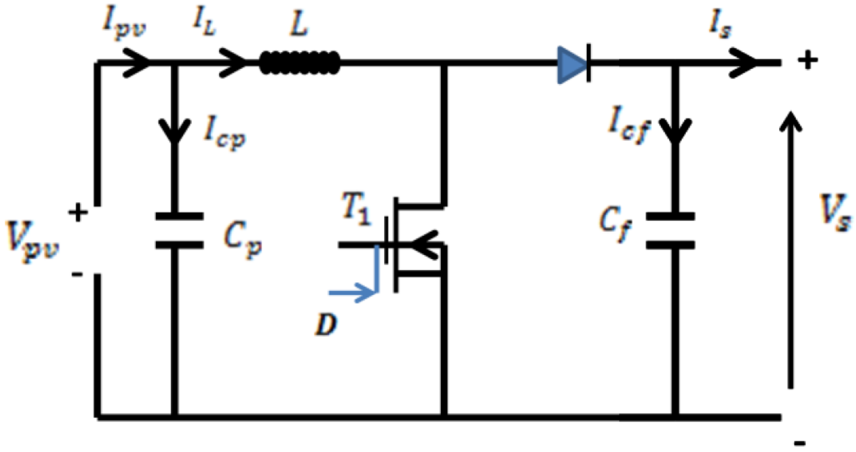


Fig.II.14. Schematic diagram of a boost converter.

By applying Kirchhoff laws on the equivalent circuits of the booster converter Figure (II.15) of the two phases of operation gives as illustrated in the following Figure:

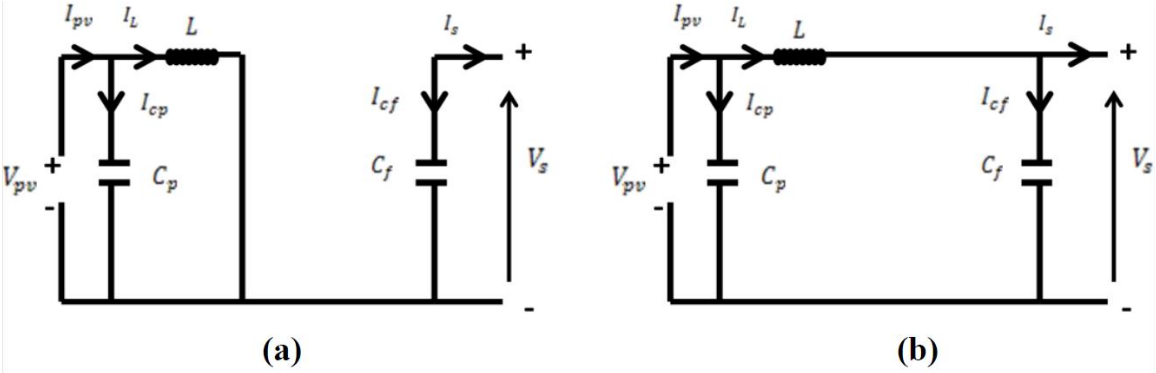


Fig.II.15. Equivalent diagrams of the boost chopper case (a): T1 closed, case (b): T1 open.

For the first period DTs:

$$\begin{cases} I_{cp}\, t \;=C_P\,\frac{dV_{PV}(t)}{dt}=I_{PV}\, t-I_L(t) \\ I_{cf}\, t \;=C_f\,\frac{dV_S(t)}{dt}=-\,I_S(t) \\ V_L\, t \;=L\,\frac{dI_L}{dt}=\;V_{PV}\, t \end{cases} \qquad (II.18)$$

For the second period $(1-D)$*T :

$$\begin{cases} I_{cp}(t)=C_P\,\frac{dV_{PV(t)}}{dt}=I_{PV(t)}-I_{L(t)} \\ I_{cf}(t)=C_f\,\frac{dV_S(t)}{dt}=I_L(t)-I_S(t) \\ V_L(t)=L\,\frac{dI_L}{dt}=V_{PV}(t)-V_s(t) \end{cases} \qquad (II.19)$$

To find a dynamic representation valid for the whole period T_s, we usually use the following expression [28]:

$$\frac{dx}{dt}T_{S=}\frac{dx}{dt_{DT_S}}DT_S+\frac{dx}{dt_{(1-D)T_S}}(1-D)T_S \qquad (II.20)$$

Applying equation (II.18) to the systems of equations (II.19) and (II.20), we obtain the equations governing the system over an entire period. The approximate model of the booster converter:

$$\begin{cases} I_L=\;I_{PV}-C_p\,\frac{dV_{PV}(t)}{dt} \\ I_s=(1-D)I_L-C_f\,\frac{dV_S(t)}{dt} \\ V_{PV}\;=L\,\frac{dI_L(t)}{dt}-(1-D)V_s \end{cases} \qquad (II.21)$$

We made our choice of converter type "Boost" to boost the voltage generated by the GPV to the needed DC voltage of 48V.

- **Sizing of Boost converter**

The determination of the passive elements of the two DC-DC converters connected to the solar panels consists in calculating the values of the inductances L_1 and the capacitance C_P and C_f.

The inductance $L1$ which corresponds to a given $\Delta i_{PV\,max}$ is expressed by [39,28]:

$$L_1 = \frac{V_{PV}}{4 \,.\Delta i_{PV\,max} \cdot f} \tag{II.22}$$

For the particular values f = 10 KHz and $\Delta i_{PV\,max}$ = 0.522 A and V_{PV} = 34.5 V, we have $L1$ = 1.652 H. The filter capacity C_P must be dimensioned so that the GPV voltage V_{PV} a maximum ripple $\Delta V_{PV\,max}$acceptable [39,28].

$$C_P = \frac{I_{PV}}{\Delta V_{PV\,max} \cdot f} \tag{II.23}$$

Finally, for f = 10 KHz, I_{PV} = 4.6 A and $\Delta V_{PV}\ max$ = 2.07 V, we have C_P = 0.22 mF. The filter capacity C_f must be dimensioned so that the DC bus voltage V_{dc} has a maximum ripple $\Delta V_{dc\,max}$ acceptable [39,28].

$$C_f = \frac{I_{opt}}{4\,.\ \Delta V_{dc\,max} \cdot f} \tag{II.24}$$

for f = 10 KHz, I_{opt} = 4.35 A et $\Delta V_{dc\,max}$ = 4.5 V, we have C_f = 0.024 mF.

II.9.2.2. Buck converter

The Buck converter can often be found in the literature as the Buck chopper or chopper series. Figure (II.17) shows the schematic diagram of the step-down converter [38, 35]. Its typical application is to convert the input voltage to a lower output voltage, where the conversion ratio changes with the duty cycle of the switch.

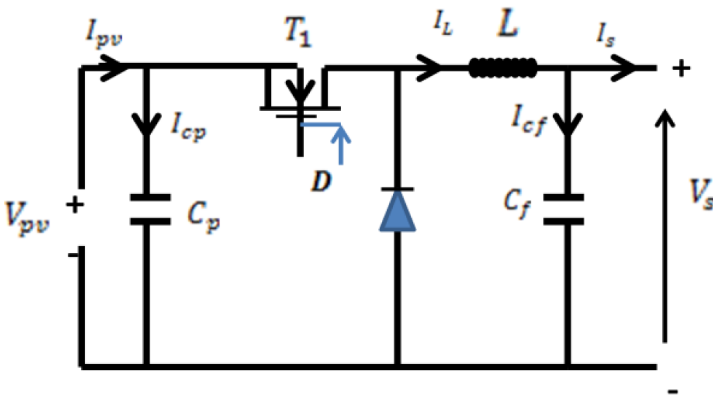


Fig.II.16. Principle's scheme of buck converter.

In order to show the actual behavior of this converter, it is essential to know in detail its mathematical model. For that we have to make the representation of the equivalent circuit by the two states of the switch and to shoot as a result the mathematical model relating the variables of input/output. Figure (II.18) shows the scheme of the equivalent circuits of a step-down converter in both cases: closed switch during DTs and open switch during (1-D) Ts [30, 38, 35, 36,28].

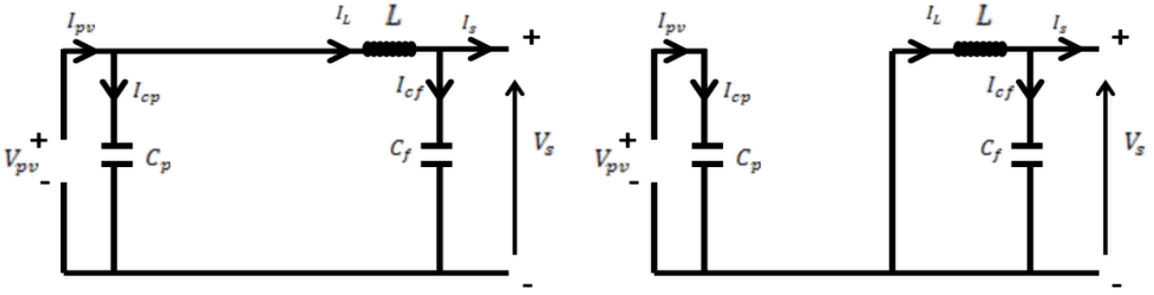


Fig.II.17. Equivalent schemes of buck chopper case (a): T_1 closed, case (b): T_1 open.

Applying Kirchhoff's laws on the two circuits of Figure (II.18), we obtain the following systems of equations: For the first period DTs:

$$\begin{cases} I_{cp}(t) = C_p \frac{dV_{PV}(t)}{dt} = I_{PV}(t) - I_L(t) \\ I_{cf}(t) = C_f \frac{dV_s(t)}{dt} = I_L(t) - I_s(t) \\ V_L(t) = L \frac{dI_L}{dt} = V_{PV}(t) - V_s(t) \end{cases} \tag{II.25}$$

For the second period $(1-D)T_s$:

$$\begin{cases} I_{cp}(t) = C_p \frac{dV_{PV}(t)}{dt} = I_{PV}(t) \\ I_{cf}(t) = C_f \frac{dV_s(t)}{dt} = I_L(t) - I_s(t) \\ V_L(t) = L \frac{dI_L}{dt} = -V_s(t) \end{cases} \tag{II.26}$$

Applying the relation (II.20) to the systems of equations (II.25) and (II.26), we obtain the equations that govern the system over an entire period [28]:

$$\begin{cases} C_p \frac{dV_{PV}(t)}{dt} T_s = DT_s(I_{PV} - I_L) + (1-D)T_s I_{PV} \\ C_f \frac{dV_s(t)}{dt} T_s = DT_s(I_L - I_s) + (1-D)T_s(I_L - I_s) \\ L \frac{dI_L}{dt} T_s = DT_s(V_{PV} - V_s) + (1-D)T_s(-V_s) \end{cases} \tag{II.27}$$

after arrangement, getting :

$$\begin{cases} I_L = \frac{1}{D}(I_{PV} - C_p\frac{dV_{PV}}{dt}) \\ I_s = I_L - C_f\frac{dV_s}{dt} \\ V_{PV} = \frac{1}{D}(L\frac{dI_L}{dt} + V_s) \end{cases} \tag{II.28}$$

II.9.2.3. Bidirectional converter connected to the battery module

The converter connected to the battery module has the structure shows in Figure (II.16). It operates as a Boost when the batteries supply electrical power to the DC bus and as a Buck in the case when the electrical energy is routed to the battery in order to charge it.

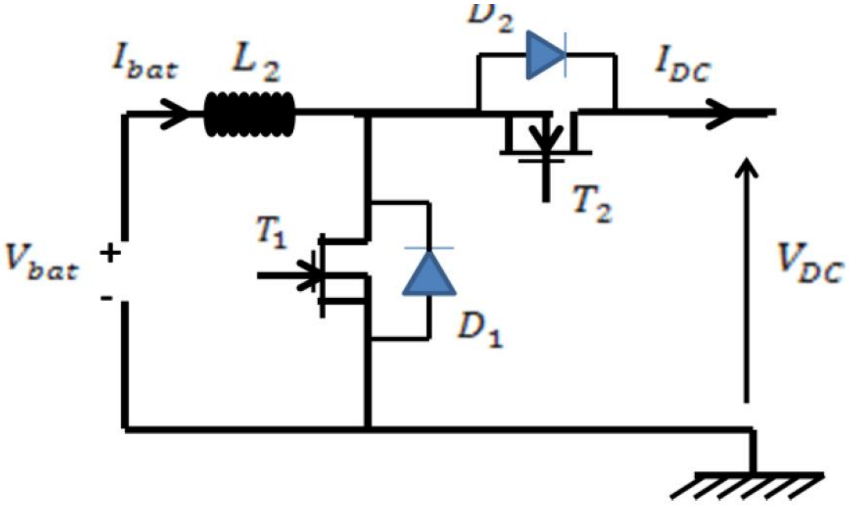


Fig.II.18. Converter connected to the battery module.

Since the operation of the chopper boost is detailed previously, the chopper Buck is presented in this part. The determination of the passive elements of the two DC-DC converters connected to the batteries. The inductance $L2$ corresponding to this undulation is given by [39,28]:

$$L_2 = \frac{V_{Bat}}{4\,.\Delta i_{Bat\,max}\cdot f} \tag{II.29}$$

For the particular values f = 10 KHz and $\Delta i_{Bat\,max}$ = 0.81 A and V_{Bat} = 48 V, we have $L2$ = 1.48 H.

II.9.2.4. Global hybrid system modeling

The modeling will only concern the main converters "Boost and Buck-Boost". The DC load is simulated as a current source. This current is called load current. This current is supposed to be known. $D1$, $D2$ and $D3$ are the control signals of the transistors respectively $T1$, $T2$ and $T3$ Figure (II.19) .A capacitor C_P is connected in parallel with the PVG. In fact, this ability protects the panel against overvoltage during a strong power demand [39,28].

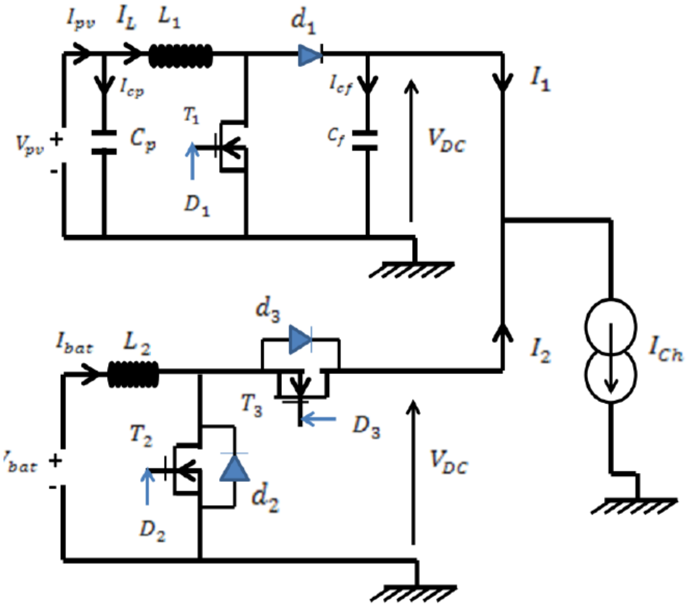


Fig.II.19. Global Hybrid system feeding DC load.

When the second converter (linked to the batteries) operates in "Boost" mode, the behavior of the two converters is described by the following system of equations:

$$\begin{cases} \frac{dI_{PV}}{dt} = \frac{1}{L}\ (\ V_{PV} - (1 - D_1)V_{dc})f_{c1}(D_1, I_{PV}) \\ \frac{dI_{bat}}{dt} = \frac{1}{L}\ (\ V_{bat} - (1 - D_2)V_{dc})f_{c2}(D_2, I_{bat}) \\ \frac{dV_{dc}}{dt} = \frac{1}{C_f}\ \big((1 - D_1)I_{PV}\big) + (1 - D_2)I_{bat} - I_{ch} \end{cases} \quad (II.30)$$

Now if the converter works in "Buck" mode the behavior of the two converters will be described by the following system of equations:

$$\begin{cases} \frac{dI_{PV}}{dt} = \frac{1}{L}\left(V_{PV} - (1 - D_1)V_{dc}\right) f_{c1}(D_1, I_{PV}) \\ \frac{dI_{bat}}{dt} = \frac{1}{L}\left(V_{bat} - D_3 V_{dc}\right) f_{c3}(D_3, I_{bat}) \\ \frac{dV_{dc}}{dt} = \frac{1}{C_f}\left((1 - D_1)I_{PV}\right) + D_3 I_{bat} - I_{ch} \end{cases} \tag{II.31}$$

Both systems can be grouped into one system [28]:

$$\begin{cases} \frac{dI_{PV}}{dt} = \frac{1}{L}(V_{PV} - (1 - D1)V_{dc}) f_{c1}(D_1, I_{PV}) \\ \frac{dI_{bat}}{dt} = \frac{1}{L}(V_{bat} - ((1 - D_2)K + (1 - K)D_3)V_{dc})(K f_{c2}(D_2, I_{bat}) + (1 - K) f_{c3}(D_3, I_{bat}) \\ \frac{dV_{dc}}{dt} = \frac{1}{C_f}\left((1 - D_1)I_{PV}\right) + (1 - D_2)I_{bat} - I_{ch} \end{cases} \tag{II.32}$$

where :

- K: is a binary variable that takes the value 1 when the second DC/DC converter (connected to the battery) operates in "Boost" mode and the value 0 when it is in "Buck" mode.

- $fC1$, $fC2$ and $fC3$ are the functions introduced in the system (II.29) to model the behavior of the diodes ie1, $d2$ and $d3$, when the converters operate in discontinuous conduction mode.

The functions$fC1$, $fC2$ and $fC3$ are defined by[28]:

$$f_{c1}(D_{1,} I_{PV}) = \begin{cases} 1\ si(D_1 = 1) ou(I_{PV} > 0) \\ 0\ si(D_1 = 0) ou(I_{PV} \leq 0) \end{cases} \tag{II.33}$$

$$f_{c2}(D_{2,} I_{bat}) = \begin{cases} 1\ si\ (D_2 = 1) ou(I_{bat} > 0) \\ 0\ si\ (D_2 = 0) ou(I_{bat} \leq 0) \end{cases} \tag{II.34}$$

$$f_{c3}(D_{3,} I_{bat}) = \begin{cases} 1\ si(D_3 = 1) ou(I_{bat} < 0) \\ 0\ si(D_3 = 0) ou(I_{bat} \geq 0) \end{cases} \tag{II.35}$$

II.10 Conclusion

In the objective to evaluate the behavior of PVG-battery hybrid source, a modeling of the two energy sources was done to simulate their dynamics behaviors. These sources are presented with different models, behaviors and characteristics.

From the simulation results of the PVG; it is clear that the irradiation has a great influence on the point of maximum power unlike the temperature has a slight influence on it. Therefore, the DC/DC converters are modeled and regrouped in a global model to represent the functioning of the whole system.

After modeling successfully the hybrid system (PV and Battery) and the DC/DC converter. In the next chapter we will interest to the hybrid system control basing on a PI, FLC and Hybrid control (PI-FLC).

Chapter III

Control and Energy management of PV-Battery hybrid system

III.1.Introduction

This chapter is dedicated to the control and energy management strategies of the hybrid system. Firstly, we present the MPPT strategy needed to obtain the maximum power point of the PVG system. After that, we present the control techniques of the DC bus voltage using PI, FLC and PI_FLC controllers. Finally, the simulation results using variable illumination and load profiles will be presented.

III.2.Maximum Power Point Tracking (MPPT) of the PV system

The MPPT control strategy (Maximum Power Point Tracking) is a functional component of a PV system; it allows the optimal operating point of the PV generator, in different conditions. Whether analogical or digital control, the control principle is the same; it is based on an automatic variation of the duty boost cycle to the appropriate value, in order to extract the maximum power output of PV generator. Many MPPT algorithms have been developed by researchers around the world such as Perturb and observe, incremental conductance, fuzzy logic, neural network . . . etc.[41,50]

MPPT is a high-efficiency DC-to-DC converter, which functions as an optimal electrical load for a photovoltaic (PV) cell, most commonly for a solar panel or array, and converts the power to a voltage or current level which is more suitable to whatever load the system is designed to drive. PV cells have a single operating point where the values of the current (I) and Voltage (V) of the cell result in a maximum power output. These values correspond to a particular resistance, which is equal to V/I as specified by Ohm’s Law.

A PV cell has an exponential characteristic between current and voltage, and the Maximum Power Point (MPP) occurs at the knee of the curve, where the resistance is equal to the negative of the differential resistance ($V/I=dV/dI$). Maximum power point trackers utilize some type of control circuit or logic to search for this point and thus to allow the converter circuit to extract the maximum power available from a cell.

MPPT is not a mechanical tracking system that “physically moves” the modules to make them point more directly at the Sun. MPPT is a fully electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. Additional power harvested from the modules is then made available as increased battery charge current.

MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different. Battery less grid-tied PV inverters utilize MPPTs to extract the maximum power from a PV array, convert this to alternating current (AC) and sell excess energy back to the operators of the power grid. MPPT charge controllers are desirable for off-grid power systems to make the best use of all the energy generated by the panels [54,57].

The benefits of MPPT regulators are greatest during cold weather, on cloudy or hazy days or when the battery is deeply discharged. Solar MPPTs can also be used to drive motors directly from solar panels. The benefits are huge, especially if the motor load is continuously changing. This is due to the fact that the AC impedance across the motor is related to the motor's speed. The MPPT will switch the power to match the varying resistance.

III.2.1.MPPT methods

There are multiple MPPT methods including [42,54] :

- Constant Voltage;
- Open Circuit Voltage;
- Short Circuit Current;
- Perturb and Observe;
- Incremental Conductance;
- Temperature Parametric.

In this work, we will focus only on the Perturb and Observe approach.

III.2.2.Perturb and Observe

The P&O algorithm is also called "hill-climbing", but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating voltage of the DC link between the PV array and the power converter [43,54]. In the case of the Hill-climbing, perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both names refer to the same technique.

In this method, the sign of the last perturbation and the sign of the last increment in the power is used to decide what the next perturbation should be. on the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power. If there is an increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation should be in the opposite direction. Based on these facts, the algorithm is implemented [43,54].

The process is repeated until the MPP is reached. Then the operating point oscillates around the MPP. This problem is common also to the In-Cond method, as was mention earlier. A scheme of the algorithm is shown in Fig.III.1.

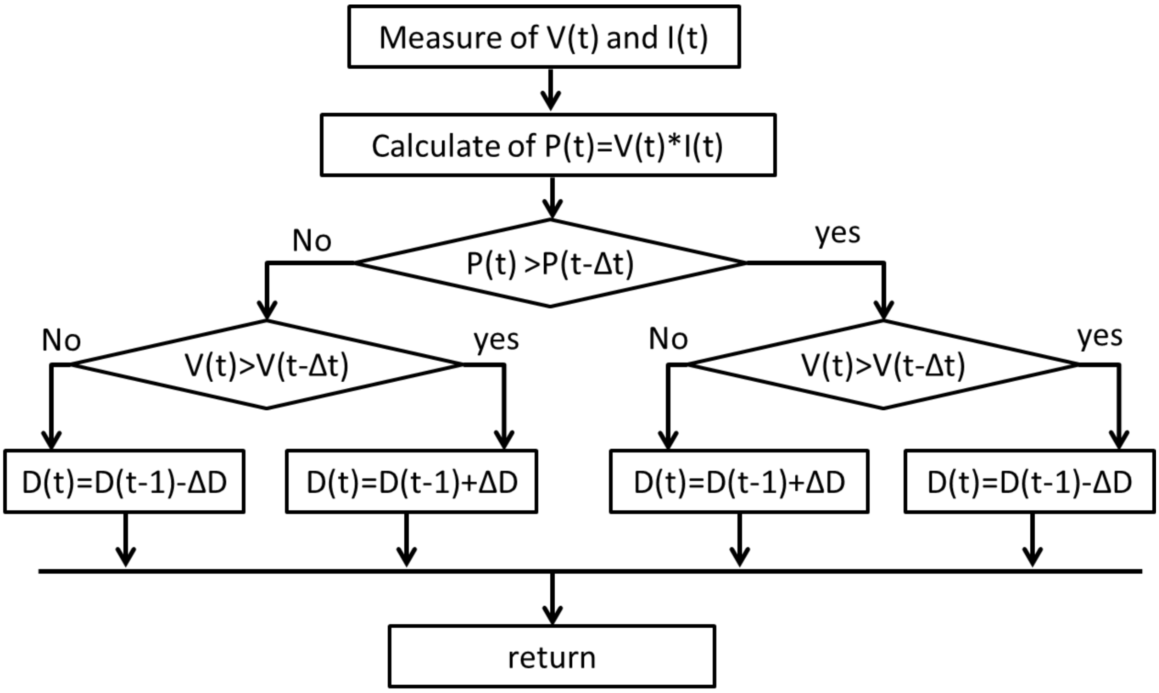


Fig.III.1. Flowchart of the perturb and observe algorithm.

III.3.DC/DC converter control with PI controller

The regulation of the DC bus voltage will be ensured by the converter associated with the battery pack. The control consists of two nested loops, one external loop for DC voltage regulator and an internal loop for battery current control. (voltage loop) develops the reference current of the battery pack I_{Bat_ref} which will be enslaved by the inner loop of current (see Figure III.2) [44,28].

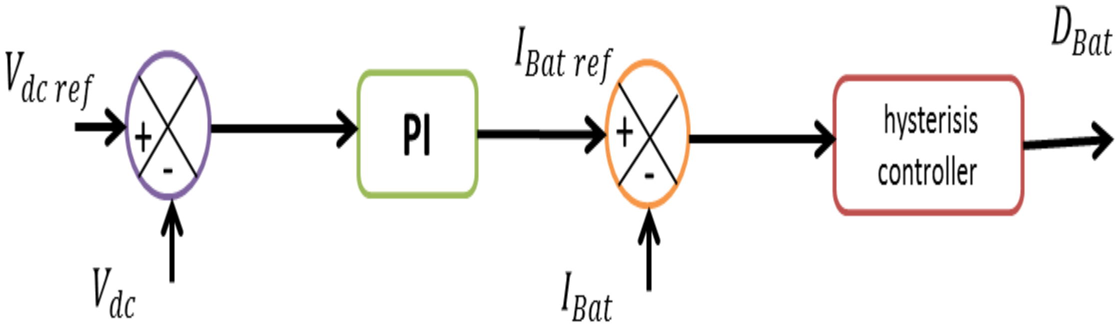


Fig.III.2. PI controller for DC bus voltage regulation.

III.4. Control of the converter linked to the battery with Fuzzy Logic Controller (FLC)

In this section, we consider replacing the PI controller by a Fuzzy Logic Controller in the objective to improve the dynamic performances of the hybrid source. Here we are going to present the FLC and its design principle.

III.4.1.Defenition

Fuzzy logic controller (FLC) is one of the most widely used applications of fuzzy set theory. It can be used instead of digital control systems using fuzzy sets. We can compute with words rather than numbers. Fuzzy sets are described by membership functions which are the main toll for the fuzzy operations. The implementation of linguistic fuzzy rules by human operators is desired for a complex and nonlinear systems without the requirements of mathematical models parameter estimation. The FLC has faster transient responses and is more robust than several control method and which are presented [45, 46, 56].

- **Fuzzy Logic Control**

The fuzzy logic control is an important application of the fuzzy set theory first introduced by L. A. Zadeh in 1965. The most important feature that distinguishes the concept of fuzzy set from the classical set concept is that fuzzy set uses linguistic variables rather than numerical variables [47,53].

Linguistic variables, defined as variables whose values are sentences in a natural language (such as small and large), may be represented by fuzzy sets. The application of fuzzy logic does not require accurate mathematical formulations. A block diagram of a fuzzy logic controller is shown in Figure (III.3) and the implementation involves the processes of fuzzification, inference and defuzzification.

The fuzzification interface converts input data into suitable linguistic values using the membership functions. During the phase of inference, the fuzzy if-then rules are evaluated using an inference engine and the controller action is inferred from the knowledge of the fuzzy rules and the linguistic variables definition. The conversion of the inferred fuzzy result to a crisp control action performed through the defuzzification [48,53].

Because its control algorithm is described by if-then rules instead of intensive mathematical equations or large look-up tables, the design of fuzzy logic non-linear controller is easier. It reduces the development cost and time and needs less data storage in the form of membership functions and rules. It is also highly reliable and robust to change in circuit parameters and external disturbances [49,53].

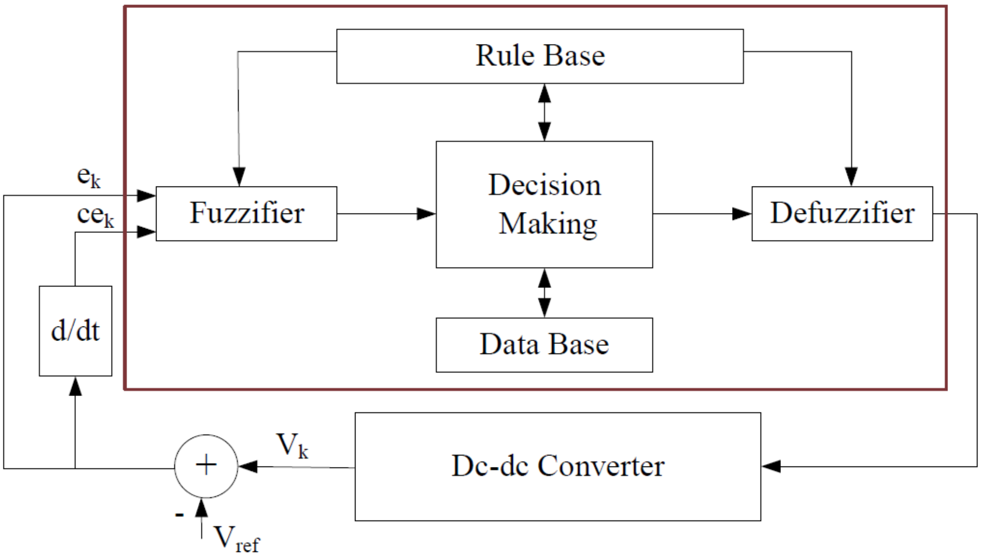


Fig.III.3. Basic configuration of fuzzy logic controller

III.4.2. Fuzzy Logic Controller Design

Fuzzy set is an extension of crisp set, where the element belongs or does not belong to the set with 0 or 100%. That is in a fuzzy set, the element may partially belong to the set, that is an element can belong to more than one set. This set is characterized by a membership function that applies a membership degree forth set with a range of 0 to 1 to each element in a given class. [53]

Design of fuzzy controllers is based on expert knowledge of the system to be controlled instead of accurate mathematical model. There are two inputs in the fuzzy controller. The first is the error e(k) between the output voltage V[k] and the reference value Vref and the second is the difference between successive errors i.e. change of error de(k) and are given by [53]:

$$e(k) = Vref - V(k) \tag{III.1}$$

$$de(k) = e(k) - e(k-1) \tag{III.2}$$

The output of the fuzzy controller is the change in current of battery ΔIbat[k], which is fed to PWM block and the PWM output is fed as switching signal to the converter. In figure III.3 the voltage at the output of the converter is compared with reference voltage and the output of the comparator is the error signal which is the input of the Fuzzy controller together with the change in error signal. The output of the controller is current which is fed to PWM block and the PWM output is fed as switching signal to the converter.

A Mamdani based control system architecture has been realized. Max–min composition techniques and center of gravity methods have been used in the inference engine and defuzzification. The max–min inference method is used to obtain the control decision. It is based on the minimum function to describe the AND operator present in each control rule and the maximum function to describe the OR operator. The output of the fuzzy controller structure is crisp, and thus, a combined output fuzzy set must be defuzzified. The sum–product composition method has been used to express the qualitative action in a quantitative action. It calculates the crisp output as the weighted average of the centroids of all output membership functions.[53]

Fuzzy logic controller consists of three components fuzzification, fuzzy inference system and defuzzification. In general a fuzzy set issued to express a fuzzy variable which is defined by a membership function. The values of membership function vary between 0 and 1. The fuzzy rule base are the IF-THEN rules. [53]

III.4.2.1. Fuzzification

Fuzzification is the process of converting input data into suitable linguistic values. The first step in the design of a fuzzy logic controller is to define membership functions for the inputs[53]. Five fuzzy levels are chosen and defined by the following fuzzy-set values for the error e and change in error de:

- NB negative big;
- NS negative small;
- ZZ zero;
- PS positive small;
- PB positive big.

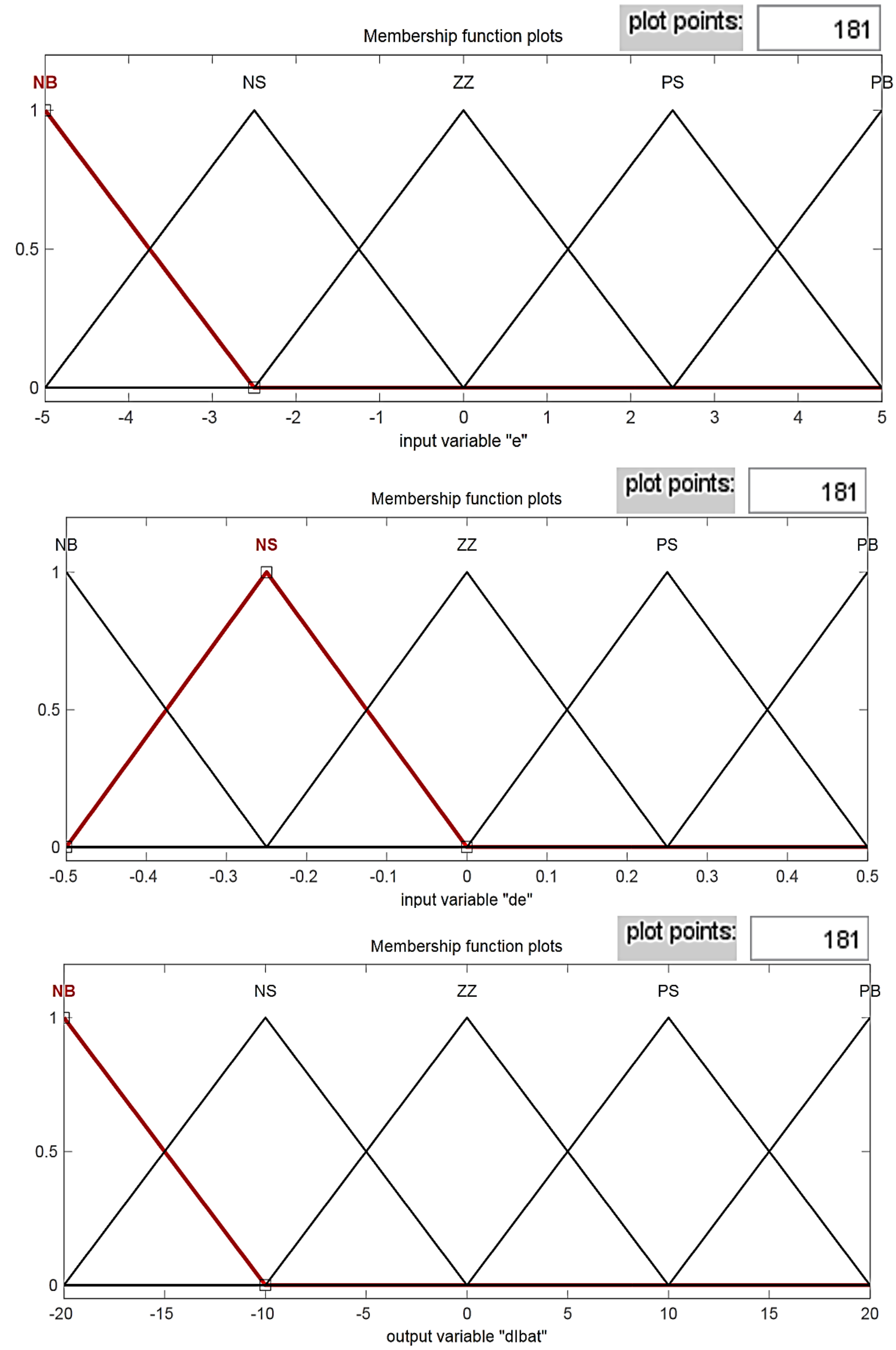


Fig.III.4. Membership functions for e, de and du (dI_{bat})

The number of fuzzy levels depends on the input resolution. Increasing the number of fuzzy levels, increases the input resolution. Due to its simplicity, the triangular membership function is chosen for the controller input. Fuzzifier determines the degree of membership in every linguistic variable for given inputs. All linguistic variables other than two will have zero membership because there are only two overlapping memberships. [53]

III.4.2.2. Rule base or decision-making

The heuristic control rules that correspond the fuzzy output to the fuzzy inputs are obtained from analysis of the system behavior. Sometimes the control actions in the rule table might also be developed using “trial and error” and from an “intuitive” feel of the system to be controlled [53]. The control rules listed in Table III.1 for the dc–dc converter are determined from converter behavior. A typical rule can be written as follows.

If e is NB and de is PS then output is ZE Error (e), change of error (de) and output represent degree of membership.

ΔI_{bat}		***e***				
		NB	***NS***	***ZZ***	***PS***	***PB***
de	***NB***	*NB*	*NB*	*NS*	*NS*	*ZZ*
	NS	*NB*	*NS*	*NS*	*ZZ*	*PS*
	ZZ	*NS*	*NS*	*ZZ*	*PS*	*PS*
	PS	*NS*	*ZZ*	*PS*	*PS*	*PB*
	PB	*ZZ*	*PS*	*PS*	*PB*	*PB*

Table.III.1. fuzzy Table (Rules).

The fuzzy IF-THEN rule expresses a fuzzy implication relation between the fuzzy sets of the premise and the fuzzy sets of the conclusion. The rules IF part describes situation for which rules are designed and THEN part describes the response of fuzzy system. For example, IF the Error is NB and Change of Error is PS THEN Duty Cycle is ZE.

If the membership functions of the input variables provide a linear mapping between the inputs and the output of the controller, any control law can be directly implemented by choosing the output as the desired control law because the output is a function of the input variables.

The derivation of the fuzzy control rules is heuristic in nature and based on the following criteria [51,52,53]:

1) If the output of the converter is far from the reference point, the change of duty cycle must be large so as to bring the output to the reference point quickly.

2) If the output of the converter is approaching the reference point, a small change of duty cycle is necessary.
3) If the reference point is reached and the output is steady, the duty cycle remains unchanged.
4) If the output is above the reference point, the sign of the change of duty cycle must be negative.
5) If the output of the converter is far from the reference point, the sign of the change of duty cycle must be negative and large in order to bring the output to the reference point quickly.

III.4.2.3. Inference mechanism

The max-min inference method is used to obtain the control decision. It is based on the minimum function to describe the AND operator present in each control rule and the maximum function to describe the OR operator.[53]

III.4.2.4. Defuzzification

Conversion of the fuzzy to crisp or non-fuzzy output is defined as De-fuzzification. That is defuzzification unit transforms the fuzzy control actions to continuous (crisp) signals, which is applied to the physical plant.[53]

Figure III.5 represents the surface view of the rules for the proposed fuzzy logic control. The rules are represented as the combinations of the two inputs error and change in error for a function of output.

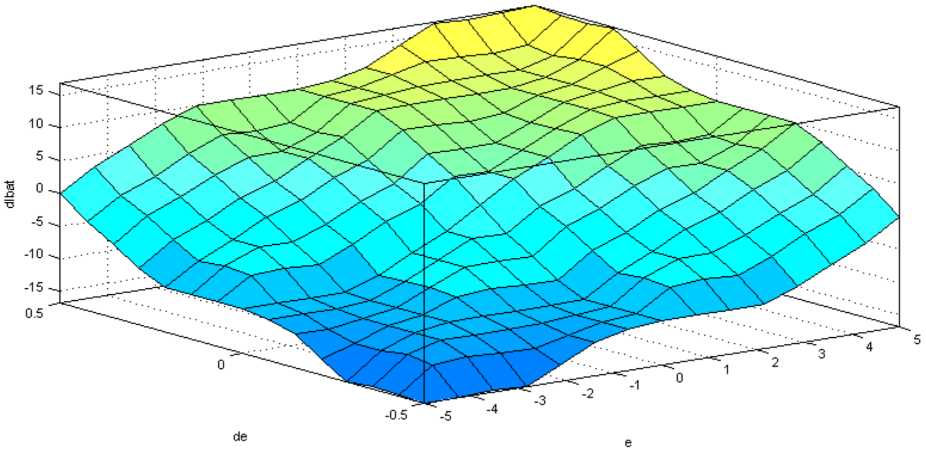


Fig.III.5. Rules in 3D surface.

The regulation of the DC bus voltage will be ensured by the converter associated with the battery pack. The control consists of two nested loops, one of which is external (voltage loop) develops the reference current of the battery pack I_{Bat_ref} which will be enslaved by the inner loop of current (see Figure III.6)

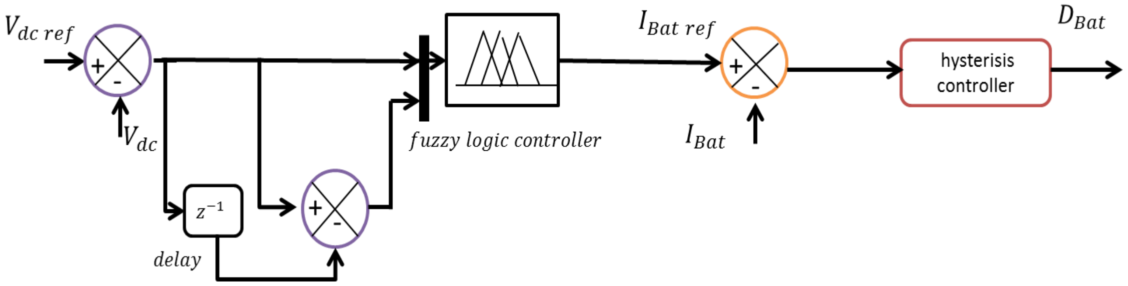
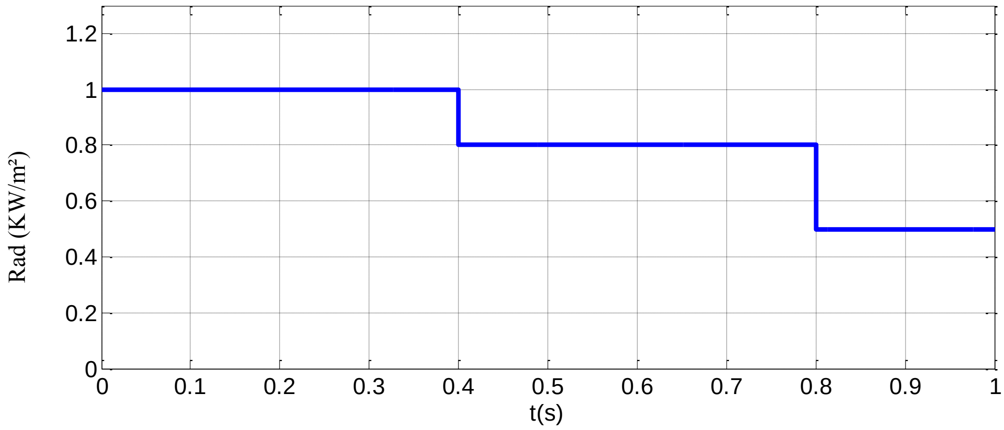


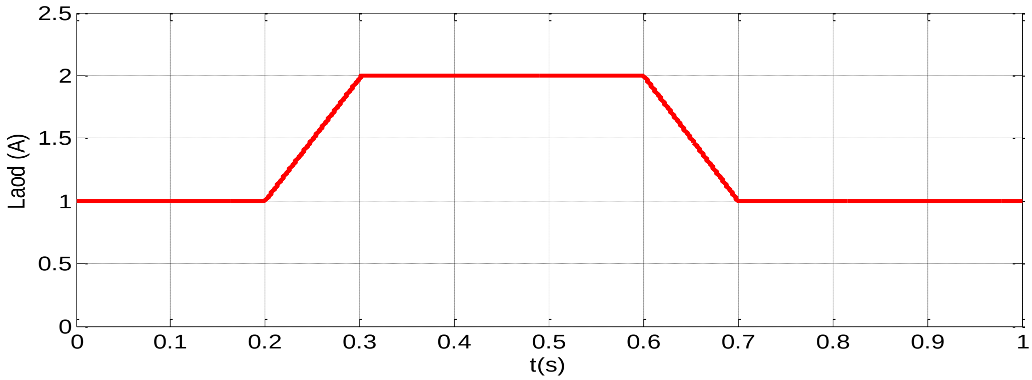
Fig.III.6. fuzzy logic controller for DC bus voltage regulation.

III.5. Comparative study and simulation results

This section is dedicated for comparing the performance of PI and FLC for regulating DC bus voltage. We consider two profiles for sun irradiations and load, as shown in the figure III.7 and figure III.8 respectively. The objective of the methodology is to evaluate and compare the performances of the PI and FLC controllers for DC bus voltage regulation.



III.7. Irradiation profile.



III.8. Load profile (current).

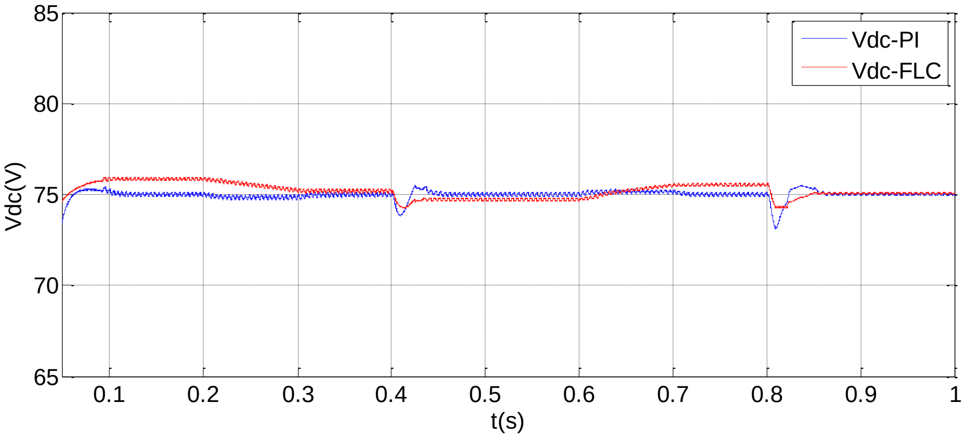


Fig.III.9. Regulation of DC bus voltage

Figure (III.9) shows the DC bus voltage controlled by the two controllers PI and FLC. As can be seen, from this latter both of the controllers PI and FLC provide acceptable performances but FLC is better. However, when the irradiation changes from 1000 W/m² to 800 W/m² and the load from 1 A to 2 A in deference instant , the DC bus voltage show a slight variation at t=0.4 s for both of them. Also at t=0.6 s the load changes from 2 A to 1A and at t=0.8 s the irradiation changes abruptly from 800 W/m² to 500W/m². The two controllers persist controlling the DC bus voltage to its desired value which is 75V with little deviation at t=0.8 s from 75 V to 74 V, one can be remark that the variation of the load has negligible effect on the DC bus voltage.

Elsewhere and as it has been mentioned in the literature, fuzzy logic provides a convenient non-linear control action as compared with the linear PI controller. Moreover, the PI parameters require a precise mathematical model of the system to be tuned; whereas, the FLC technique does not require specific and precise mathematical models for its designing and tuning, and it works well in case of imprecise, uncertain and obscure model. Furthermore, the FLC has much better performance, in terms of rapidity, accuracy and stability, and it works well with complex and time varied systems.

Figure III.10 presents the generated PV power using an irradiation profile. In fact, the produced PV power change according to the variations of sun irradiation at instants t=0.4 s and t=0.8 s.

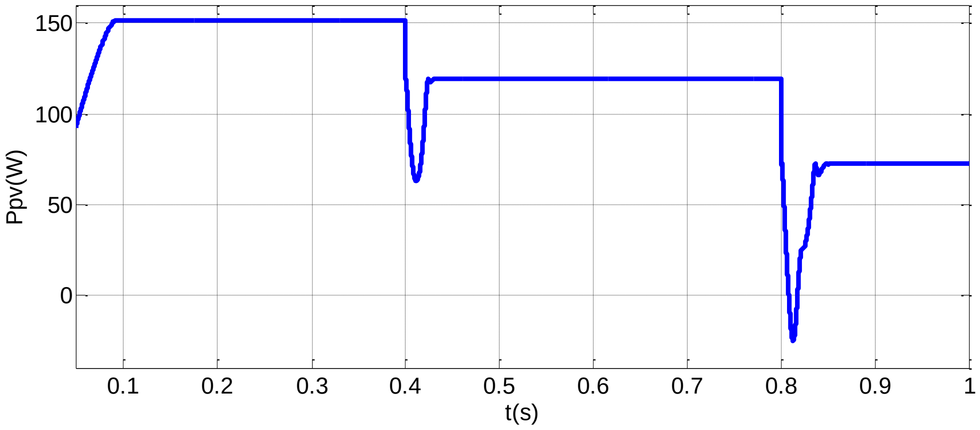


Fig.III.10. PV power.

As can be seen from figure III.11 that the load power is the image of the current (see figure III.8).

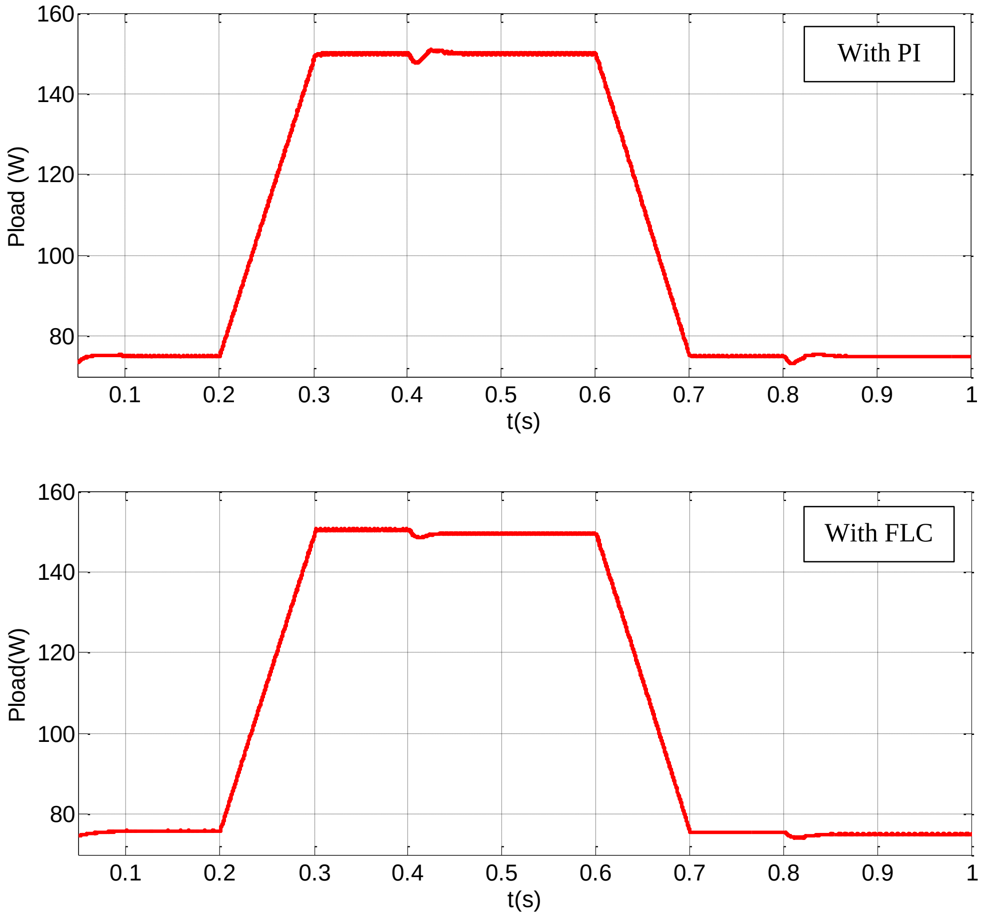


Fig.III.11. Load power.

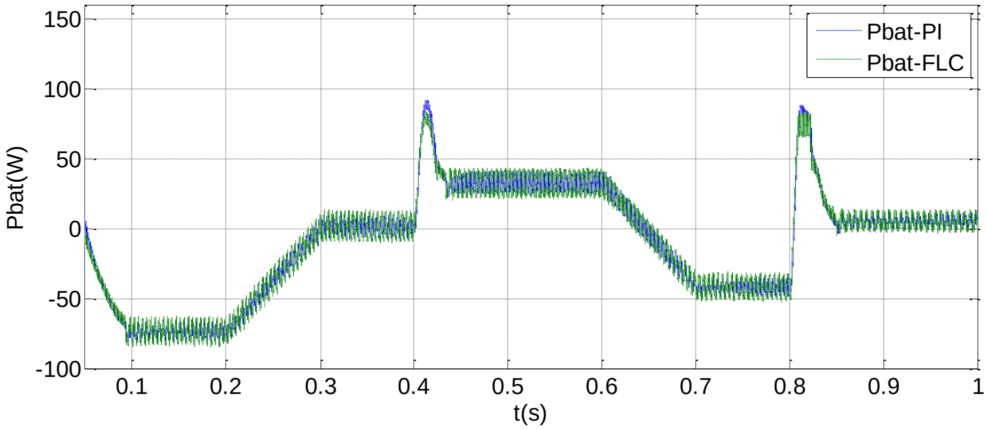


Fig.III.12. Battery power.

Figure III.12 shows the battery power delivered or stored to ensure the balance between the generated and consumed powers. Indeed, from t=0 to 0.3s and from t=0.6 s to t=0.8 s the battery power is negative that means it is in charging mode. Whereas, from t=0.4s to 0.6s and from t=0.8 to t=1 s the battery power discharge (positive value) because the load demand is greater than the produced power from the PV. It is noted that at t=0.4 s and at t=0.8 s peaks value of the battery power in the two cases (PI and FLC) due to brusque variation of the PV power at the same instance (see figure III.10).

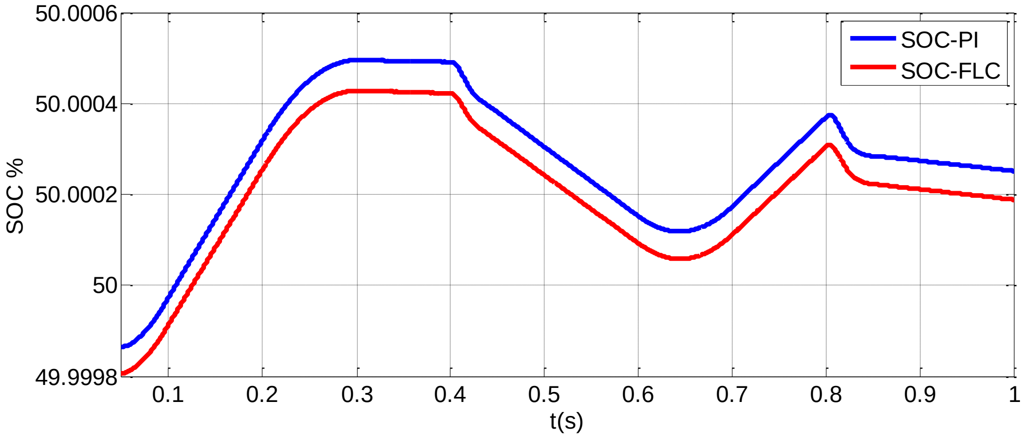


Fig.III.13. SOC Battery state of charge .

Figure III.13 shows the SOC of the battery. From this result, it is clear that the battery states of energy are asymptotically the same during the proposed profile. This confirms that the controllers can enhance the dynamic performances of the hybrid source without influencing on the energetic state.

- **Test under temperature variation**

This section is for testing the performance of PI for regulating DC bus voltage. We consider three profiles for temperature, sun irradiations and load, as shown in the figure III.14 and figure III.15 respectively. The objective of the methodology is to evaluate and compare the robustness and stability of the PI and FLC controllers.

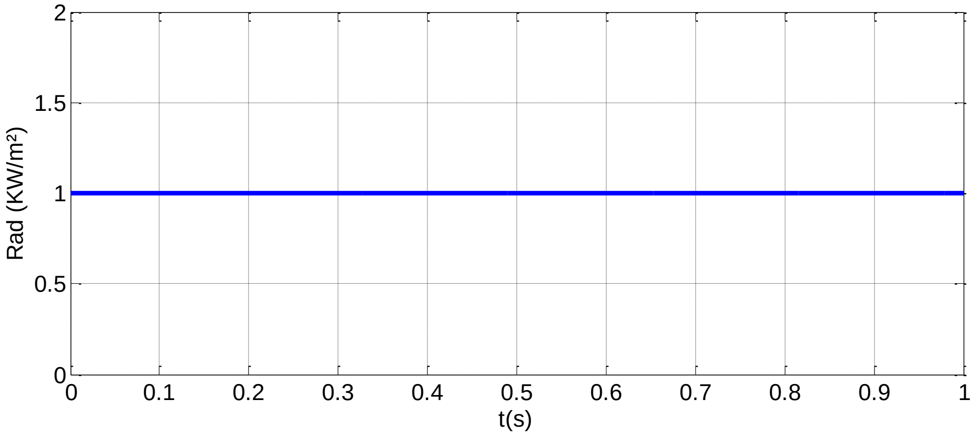


Fig.III.14. Irradiation profile.

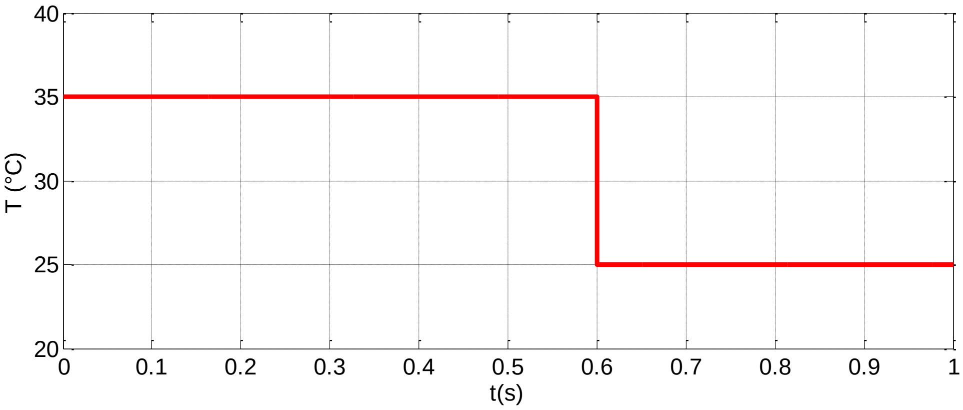


Fig.III.15. Temperature profile.

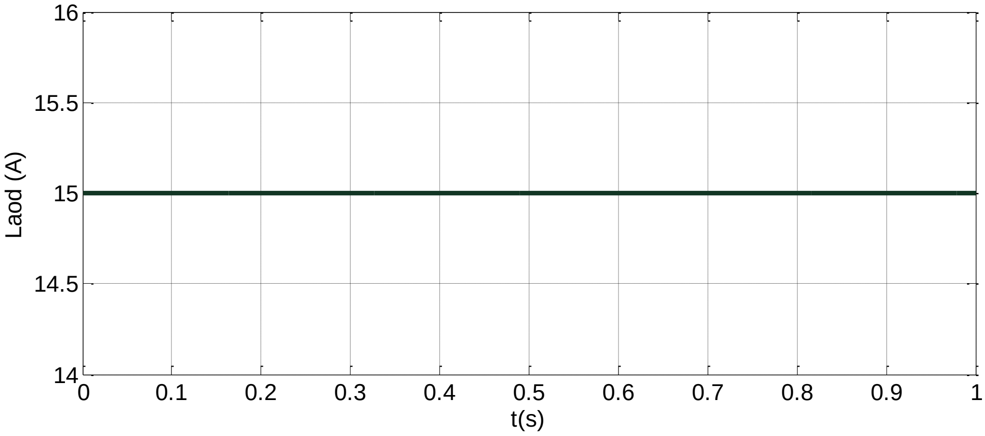


Fig.III.16. Load profile (current).

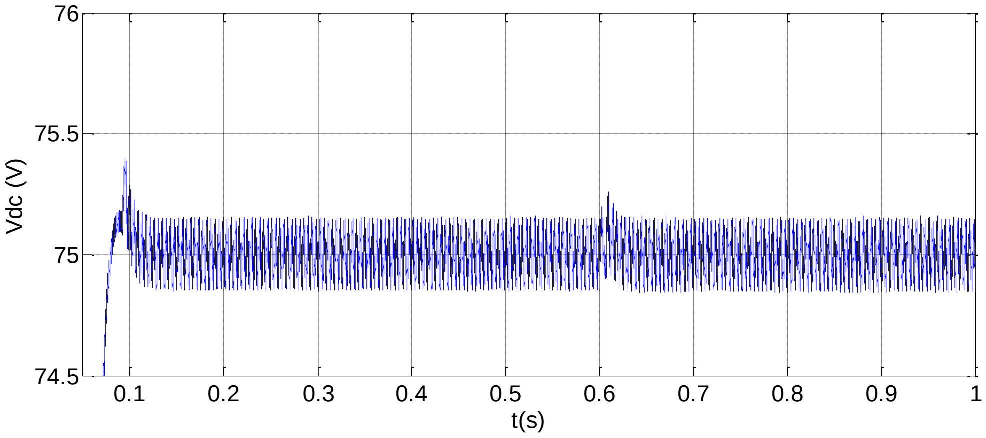


Fig.III.17. Regulation of DC bus voltage.

Figure (III.17) shows the DC bus voltage controlled by the controller PI. As can be seen, from this latter the controller provide acceptable performances. However, when the temperature changes from 35 °C to 25 at t=0.6 s, the DC bus voltage show a slight variation at t=0.6 s. The controller persist controlling the DC bus voltage to its desired value which is 75V, one can be remark that the variation of the temperature has negative effect on the DC bus voltage, that the temperature decreases the DC bus voltage increases.

Figure III.18 presents the generated PV power using a temperature profiles. In fact, the produced PV power change according to the variations of temperature at instants t=0.6 s.

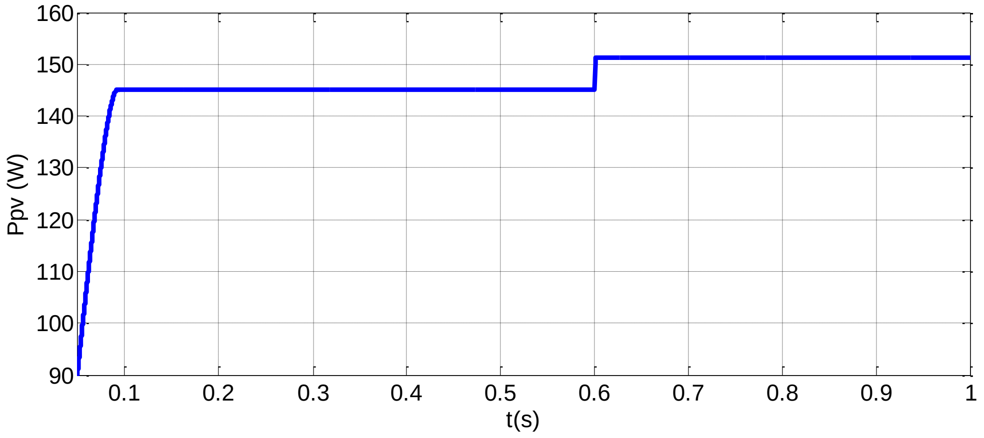


Fig.III.18. PV Power.

As can be seen from figure III.19 that the load power is the image of the current (see figure III.16) it’s remarked that effecting by the variation of temperature.

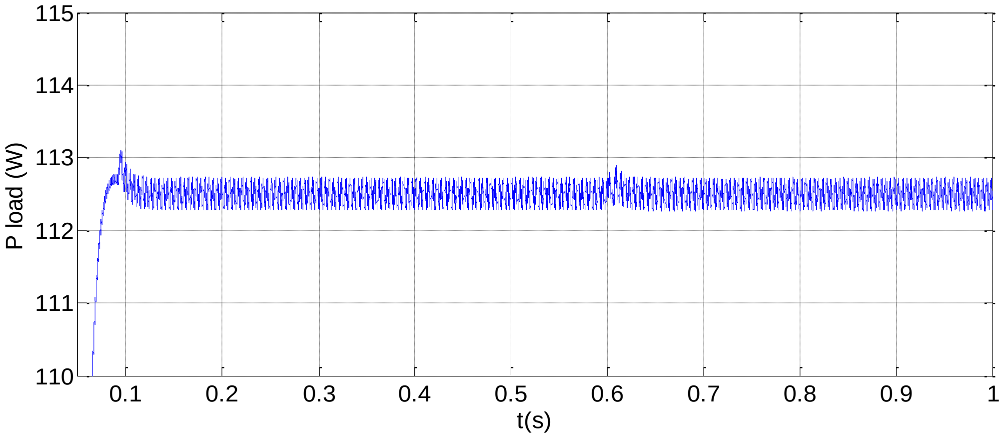


Fig.III.19. Load Power.

Figure III.20 shows the battery power delivered or stored to ensure the balance between the generated and consumed powers. Indeed, at t=0.6 s decreasing in Pbat due to brusque variation of the PV power at the same instance (see figure III.10).

Figure III.21 shows the SOC of the battery.

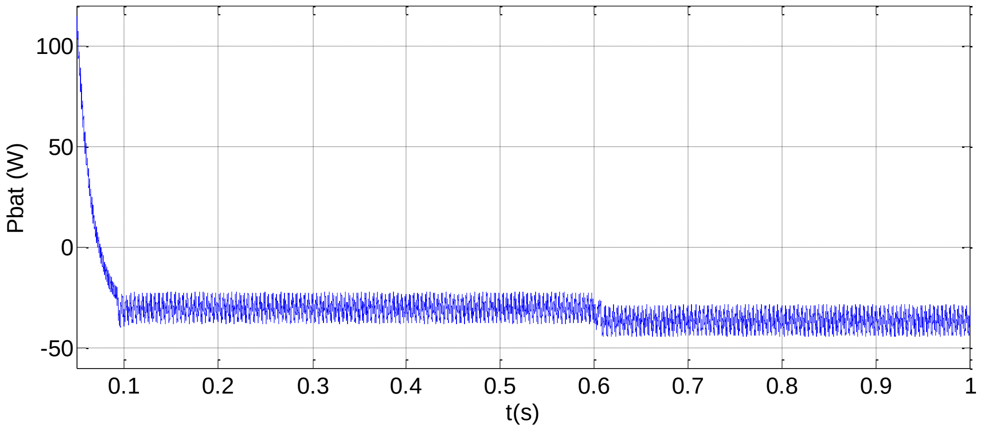


Fig.III.20. Battery Power.

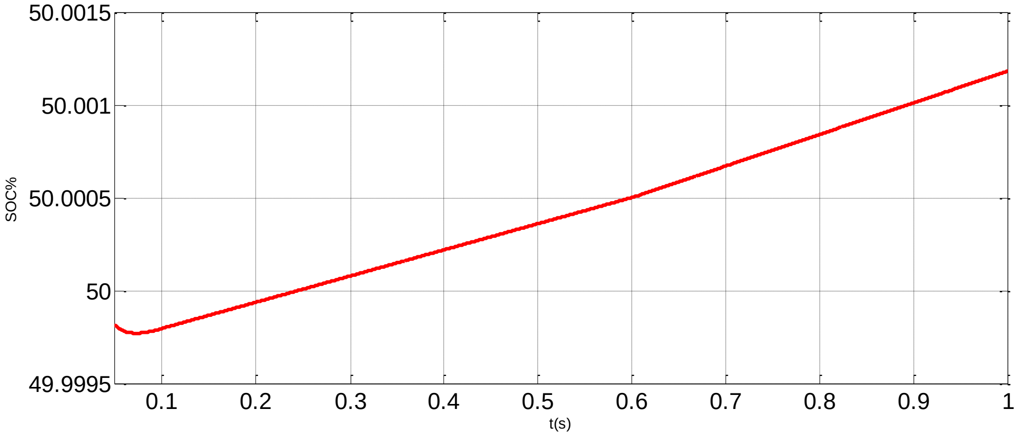


Fig.III.21. SOC State of charge of battery.

III.6. Hybrid control study and simulation results

From the last section, it is clear that FLC controller has some advantages in terms of perturbation reject and stability. Also, PI controller has good dynamic performances. For this reason, we use a hybrid controller PI-FLC proposed in [56] to obtain the advantages of the two controllers. The structure of this controller is described in figure below. The PI controller is used firstly to control the V_{dc} inaccuracy before that the FLC controller training its output.

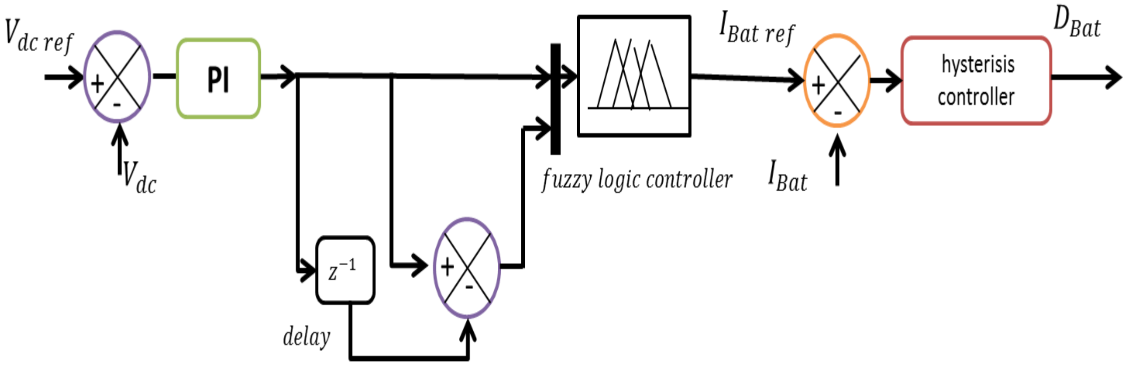


Fig.III.22. Hybrid controller PI-FLC.

In this simulation we used the same irradiation and load (current) profiles, the same conditions we had used them in the previous simulation of comparing between PI and FLC.

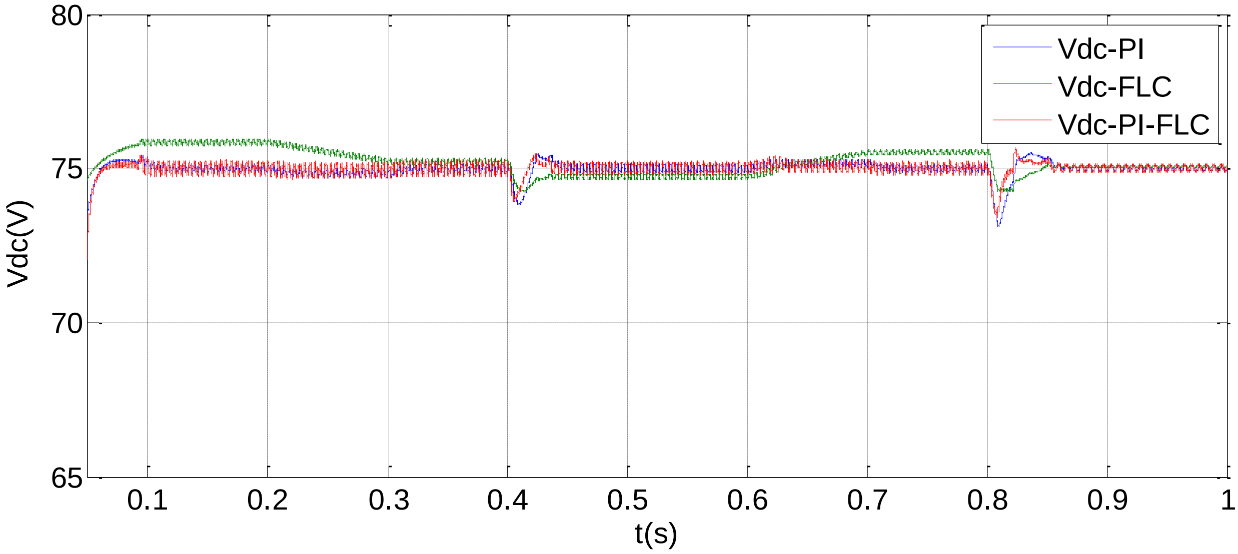


Fig.III.23.regulation of DC bus voltage with hybrid controller

Figure (III.23) shows the DC bus voltage controlled by the three controllers PI and FLC and PI-FLC. As can be seen, all of the controllers provide acceptable performances. The three controllers persist regulating the DC bus voltage to its desired value of 75V. It be remarked that the FLC controller is better than the others in terms of stability, robustness, precision and rapidity.

As can be seen in figure III.24 the influence of PV powers delivered, one can be remark that there is a small difference between the powers due to the persisting of controllers for regulating the DC bus voltage to desire value 75 V.

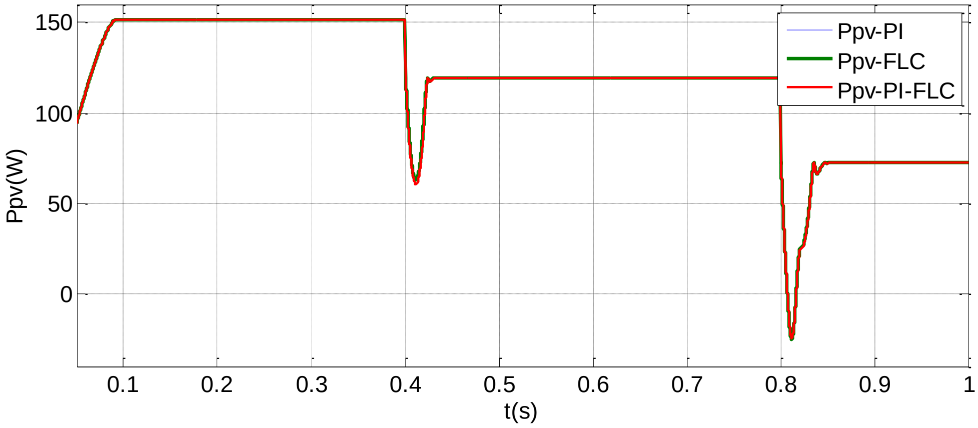


Fig.III.24. Ppv powers influence

Figure III.25 shows the battery power delivered or stocked to ensure the balance between the generated and consumed power. Indeed, we can remark the same variations in the three cases (PI and FLC and PI-FLC) due to brusque variation of the PV power at the same instances (see figure III.24).

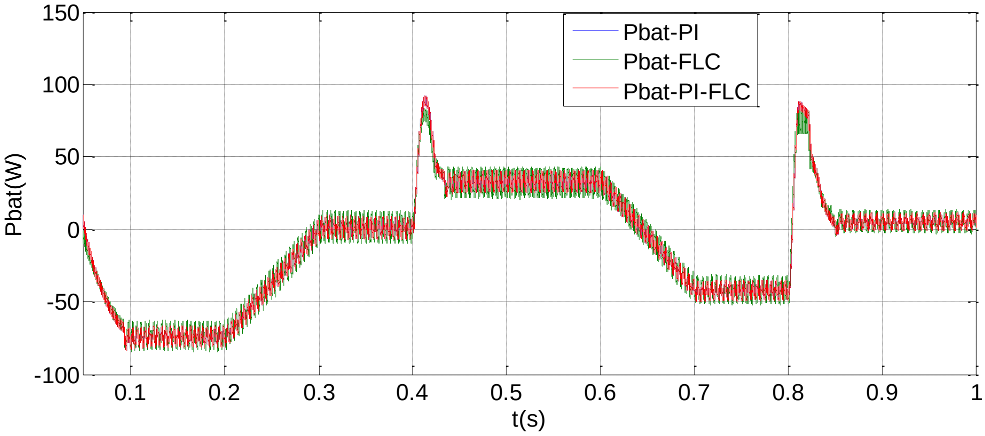


Fig.III.25. Battery power with hybrid controller

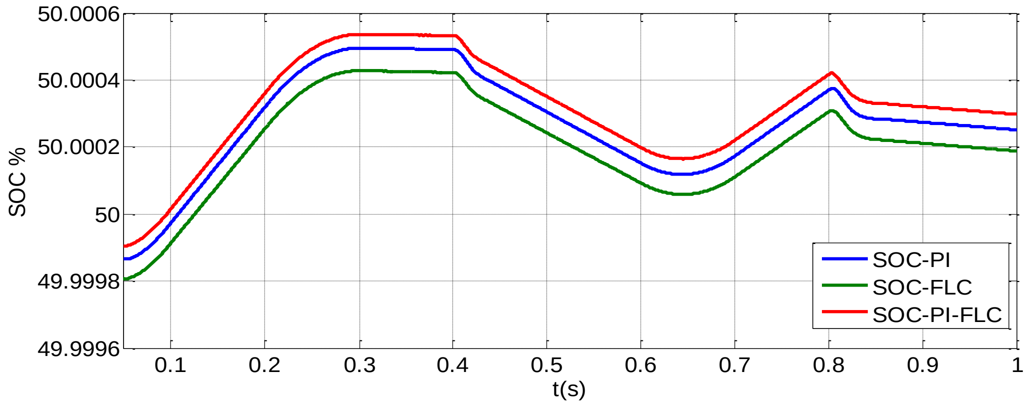


Fig.III.26. SOC State of charge of battery.

Figure III.26 shows SOC of the battery. From this result, it is clear that the battery states of energy are asymptotically the same during the proposed load profile. This confirms that the controllers can enhance the dynamic performances of the hybrid source without influencing on the energetic state of the battery.

III.6.Specific scenario with simulation results

This section is for presenting the performance of PI-FLC for regulating the DC bus voltage in unwanted status -scenario- . We suggest variable profile for sun irradiations as shown in the figure III.27 and constant profile for load as shown figure III.28, The state of charge (SOC) of the battery is very low (0.55%).

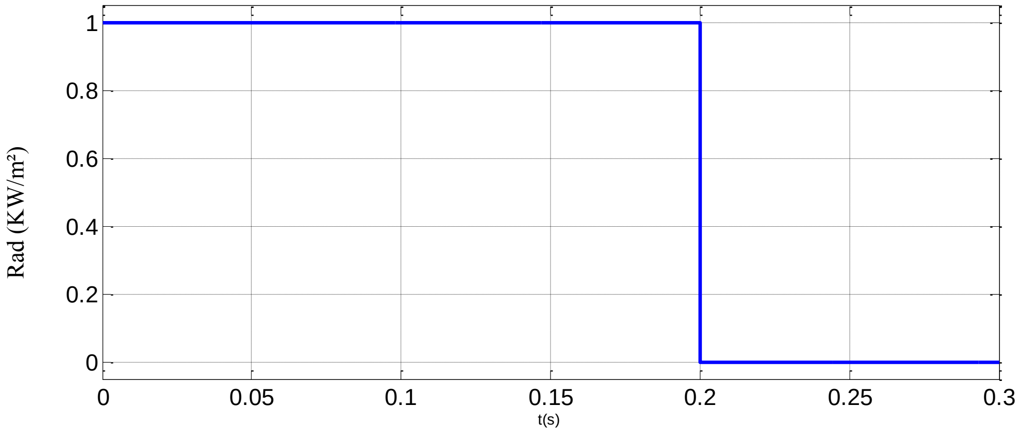


Fig.III.27. Irradiation profile.

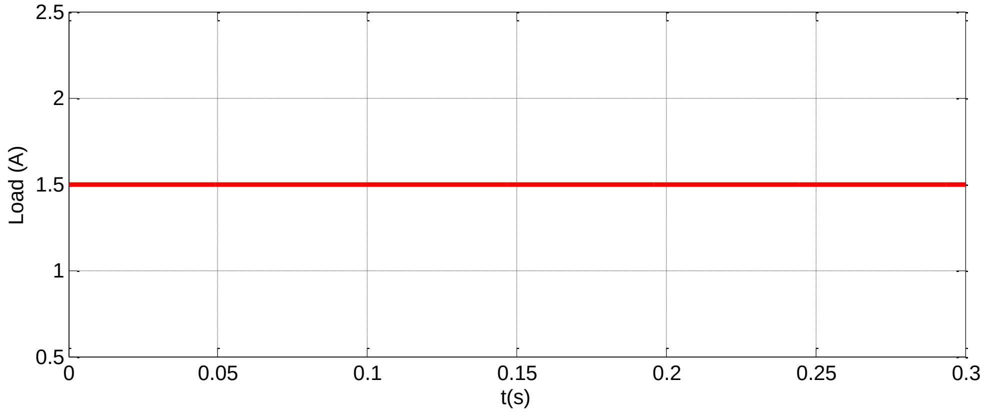


Fig.III.28. Load profile.

Figure III.29 present the DC bus voltage in unwanted scenario as can be seen at t=0.2s. It can be observed that DC voltage disturbance is appeared due to irradiation absence and the battery state of charge don't permit to ensure the load requirement.

The chattering has no meaning just that the controller PI-FLC is persisting to find current to regulate DC bus but there's no power delivered so it's not problem of control.

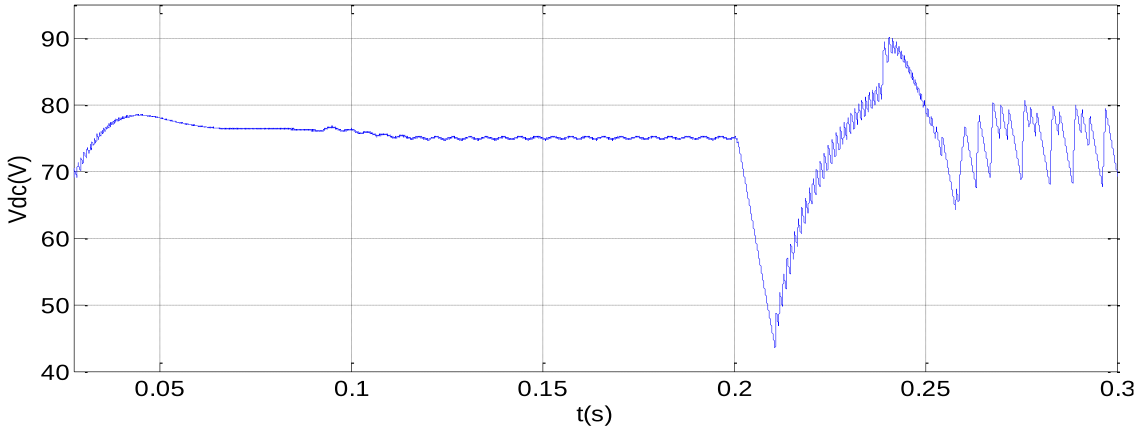


Fig.III.29. DC bus voltage in unwanted scenario.

Figure III.30 (curve Ppv) presents the generated PV power in the present scenario.

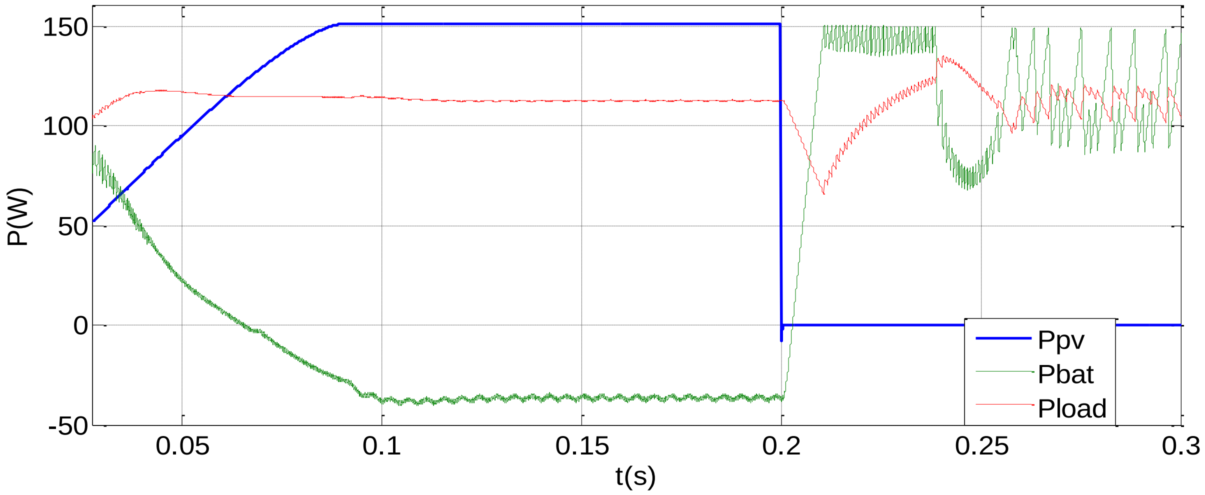


Fig.III.30. Powers with hybrid controller in Unwanted status.

Due to brusque variation of the PV power at the same instance (see figure III.30), the same changes happen on load power as shown in (curve P_{load}). Curve P_{bat} shows the battery power delivered or stored to ensure the balance between the generated and consumed power. It is clear that battery try to replace the PVG system but due to the low rate of its SOC, it can't deliver the required load power and the chattering phenomena is appeared which confirm the instability of the system.

Through this scenario and the obtained results, it is noted that the absence of the sun irradiation and the low level of battery's SOC naturally lead to the system completely stopped and from this, system needs another source of energy reserve to cover the inability of the system mentioned above in the same scenario. As a result, we propose the fuel cell as an additional source which is considered as a renewable energy storage unit supplied with hydrogen.

III.7 Conclusion

This chapter described the control and energy management of the battery/PV hybrid system in different conditions. The Perturb and Observe MPPT strategy was presented and applied to the PV in order to achieve the MPPT.

DC bus control was ensured using a cascade DC/DC inverter and Battery current. This last is ensured by hysteresis controller and the voltage is controlled using PI controller. After that this last was replaced with FLC one. The two controllers offer good performances however the FLC one more robust more PI, We have tested too PI controller to under temperature variation.

Finally, to benefice the advantages of the two controllers we have tested hybrid PI_FLC controller. The obtained results confirm the capability of this controller to provide good performances in terms of disturbance reject and stability.

General conclusion

General conclusion

The exploitation of renewable energies, especially solar energy, is emerging as a solution to several economic and natural problems such as pollution, and to urge the exploitation and simplification of ways is the duty of scientific researchers in this purview, and in this study we explained initially and in general some sources of renewable energy and focused on the solar energy and the PV system, as any energy needs to be stored for this we use the battery lead-acid, and we described a study of the mathematical model of the hybrid system and the simulation results,

In this study we adopted the classical PI controller to control DC voltage as an initial experiment and then replaced it with a fuzzy logic controller and then integrated it into the so-called PI-FLC. In order to control the DC bus voltage and make it more robust (less sensitive) to perturbation which is exposed to PV-battery system, requires accurate control to obtain the optimal result.

The problem we encountered was that when the sun is missing, the photovoltaic generator stops producing power. The battery is ready for this condition. It stores enough energy for use throughout the night, but sometimes a different circumstance may occur, such as the cloudy atmosphere. The photovoltaic generator stops and the battery's state of charge SOC is low, so we suggest here to use another energy source plays the role of feeding in this case and this source is the fuel cell, which has been explained, and its characteristics, advantages and disadvantages and areas of use in the first chapter.

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