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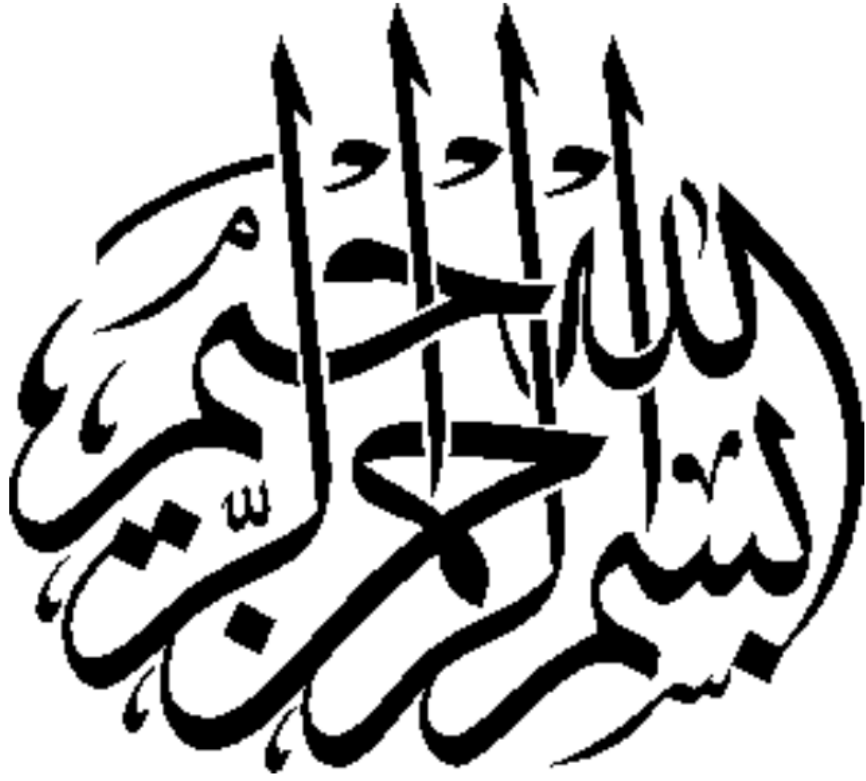
**Presented by:**

- Allag Dhia Elhak
- Touil oussama
- Ghenaim Abdelkamal
- Gheraissa Hocine

**Supervised by:**

- Dr. Mahmoudi Abdelkader

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﴿ رَبَّنَا لَا تُؤَاخِذْنَا إِنْ نَسِينَا أَوْ أَخْطَأْنَا رَبَّنَا وَلَا تَحْمِلْ عَلَيْنَا إصْرًا كَمَا حَمَلْتَهُ  
عَلَى الَّذِينَ مِنْ قَبْلِنَا رَبَّنَا وَلَا تُحَمِّلْنَا مَا لِطَاقَةِ لَنَا بِهِ وَاعْفُ عَنَّا وَاعْفِرْ لَنَا  
وَارْحَمْنَا أَنْتَ مَوْلَانَا فَانصُرْنَا عَلَى الْقَوْمِ الْكَافِرِينَ ﴾ سورة البقرة : الآية 286 .

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# DEDICATION

*In the name of God, the Merciful Praise be to Allah  
Almighty*

*We dedicate this humble work as respect, appreciation and  
thanks:*

*To our dear fathers, mothers and brothers who helped us from  
near and far.*

*To everyone who contributed to the development of this  
humble work and all these are dear to us.*



## Summary

Failures in photovoltaic (PV) power systems, whether due to manufacturing defects, material and electrical failures resulting from weather conditions, can significantly reduce efficiency and energy production, as well as compromise the overall safety and reliability of the PV installation. Swift detection and diagnostic isolation methods are essential for high operational safety, efficiency, and system reliability in PV cell installations. This work is part of the detection and identification of sensor devices and material failures in PV power systems using a modern technology based on artificial intelligence. In the first step of this work, we employed a Model-based method (residual), and in the second part of the work, we utilized a Signal-based method (artificial intelligence) to identify and classify types of failures in PV systems. The results obtained clearly demonstrate the performance of the developed networks in quickly detecting the occurrence of failures, estimating their durations, as well as providing strong decision-making capabilities in identifying the type of failure in the PV system

**Résumé:** Les défaillances dans les systèmes d'énergie photovoltaïque, qu'elles soient dues à des défauts de fabrication, des défaillances matérielles et électriques causées par les conditions météorologiques, peuvent réduire considérablement l'efficacité et la production d'énergie, ainsi que compromettre la sécurité et la fiabilité globale de l'installation photovoltaïque. Des méthodes rapides de détection et d'isolement des défaillances sont indispensables pour garantir une sécurité opérationnelle élevée, une efficacité optimale et la fiabilité du système dans les installations de cellules photovoltaïques. Ce travail fait partie de la détection et de l'identification des dispositifs de capteurs et des défaillances matérielles dans les systèmes d'énergie photovoltaïque en utilisant une technologie moderne basée sur l'intelligence artificielle. Dans la première étape de ce travail, nous avons utilisé une méthode basée sur le modèle (résiduelle), et dans la deuxième partie du travail, nous avons utilisé une méthode basée sur le signal (intelligence artificielle) pour identifier et classer les types de défaillances dans les

systemes photovoltaïques. Les résultats obtenus démontrent clairement les performances des réseaux développés dans la détection rapide des défaillances, l'estimation de leur durée, ainsi que la prise de décision solide pour identifier le type de défaillance dans le système photovoltaïque.

**ملخص:** يمكن أن تؤدي الأعطال في أنظمة الطاقة الكهروضوئية لأنواع التصنيع، أو الأعطال المادية والكهربائية الناتجة عن الظروف المناخية إلى تقليل الكفاءة وإنتاج الطاقة بشكل كبير، فضلاً عن سلامة وموثوقية التركيب الكهروضوئي بأكمله. لا يتم تحديدها وتصحيحها بسرعة. تعد طرق اكتشاف الأعطال والعزل التشخيصي ضرورية للسلامة وكفاءة التشغيل العالية وموثوقية النظام لتركيب الخلايا الكهروضوئية. هذا العمل هو جزء من الكشف والتعرف على أجهزة الاستشعار والأعطال المادية في أنظمة الطاقة الكهروضوئية بتقنية حديثة تعتمد على الذكاء الاصطناعي. في الخطوة الأولى من هذا، استخدمنا

(Model based method (residual)) ، وفي الجزء الثاني من العمل، استخدمنا (Signal based method (artificial intelligence)) تحديد وتصنيف أنواع الأعطال في الأنظمة الكهروضوئية. تظهر النتائج التي تم الحصول عليها بوضوح أداء الشبكات المطورة للكشف السريع عن ظهور الأعطال مع تقدير أوقاتها وكذلك القرار القوي لتحديد نوع الأعطال في النظام الكهروضوئي.

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## Notations

$x(t)$  Observed signal

$y(t)$  Output signal

$u(t)$  Input signal

$y_m(t)$  Measured signal

$r(t)$  Residuals

$\hat{y}(t)$  Estimated signal

$f(t)$  Fault signal

$d(t)$  Disturbance signal

$e(t)$  Error signal

$\theta_n$  Nominal parameter vector

$\theta$  Estimated parameter vector

$A \in Rn \times n$  State or evolution matrix

$B \in Rn \times m$  Input matrix

$C \in Rp \times n$  Output or observation matrix

$\mathcal{D}_x$  Disturbance action matrix

$\mathcal{F}_x$  Fault action matrix

$\mathcal{F}_y$  Fault action matrix

$L$  Observer gain matrix

$W$  Parameter matrix

$w_T$  Network weight matrix

$g$  Nonlinear function of the networks

$d_k$  Desired network output

$F$  Neuron transfer function

$\alpha$  Learning coefficient

$V_{oc}$  Open-circuit voltage point

$I_{sc}$  Short-circuit current point

$T$  Temperature [ $^{\circ}\text{C}$ ]

$G$  Solar irradiation [ $\text{W}/\text{m}^2$ ]

$I$  Current supplied by the cell [ $\text{A}$ ]

$V$  Voltage at the cell terminal [ $\text{V}$ ]

$I_{ph}$  Current equivalent to the received solar radiation on the cell [ $\text{A}$ ]

$I_0$  Reverse saturation current of the diode [ $\text{A}$ ]

$V_t$  Diode thermal voltage [ $\text{V}$ ]

$R_s$  Cell series resistance [ $\Omega$ ]

$R_{sh}$  Cell shunt resistance [ $\Omega$ ]

$a_1$  Diode ideality factor of D1

$a_2$  Diode ideality factor of D2

## Chapter I

### Photovoltaic systems: An Overview

#### I.1. Introduction

Photovoltaic solar energy refers to the energy recovered and transformed directly electricity from sunlight through photovoltaic panels. She results from the direct conversion in a semiconductor of a photon into an electron.

Photovoltaic solar energy is a non-polluting source of energy is available in abundance over the entire earth's surface, and despite significant attenuation when it passes through the atmosphere, the amount that remains is still quite large when it hits the ground. We can thus count on 1000W/m<sup>2</sup> peak in areas temperate and up to 1400 W/m<sup>2</sup> when the atmosphere is slightly polluted.

#### I.2. What is photovoltaics?

Photovoltaics is the technology that generates direct current (DC) electrical power measure in Watts (W) or kilowatts (kW) from semiconductors when they are illuminated by photons. As long as light is shining on the solar cell (the name for the individual PV element), it generates electrical power. When the light stops, the electricity stops. Solar cells never need recharging like a battery. Some have been in continuous outdoor operation on Earth or in space for over 30 years [1] .

### I.3. History of photovoltaics

The photovoltaic effect, discovered by Antoine Becquerel in 1839, allows light energy to be converted into electricity. This principle is based on semiconductor technology. It consists of using photons to release electrons and create a potential difference between the terminals of the cell which generates a direct electric current. Heli electricity appeared in 1930 with cuprous oxide and then selenium cells. But it was not until 1954, with the production of the first silicon photovoltaic cells in the laboratories of the Bell Telephone company, that the possibility of supplying energy was foreseen. Very quickly used to power space vehicles around the 1960s with space satellite equipment. Then from 1970, the first terrestrial uses concerned the electrification of isolated sites. During the 1980s, terrestrial photovoltaic technology progressed steadily with the installation of several power plants of a few megawatts, and even became familiar to consumers through many low-power products using it: watches, calculators, radio beacons and meteorological, pumps and solar refrigerators. The progress of photovoltaic cell production techniques as well as the increase in production volumes led, from the 1990s, to a drop in prices. Modules are produced in China (nearly 60% of production Photovoltaic Solar Energy Course total), in Japan, the US, Germany and Europe, with in particular large companies such as Yingli Green Energy, First Solar and Sentech Power. The global production of photovoltaic modules increased from 5 MWp in 1982 to more than 18GWp in 2013. Concerning Algeria, the Algerian group Condor Electronics, launched in July 2013 in the production of photovoltaic panels whose power varies between 70 W and 285 W and at competitive prices.

As part of the realization of the Algerian national renewable energy program, a 400 MW photovoltaic project was launched, part of the complementary electricity production program, planned for the summer of 2014. This project consists of the realization 23 photovoltaic solar power plants, in the highland's region and in the south west region; as well as in the region of the great south. In the next ten years, it is planned to build a renewable energy park of 5539 MW. The objective for 2030 is 12,000 MW of renewable energy for internal electricity consumption. The cumulative installed photovoltaic power worldwide reached 138.9 GW at the end of 2013. [2]

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

When light hits the surface of materials it might be reflected, transmitted or absorbed mostly converting the photon energy to heat. However, some materials have the characteristic of converting the energy of incident photons in to electricity. Photons give their energy to electrons based on the conservation of momentum and energy principals. The liberated electrons can move across the crystal. This is called photovoltaic effect These materials which have an energy band gap between the conduction band and the valence band are named semiconductors. Valence band is the energy level in which the electrons are bound to host atoms, while the conduction band is the energy level of electrons taken from an external source causing them no longer bound to the host atom. At the absolute zero temperature no electron is in the conduction band. As the temperature elevates some electrons receive energy and go up from the valence band to the conduction band creating an energy-hole-pair (EHP). If the energy of the incident photon is larger than the energy band gap of the semiconductor the photon energy will be absorbed and EHP will be produced. The remainder of the difference between photon energy and band gap dissipates into heat. Semiconductors are classified into two groups, the direct band gap and indirect band gap semiconductors. A direct band gap material can be several times thinner than the indirect band gap ones while still capable of absorbing a considerable amount of incident radiation There exists an electrical field in semiconductor materials to which the liberated electrons can drift. The force caused by this electrical field leads the electrons to travel to n-side of the junction whereas the holes to its p-side. Adding some materials by means of doping invigorates the electrical field. For more clarification, as an instance, phosphor gives electron to silicon and boron adds holes creating n type and p type silicon respectively. The current from pside to n-side through external wire depends on the number of EHPs generated in the junction; this current is named photo current. To maximize photo current the number of photons absorbed in either junction itself or the diffusion length should be increased. [3]

## I.5. Solar energy

The energy received from the sun on the earth's surface in one hour equals to the amount of approximately one-year energy needs of the earth. Sun acts like a black body radiator with the surface temperature of 5800 K which leads to a 1367 W/m<sup>2</sup> energy density over the atmosphere.

While designing PV systems, the spectral factor should be studied and taken into consideration.

The importance of having a profound knowledge of the sun spectrum lies on the fact that this knowledge can help to understand the effects of atmosphere on the radiation and guides us to select the best materials for solar cells.

As it is observed in Fig. 1, almost the entire spectrum at low temperatures is located outside the visible range, specifically in the infrared section. The visible range contains the highest energy density. Therefore, the materials chosen for the solar cells should have the capability to absorb the energy in the visible range.

Sunlight is comprised of direct radiation – also named beam radiation – which is the sunlight received by the surface of earth diffuse radiation which is also called scattered sunlight and albedo radiation that is the reflected sunlight from the ground. The sum of these three components of light is named global radiation.

When the global radiation enters the atmosphere of the earth, molecules in the atmosphere might cause three cases, they may absorb, scatter or pass the light unaffected. The ultra violet region of sunlight is mostly absorbed by the ozone layer of the atmosphere while the CO<sub>2</sub> and water vapor particles are influential on the visible and infrared regions. The objects on the ground level might also reflect or absorb the light. Air mass is a critical factor affecting the amount of energy absorbed on the ground surface. As a result of particulate matter

existence in atmosphere and the length of the path solar light travels through atmosphere, the AM0 irradiance level – just above the atmosphere – drops from 1367 to 1000 W/m<sup>2</sup> corresponding to the AM1 –at sea level. AM1.5 is addressed as the standard test condition

in solar cell design. [3]

### **I.5.1. Units used**

Illuminance or irradiance is defined as the power received by a surface. It is expressed in W/m<sup>2</sup> (watts per square meter). The SI (International System of Units) recommends using the symbol E.

Irradiation or radiation is the energy received by a surface. It is expressed in J/m<sup>2</sup> (joules per square meter). The ISES (International Solar Energy Society) recommends the symbol H. Other commonly used units include Wh/m<sup>2</sup> (watt-hours per square meter), although the latter should not be used since it does not belong to the International System of Units (SI).[3]

### **I.5.2. Quantities related to illuminance**

#### **a) Duration of sunshine**

The duration of sunshine is measured with heliographs whose threshold is 120 W/m. Be careful not to confuse the number of hours of sunshine and the number of hours of equivalent full sunshine, derived from the annual global irradiation measured in the horizontal plane. [4]

#### **b) Solar fraction**

This is the parameter that represents the cloudiness conditions of the sky. Cloudiness is the ratio between the surface of the sky covered by clouds and the total surface of the sky above the corresponding territory. Since this notion is purely descriptive, it is related to the sunshine fraction, which is a measurable quantity once the durations of sunshine recorded by the heliograph are known, and which is derived from the ratios  $S/S_0$ , where S is the measured duration of sunshine and  $S_0$  is the maximum duration of sunshine.[4]

#### **c) Radiation spectrum**

The solar spectrum is the spectral distribution as a function of wavelength or frequency, as shown in the (figure I.1) below. The energy of each photon is related to the frequency  $\nu$  or the wavelength  $\lambda$  by the following formula:

$$E = h \cdot \nu = h \cdot c / \lambda$$

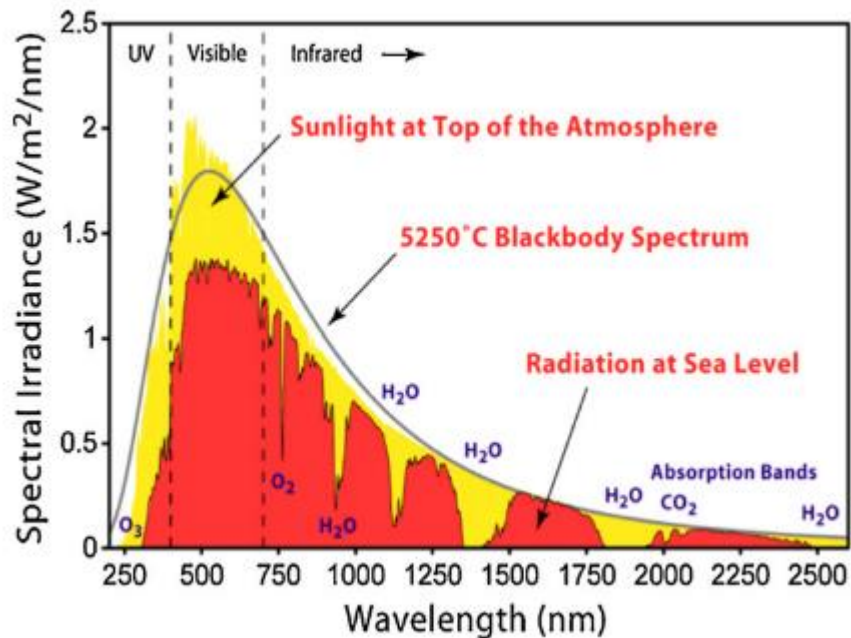
where h is Planck's constant, and c is the speed of propagation.

The spectrum of extraterrestrial radiation corresponds to the emission of a blackbody at 5800 K. A standard curve, compiled from data collected by satellites, is known as AM0. Its energy distribution is divided into[5]:

Ultraviolet UV  $0.20 < \lambda < 0.38 \mu\text{m}$  6.4%

Visible  $0.38 < \lambda < 0.78 \mu\text{m}$  48.0%

Infrared IR  $0.78 < \lambda < 10 \mu\text{m}$  45.6%



**Figure I.1.** The solar radiation spectrum regarding to its wavelength

#### d) Solar radiation

The heat generated during the thermonuclear fusion of hydrogen at the core of the Sun travels through its various layers until it reaches the surface (photosphere) where it is released as solar radiation or particle flux. Therefore, the heat of the Sun is converted, at its surface, into light in the form of particles called photons. This flow of photons forms electromagnetic waves that propagate without loss of energy in all directions of space, including towards the Earth.

The radiation emitted by the Sun is composed of a set of electromagnetic waves ranging from cosmic rays, particles with extremely high speed and energy, to radio waves and gamma rays, passing through visible light.[6]

Solar radiation is divided into two parts:

### a) Global radiation

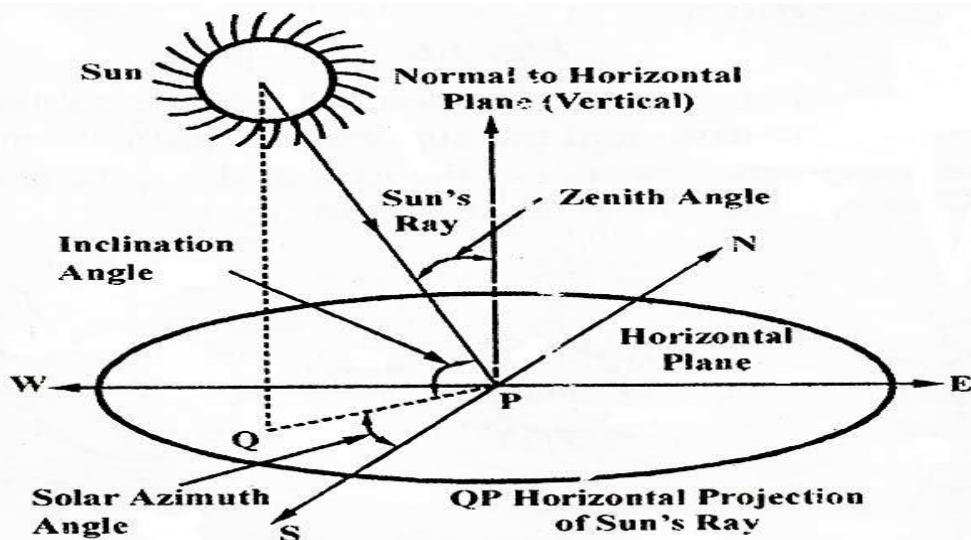
Global radiation is the sum of all received radiation (direct radiation, diffuse radiation, and albedo).

### b) Reflected radiation

It is the useless part of solar radiation that is scattered by atmospheric obstacles.

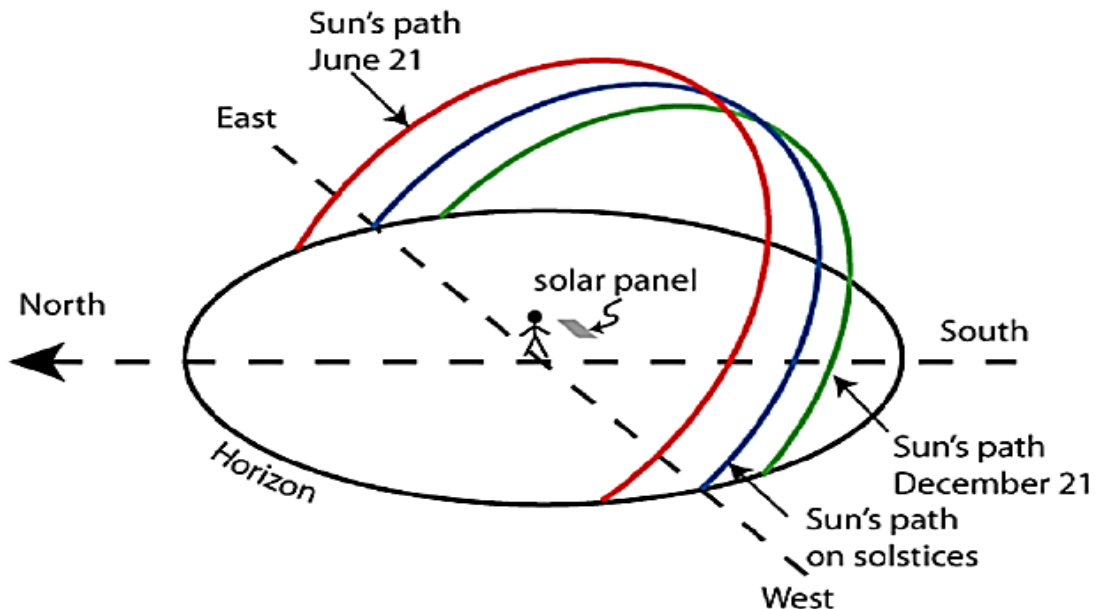
## I.6. Apparent path of the sun

For an observer located on the surface of the Earth, the sun follows an apparent path that depends on the latitude (elevation) and longitude (azimuth) of the location. Recall that latitude is the angular distance of any point on the globe relative to the equator (ranging from  $0^\circ$  to  $90^\circ$  in the northern hemisphere). As for longitude, it is also an angle given relative to the Greenwich meridian when moving eastward (figure I.2). The apparent movement of the sun is about  $240^\circ$  in azimuth and  $70^\circ$  in elevation for latitudes.[7]



**Figure I.2.** Representation of angular latitude (elevation) and azimuth

The sun moves during the day and throughout the seasons (figure I.3). However, the solar panel is usually in a fixed position, which results in valuable energy losses. A fixed installation, ideally oriented towards the south, delivers power that slowly increases early in the morning and decreases significantly in the afternoon. A significant portion of the recoverable energy is thus lost.



**Figure I.3.** Definition of the position of the sun (latitude and azimuth).

If the installation constantly faces the sun, it generates a maximum amount of electricity. A fixed installation of 1 kW, oriented optimally, produces about 5 kWh of solar electricity per day of sunlight. The same 1 kW installation with a "tracker," however, can provide up to 10 kWh per day, which is a 50% increase in energy gain. Thus, only automatic rotation can allow the solar panel to deliver maximum power.[7]

## I.7. Operating Principles of a cell

### I.7.1. Semiconductor materials

Solar photovoltaics is made of a semiconductor material. A semiconductor is not a good conductor of electricity and is a material whose resistivity lies between the conductor and the insulator (i.e.,  $10^{-4}$ – $0.5$  ohmmeter), for e.g., silicon, germanium, selenium. However, the resistance of the semiconductor decreases with increase in temperature, which shows that a semiconductor has a negative temperature coefficient. The valence band of the semiconductor is almost filled by electrons; whereas the conduction band is nearly empty. The forbidden energy gap

is very less, about 1 eV, therefore, a small amount of energy is required for valence electrons to move toward conduction band. [8]

### **I.7.2. Classification of Semiconductors**

Semiconductors can be classified as: (1) intrinsic (pure semiconductor) and (2) extrinsic (impure semiconductor)

#### **a) Intrinsic semiconductor:**

Intrinsic semiconductor can also be known as a pure semiconductor. At room temperature, electron–hole pairs are created. When a potential is applied across it, conduction commences through free electrons and holes caused due to the breaking of covalent bonds through thermal energy. Therefore, the current flow in the intrinsic semiconductor is a combination of electron and hole.[8]

#### **b) Extrinsic semiconductor:**

At room temperature, the intrinsic semiconductor has very less conduction. Therefore, for improving the conductivity of the intrinsic semiconductor, a small amount of impurity is added. This semiconductor is now called an extrinsic semiconductor.

The process of the addition of impurities to the intrinsic semiconductor is called doping. In this process, either the number of electrons increases or the number of holes increases depending on the type of impurity added. Two types of impurities are added: (1) pentavalent and (2) trivalent. Addition of pentavalent impurity produces free electrons, while in case of trivalent impurity, additional holes are generated. Further differences between intrinsic and extrinsic semiconductor are given in (Table 1).[8]

**Table 1:** Difference between intrinsic and extrinsic semiconductor

<b>Factors</b>	<b>Intrinsic semiconductor</b>	<b>Extrinsic semiconductor</b>
Purity of semiconductor	Pure semiconductor	Impure semiconductor
Density of electrons	Density of electrons is equal to the density of holes	Density of electrons is not equal to the density of holes
Electrical conductivity	Electrical conductivity is low	Electrical conductivity is high
Temperature effect	Dependence on temperature only	Dependence on temperature as well as on the amount of impurity only
Impurities	No impurities	Trivalent impurity, pentavalent impurity

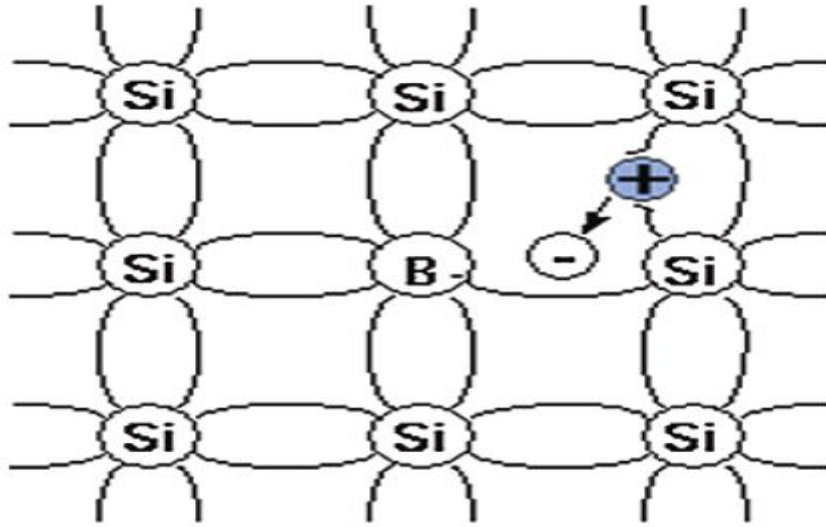
### I.7.3. Types of Extrinsic Semiconductors

#### b) P-type semiconductor:

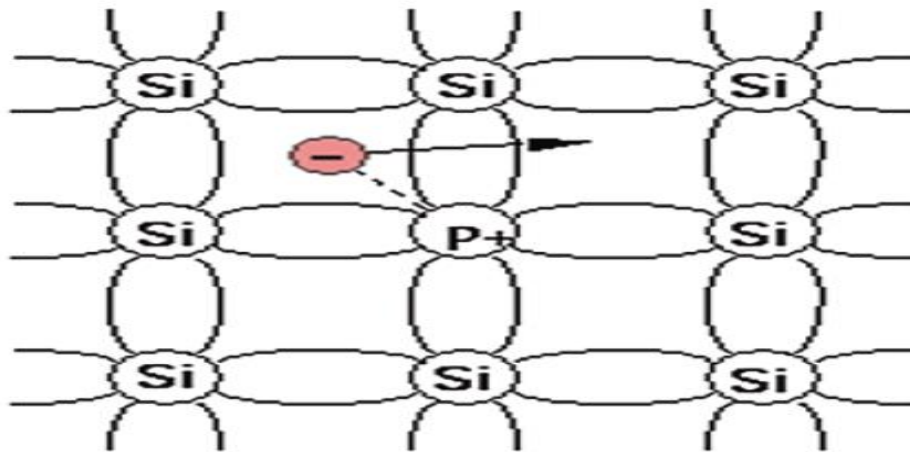
P-type semiconductor is formed by the addition of a small quantity of trivalent type impurity to an intrinsic semiconductor. The trivalent impurities result in additional holes, which accept the electrons in the semiconductor; therefore, these impurities are also called acceptor impurities (figure I.4). [8]

#### c) N-type semiconductor:

N-type semiconductor is formed by the addition of a small quantity of pentavalent type impurity to an intrinsic semiconductor. The addition of pentavalent impurities in pure semiconductor causes additional electrons in the semiconductor. The pentavalent impurities are also known as donor impurities as they donate free electrons to the semiconductor (figure I.5). [8]



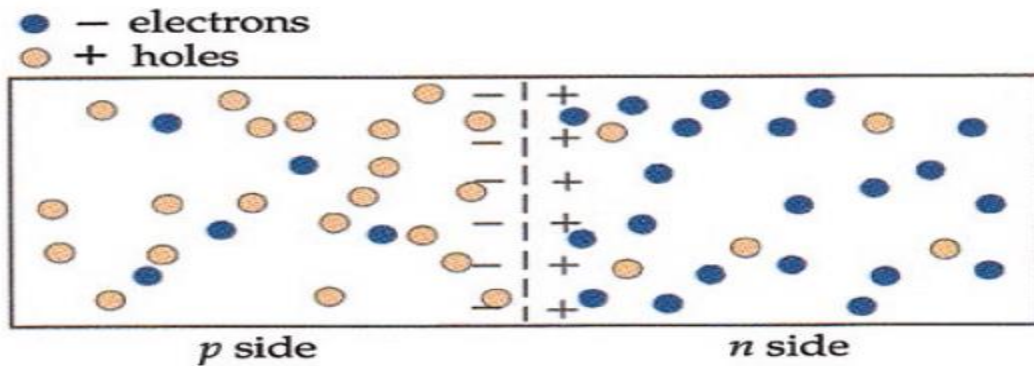
**Figure I.4.** Structure of p-type semiconductor



**Figure I.5.** Structure of n-type semiconductor

## I.8. Formation of Photovoltaics

To develop a photovoltaic cell, two kinds of semiconductors are sandwiched together. When p-type and n-type semiconductors are joined together, they form a p–n junction or a solar cell. The p–n junction is the control element for a solar cell; thus, electrons will only flow in one direction but not in the other. In forward biased direction, current flows from p to n semiconductor or behaves like a short circuit, while in reverse direction, current does not flow and thus behaves like an open circuit. Structure of p–n photovoltaic cell is shown in (figure I.6). When the photovoltaic cell is exposed to sunlight, it reduces the width of the depletion layer and the current flows into the connected electrical



load.[8]

**Figure I.6.** Structure of photovoltaic

## I.9. Generations of Photovoltaic

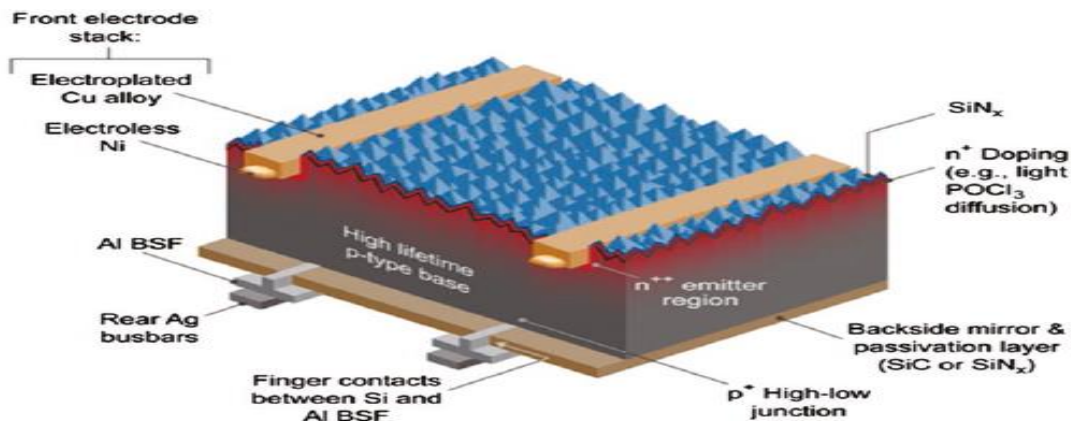
### I.9.1. First Generation

First generation solar cells refer to single-junction devices with large surface area, good quality, highly efficient, and high cost. These cells are usually fabricated using a silicon wafer. Structural view of crystalline solar cell is shown in (figure I.7). This generation of solar cell consists of monocrystalline and polycrystalline silicon solar cells. The monocrystalline silicon solar cell is the oldest solar cell technology. It is drawn from the Czochralski (CZ) method. A silicon ingot is made from a molten vat. Then, it is sliced into a number of ingots forming the substrate of the solar cell. The monocrystalline panels have shown the highest laboratory efficiency at about 24 %.

The main drawback of the monocrystalline solar cell is its high cost due to the expensive fabrication process.

Another drawback is its decrease in efficiency as temperature increases to about 25 °C. Proper maintenance is required for installing the panel such that air circulation is provided over the panel. Polycrystalline silicon solar cells are cheaper than monocrystalline solar cells, but suffer from less efficiency due to nonuniform lattices.

Instead of a single large ingot, it has a number of ingots drawn from molten vat. The polycrystalline silicon solar cell has shown efficiency of only 12–14 %.



**Figure I.7.** Structural view of crystalline solar cell

The first-generation solar cell is more attractive due to its high efficiency. However, they are very uneconomical.[8]

## I.9.2. Second Generation

The second generation includes thin-film solar cell. A structural view of thin-film solar cell is shown in (figure I.8). They are more economical than silicon crystalline solar cell, but lack efficiency. The development of dye-sensitized solar cells (DSSCs) belongs to the third generation in the era of solar cells, reflecting low cost and high-efficiency features. However, the efficiency of DSSC is not greater than crystalline solar cell, but much greater than thin-film solar cell. These have more attractive features due to their environmental friendliness.

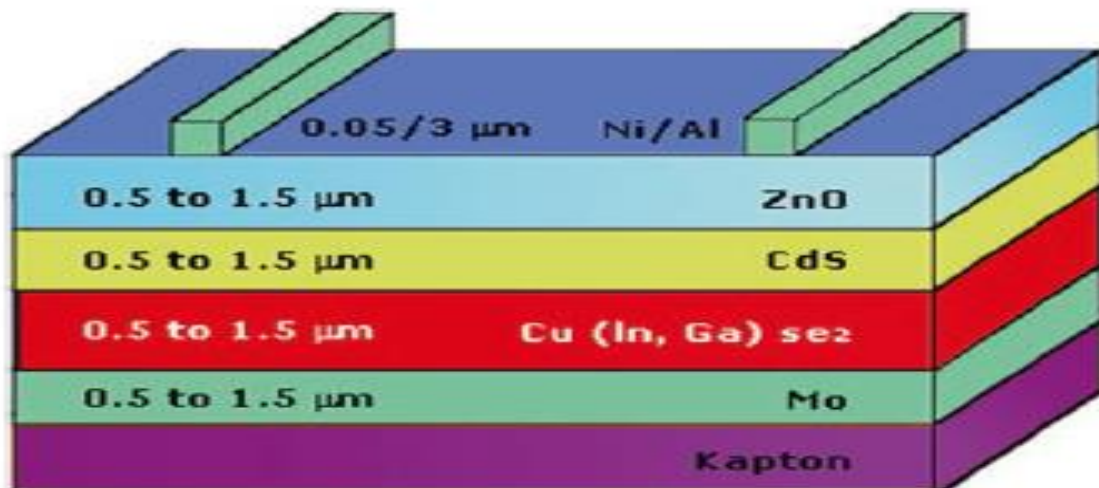
In a thin-film PV cell, a thin layer of semiconductor PV materials is deposited on glass, metal, or plastic foil. Due to their non-single-crystal structure, thin films suffer from poor efficiency and also require larger array areas, and thus,

area related costs such as mountings also increase. Cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si) are examples of thin-film technologies used as outdoor applications for photovoltaic solar power production.

A CdTe solar cell is fabricated by using a thin film of CdTe. This semiconductor layer absorbs photons and converts it into electricity. The main advantages of solar cells include low fabrication cost and increasing efficiency

The CdTe material has a high optical absorption coefficient for visible portion of the thin film of CuInSe<sub>2</sub> (CIS)-based photovoltaic (PV) modules and comprises low-cost substrates. CIS solar cell technology has high absorption coefficient of the solar cell absorber layer. Gallium arsenide-based thin film solar cells have been manufactured and investigated to determine their suitability for future solar power systems. The vapor of gallium arsenide is deposited onto substrates of aluminum foil. Gallium arsenide (GaAs) is a compound of the Solar Photovoltaic Technology and Its Sustainability elements gallium and arsenic. It can be used for manufacturing infrared light-emitting diodes, solar cells, etc. Recently, the efficiency of GaAs has been registered as 28.8 %).

A demerit of CdTe is that cadmium is a deadly poison, and hence not very eco-friendly.[8]



**Figure I.8.** Structural view of thin-film solar cell

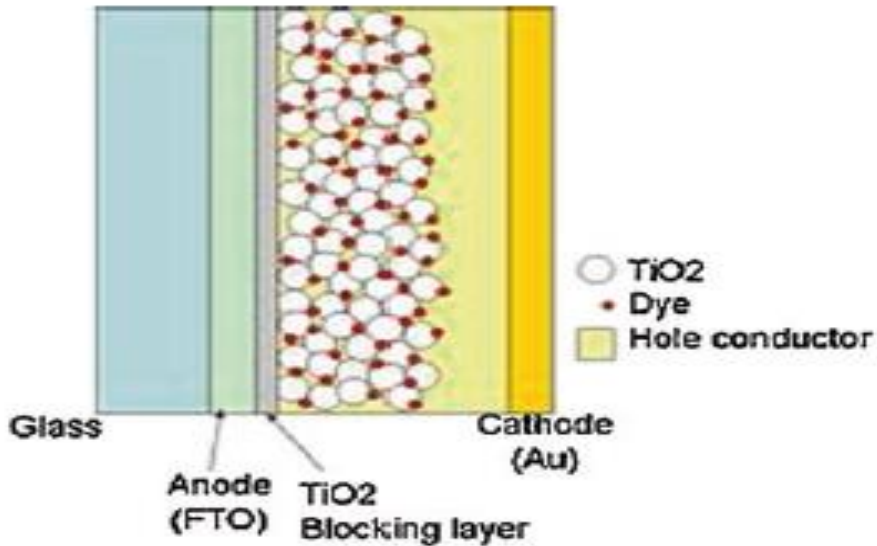


Figure I.9. Structural view of dye solar cell

### I.9.3. Third Generation

The third generation refers to organic/dye-sensitized solar cell; structural view of a dye solar cell can be seen in (figure I.9). A DSSC consists of a titanium dioxide photo-anode electrode, a counter electrode as a cathode, an absorbed dye, and an electrolyte. Dye-sensitized solar cell (DSSC) is a semiconductor photovoltaic device that converts solar radiation from the sun into electric current. The natural dye sensitizer is excited when the DSSC is exposed to sunlight, and thus causes the formation of electrons from the titanium dioxide photoanode. Then, the electrons move to the counter cathode through the electrolyte and complete the circuit.

Conducting glass is used as a substrate for improving the electrical conductivity of the DSSC. Mainly, indium-doped tin oxide and fluorine-doped tin oxide are used as substrates. The most attractive features of DSSC include low cost, simple fabrication, and low density. These can be employed for rooftop solar applications being lightweight. [8]

## I.10. Modeling of the photovoltaic system

The modeled conversion chain is presented in (figure I.11). It consists of a photovoltaic panel, a DC/DC (Direct Current) converter with MPPT control, a DC/AC converter with PWM (Pulse Width Modulation) control, a passive LC filter and a load.

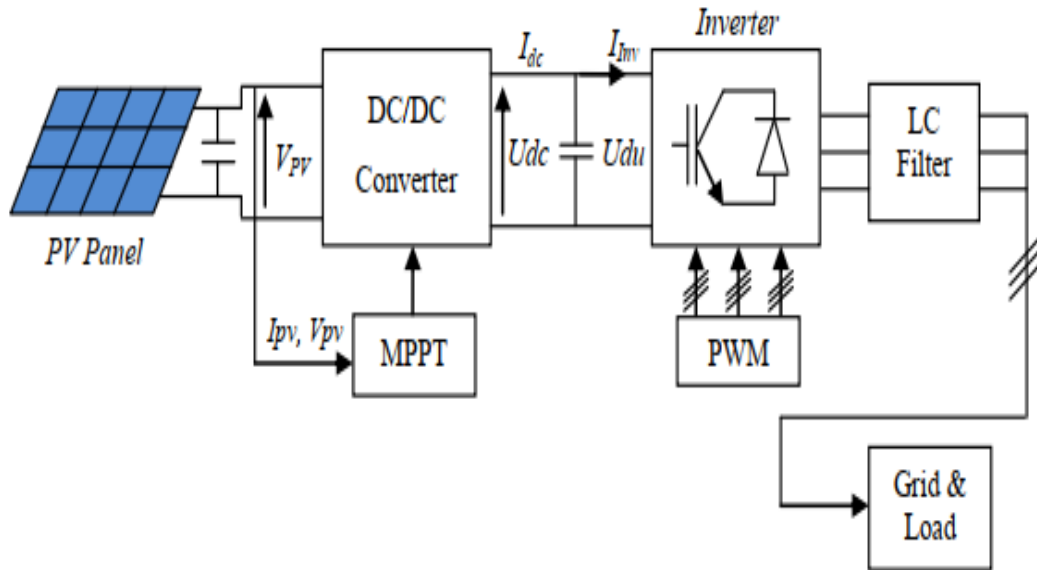
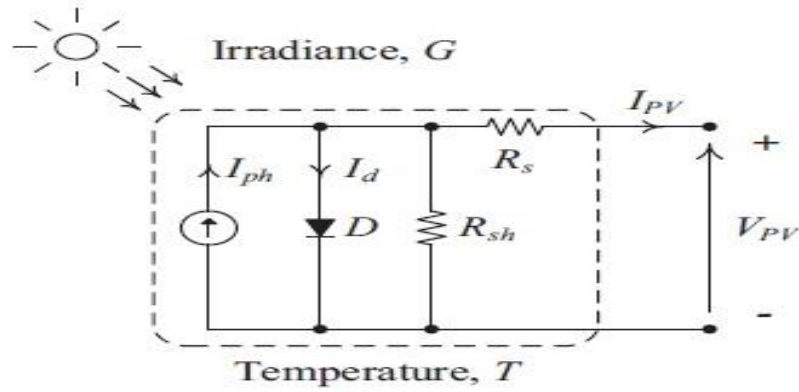


Figure I.11. Synoptic diagram of the photovoltaic conversion chain.

### I.10.1. Photovoltaic cell

(Figure I.12) shows the equivalent circuit of a photovoltaic cell. The current generator ( $I_{ph}$ ) is connected in parallel with a diode, a series resistance ( $R_s$ ) which is the internal resistance of the cell depending on the resistance of the semiconductor used and on the contact resistance of the collector grids, with a shunt resistor ( $R_{sh}$ ) which corresponds to the leakage current at the junction.



**Figure I.12.** *Electrical equivalent circuit of the photovoltaic cell*

The mathematical equation for the current-voltage characteristic is deduced directly from Kirchhoff's law:

$$I_{pv} = I_{ph} - I_d - I_{sh}.$$

where  $I_d$  is the current of the diode (A) and  $I_{sh}$  is the shunt resistance current (A). Then, the expression of the electric current produced by the cell is:

$$I_{pv} = I_{ph} - I_s \left( \exp \left( \frac{V_{pv} + I_{pv} R_s}{V_{tn}} \right) - 1 \right) - \left( \frac{V_{pv} + I_{pv} R_s}{R_{sh}} \right)$$

Where  $I_{ph}$  is the photo-current (A) with:

$$I_{ph} = (I_{ph,n} + K_1 \Delta T) \frac{G}{G_n}$$

in which  $I_{ph,n}$  is the nominal photocurrent (A),  $K_1$  is the temperature coefficient of short-circuit current ( $A \cdot k^{-1}$ ),  $\Delta T = T_m - T_n$  with  $T_m$  the module temperature ( $^{\circ}C$ ),  $T_n = 25^{\circ}C$  which is the nominal temperature,  $G$  is the irradiance ( $W \cdot m^{-2}$ ) and  $G_n = 1000 W \cdot m^{-2}$  is the nominal irradiance. Besides,  $I_s$  is the reverse saturation current of the diode (A),  $V_t$  is the thermal voltage (V),  $V_{pv}$  is the

voltage of the cell (V) and  $n$  is the ideality factor of the diode. In the case of a module,  $N_5$  cells are assembled in series.

### I.10.2.MPPT command

The position of the maximum power point (MPP) in a photovoltaic system depends on the level of sunshine and temperature. A Maximum Power Point Tracker (MPPT) converter with a control algorithm is used to maintain the maximum power supply. The Perturbation and Observation (P&O) algorithm is a common method used in MPPT, which only requires measuring the voltage and current of the photovoltaic panel to determine the MPP. By perturbing the voltage and observing the resulting power output, the P&O algorithm adjusts the duty cycle to approach the MPP. The algorithm considers the aging of the panel over time.

## I.11.Photovoltaic module

### I.11.1.Composition of a photovoltaic module

A photovoltaic solar module is generally composed of six elements (figure I.13):

Aluminum frame.[9]

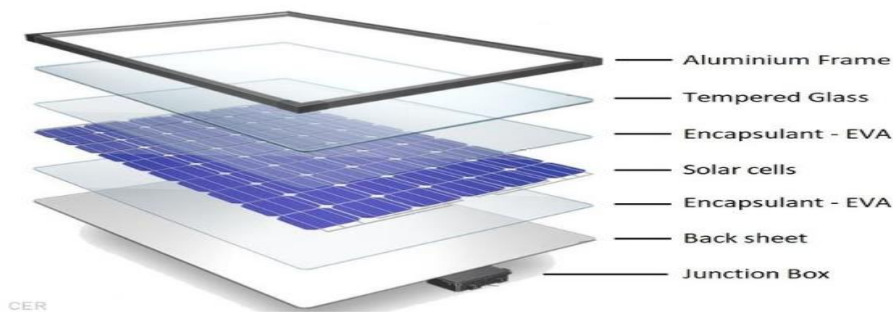
Sealant to fix the module.

Glass: for module protection.

EVA layer (EVA: ethylene-vinyl acetate): to resist weather and moisture.

Photovoltaic cells.

White Tedlar sheet: for additional mechanical strength of large modules.



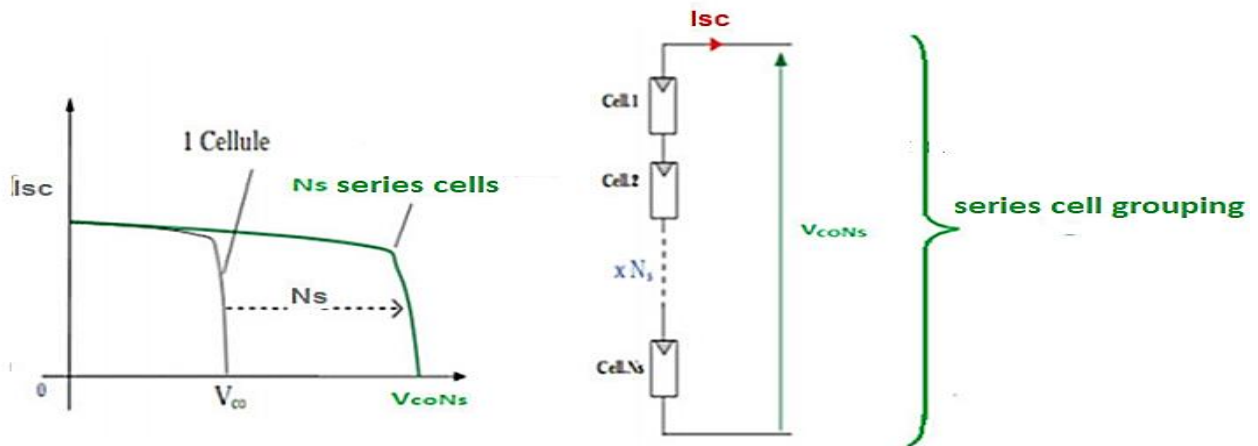
**Figure I.13.** Composition of a photovoltaic solar module

## I.12.2. Series and Parallel Connection of a PV Module

Modules can also be connected in series and parallel to build a photovoltaic array in order to increase voltage and current for use. However, it is important to take precautions as the existence of less efficient cells or shading/occlusion of one or more cells (due to shade, dust, etc.) can permanently damage the cells[10]

### I.12.2.1. Series connection

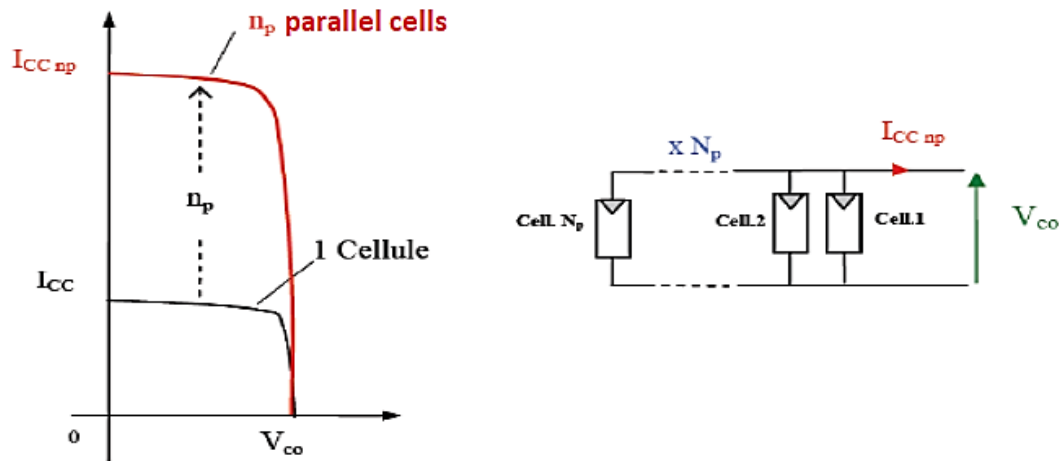
By adding identical cells or modules in series, the current of the branch remains the same but the voltage increases proportionally to the number of cells (modules) in series.



**Figure I.14.** Resulting characteristic of a grouping of  $n_s$  cells in series

### I.12.2.2. Parallel connection

By adding identical modules or cells in parallel, the voltage of the branch is equal to the voltage of each module and the current increases proportionally to the number of modules in parallel in the branch.



**Figure I.15.** Resulting characteristic of a grouping of  $n_p$  cells in parallel

### I.12.2.3. Protection of a PV module

Under certain conditions of non-uniform illumination and operation close to short-circuit, a cell in a series grouping may even be subjected to the reverse voltage of the other cells ( $n_s-1$ ) applied in reverse and thus operate as a receiver, dissipating a significant amount of power that can destroy it if the thermal stress is too high or if the avalanche voltage is exceeded. To avoid this, a  $D_p$  diode must be connected in parallel, called a "by-pass diode," to the terminals of a basic grouping of 30 to 40 silicon cells at most. The spontaneous triggering of this parallel diode, as soon as a reverse voltage appears at the terminals of the grouping, limits it to the value  $V_d$  of the forward conduction voltage of the chosen diode and the power dissipated at  $V_d \cdot I_s$ . Commercialized modules now include these parallel diode protections against reverse voltages. In a dual manner, a  $D_r$  anti-return diode must protect parallel paths from reverse currents.[11]

Finally, (figure I.16) shows the typical wiring of a network of cells or photovoltaic modules equipped with these protection diodes.

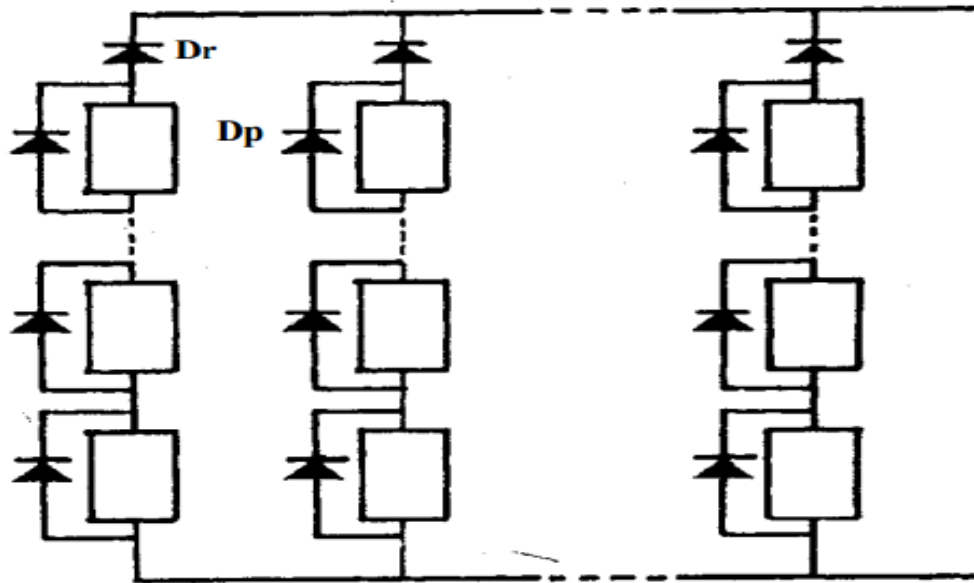


Figure I.16. Series/parallel wiring of photovoltaic modules with their protection diodes.

### I.13.1. Characteristics of a photovoltaic generator

#### I.13.1.1. Electrical Characteristics of a Photovoltaic Generator

#### I.13.1.2. Current-Voltage Characteristics

The following figures illustrate respectively the current-voltage and power characteristics under standard condition

( $G = 1000 \text{ W} / \text{m}^2$ ;  $T = 25\text{C}^0$ )

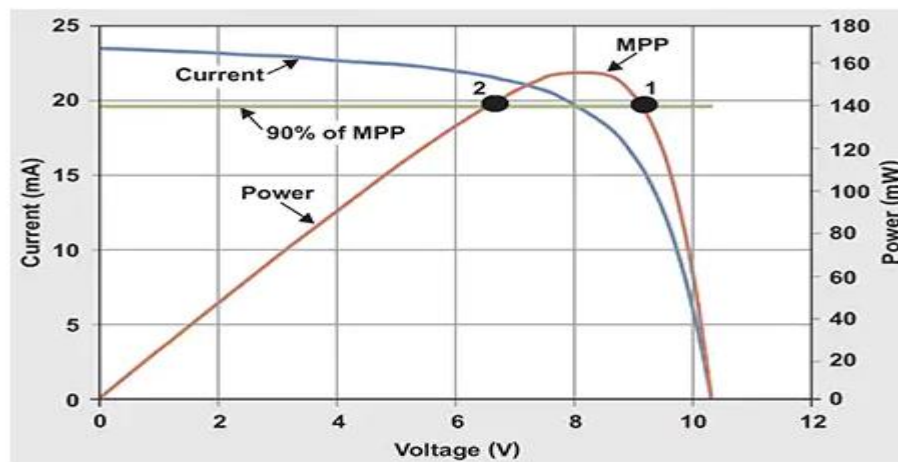


Figure I.17. Influence of illumination on I(V) and P(V)

### I.13.1.3. Conversion Efficiency

The conversion efficiency is defined as the ratio between the maximum power produced and the power of the solar radiation that reaches the photovoltaic module. If  $S$  is the surface area of this module, and  $E$  is the irradiance in  $W / m^2$ , the energy efficiency is written as:

$$\eta = \frac{P_m}{E \cdot S}$$

$P_m = I_m \cdot V_m$ , is the maximum power. This efficiency is often measured under standard test conditions (STC), which means under the irradiance of  $1000W/m^2$ , at a temperature of  $25^\circ C$ , and under an AM1.5 spectrum (air mass: masse d'air in French). The latter describes the angle of incidence and the path traveled by the incident solar radiation from the sun. [9]

$P_m = I_m \cdot V_m$ , is the maximum power. This efficiency is often measured under standard test conditions (STC), which means under the irradiance of  $1000W/m^2$ , at a temperature of  $25^\circ C$ , and under an AM1.5 spectrum (air mass: masse d'air in French). The latter describes the angle of incidence and the path traveled by the incident solar radiation from the sun.[9]

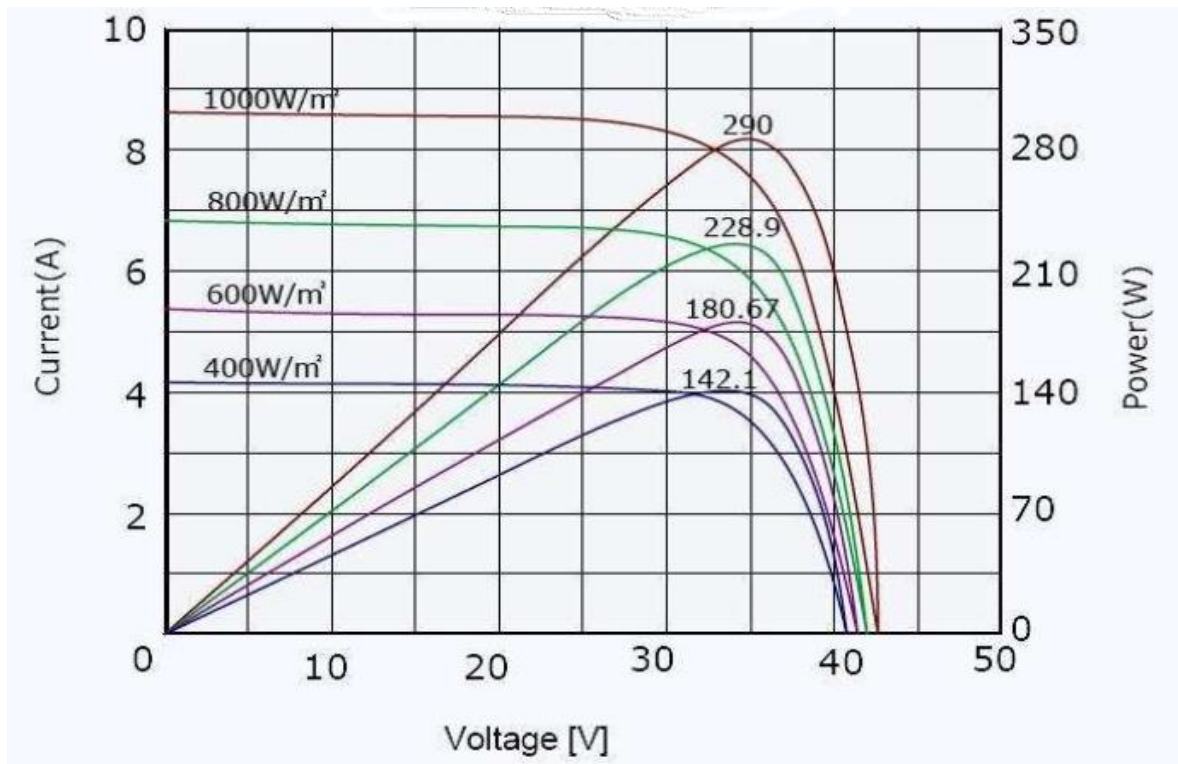
$$FF = \frac{P_{max}}{I_{cc} * V_{co}} = \frac{I_{op} * V_{op}}{I_{cc} * V_{co}}$$

## II. Influence of Irradiance and Temperature

### II.1.1.1. Influence of Irradiance

The following (figure I.18) shows the variation of current with respect to voltage for different light intensities and the maximum power points for each case. It can be observed that the maximum power points shift only slightly and are situated around the same value. It can also be noted that the current is directly proportional to the solar radiation. On the other hand, the voltage is relatively

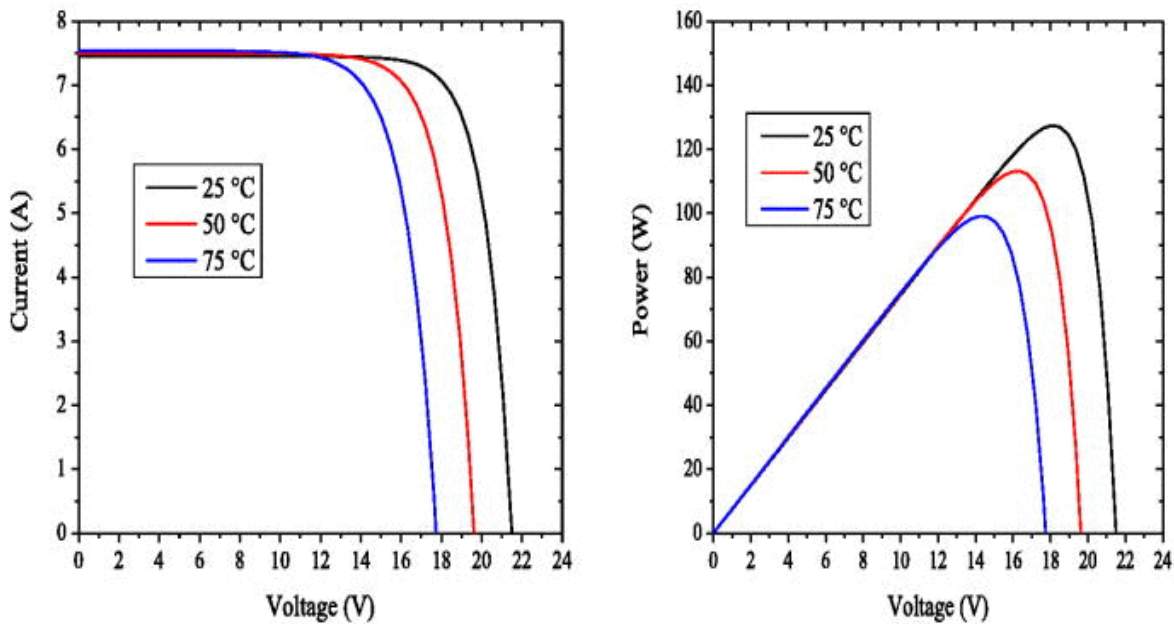
little degraded. It can be inferred that the cell can provide a correct voltage even at low illumination.



**Figure I.18.** The influence of temperature on the I (V) and P(V) characteristics

### I.13.2.2. Influence of temperature

Temperature has a significant influence on the performance of a photovoltaic cell. Experimentally, it is observed that the short-circuit current varies little with temperature, while the open-circuit voltage is much more affected (of the order of  $-0.4\%/K$ ). Therefore, temperature has a significant impact on the efficiency of a photovoltaic cell (power loss of around 9-15% for a temperature increase of  $30^\circ$ ).[5]



**Figure I.19.** The influence of temperature on the I(V) and P(V) characteristics

## I.14. Orientation of solar panels

### I.14.1. Choosing the orientation of modules

The orientation of solar panels should ideally be facing due south. However, two parameters should be taken into account when choosing the orientation:

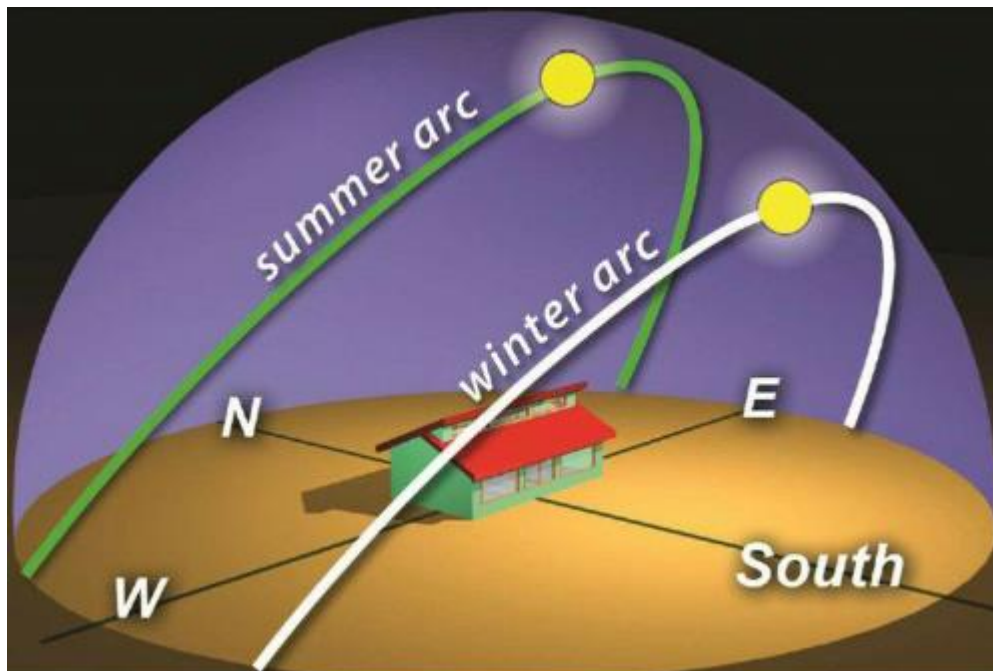
- Surrounding obstructions
- Orientation of the site

In cases where there are significant obstructions to the east (such as vegetation, buildings, etc.), it may be better to orient the photovoltaic

array slightly towards the west instead of facing due south. This will result in increased energy production in the afternoon without sacrificing morning production, which may be affected by the obstructions.[13]

### I.14.2.Choice of module inclination

The goal is to produce the most energy throughout the year. Production is maximized when the sun's rays are perpendicular to the module. The impact of radiation on photovoltaic modules varies significantly between summer and winter. Additionally, the duration of sunlight also varies greatly between summer and winter, to the point that each winter month represents less than 5% of the total production. Therefore, it is necessary to determine the inclination that will allow for the most energy production throughout the year. This depends on the latitude of the location as well as the orientation of the sensors.[13]



**Figure I.20.** Representation of a photovoltaic module inclined at 35 degrees.

## **I.15. Autonomous photovoltaic system**

### **I.15.1. The photovoltaic generator**

The PV generator represents the part of the electrical energy production system. It is composed of one or several PV modules. These modules are made up of an assembly of photovoltaic cells. They can be connected in series to increase their operating voltage, and in parallel to increase their current.

### **I.15.2. Energy storage**

In a PV installation, storage refers to the preservation of energy produced by the PV generator for later use. Solar energy management requires storage to be considered based on weather conditions and to fulfill two main functions [14]:

- To provide electricity to the installation when the PV generator is not producing energy (such as during the night or in bad weather).
- To provide the installation with higher power than that provided by the PV generator

### **I.15.3. Regulator**

Charge regulator systems are components of a photovoltaic system designed to control the charging and discharging of a battery in order to maximize its lifespan. Its main role is to reduce the current when the battery is almost fully charged. As a battery approaches a full state of charge, small bubbles begin to form on the positive electrodes. The charge regulator performs two main functions:

- Protection of batteries against overcharging and deep discharges.
- Optimization of the energy transfer from the PV array to the load.



**Figure I.21.** Autonomous photovoltaic system

### **I.16. Use of photovoltaic energy**

This section essentially consists of one or more receivers: these are the various equipment that use the solar electrical energy produced and controlled (lighting, pumping, etc.) [9].



**Figure I.22.** An application of photovoltaic systems.

## **I.17. Advantages and disadvantages of PV (photovoltaic) energy**

### **I.17.1. Advantages:**

1. Renewable: PV energy is generated from sunlight, which is a renewable and sustainable resource that will never deplete.
2. Environmentally friendly: PV energy does not emit any greenhouse gases, pollutants, or harmful emissions during operation, which makes it a clean and green energy source.
3. Low operating costs: Once the PV system is installed, it requires little maintenance and has low operating costs. The sunlight is free, and there are no fuel or maintenance costs.
4. Long lifespan: PV systems typically have a long lifespan, with some panels lasting up to 25 years or more.
5. Modular: PV systems can be scaled up or down to meet specific energy needs, making them suitable for both residential and commercial use.[15]

### **I.17.2. Disadvantages:**

1. High initial cost: PV systems require a significant initial investment, which can make it expensive for some homeowners or businesses to install.
  2. Weather dependent: PV energy production is dependent on sunlight, so it is not as reliable as traditional energy sources like coal or natural gas. Cloudy or overcast weather can significantly reduce energy production.
  3. Space requirements: PV systems require a significant amount of space to install, especially for large-scale commercial applications.
  4. Energy storage: PV energy must be stored in batteries or other storage devices to provide continuous energy when sunlight is
-

not available. This adds additional costs and complexity to the system.

5. Environmental impact: The production of PV panels can have environmental impacts due to the use of toxic chemicals and heavy metals in the manufacturing process. Proper disposal of old panels can also be a challenge.[16]

### **I.18. Conclusion**

In PV (photovoltaic) energy has many advantages such as being a renewable, environmentally friendly, low operating cost, and having a long lifespan. However, it also has some disadvantages such as high initial cost, weather dependency, space requirements, energy storage needs, and potential environmental impacts. Despite these disadvantages, PV energy is a promising and growing energy source that can help reduce greenhouse gas emissions and combat climate change. As technology continues to improve and costs decrease, PV energy will likely become even more accessible and widely used in the future.

## Chapter II

### **II-1. Introduction:**

The diagnosis of faults in industrial systems has been a prominent research theme since the early days of automation. Usually, two essential steps are distinguished to establish diagnosis: detection and localization, as well as identification. This introduction aims to demonstrate the usual techniques in the field of fault diagnosis and its various types, as well as the terminology of diagnosis. In the literature of this field, several definitions, sometimes distinct, can be found. Therefore, we begin our work by providing explanations of words that are essential for a good understanding.

### **II.2 Terminology and Definition**

Firstly, we explain the essential terms used in the field of diagnostics

#### **II.2.1 Normal Operation of a System**

Operation is considered normal when the characteristics of the physical system remain close to their nominal values. Otherwise, it is referred to as faulty.

#### **II.2.2 Malfunction**

A malfunction refers to an irregular anomaly that occurs in a function saturated by the physical system.

#### **II.2.3 Fault**

The concept of a fault is important in the context of monitoring for the operation and maintenance of industrial processes. A fault is any deviation between the measured behavior of the device and its theoretical behavior. In the absence of a fault, this deviation is ideally zero. Faults can occur at the sensor level, actuator level, or within the process itself.

#### **II.2.4. Failure**

A failure is an anomaly in the physical system that represents an unacceptable operation in terms of performance. Certainly, a failure implies the occurrence of a defect when there is a deviation between the measured and theoretical characteristics. However, a defect does not necessarily result in a failure since the device may still perform its main function.

#### **II.2.5. Breakdown**

A breakdown is the inability of a process to perform a vital function. A breakdown is the result of a failure and thus a defect:

---

*Défaut*       $\longrightarrow$       *Défaillance*       $\longrightarrow$       *Panne*

Within the context of conditional protective maintenance, it is evident that diagnosis allows for the detection and localization of a defect before it leads to a breakdown that would cause the system to stop.

### II.2.6. Perturbation

An input to the physical system that is not a command. In other words, it is an uncontrolled input.

### II.2.7. Residue

An indicator of faults based on the difference between measurements and estimates.

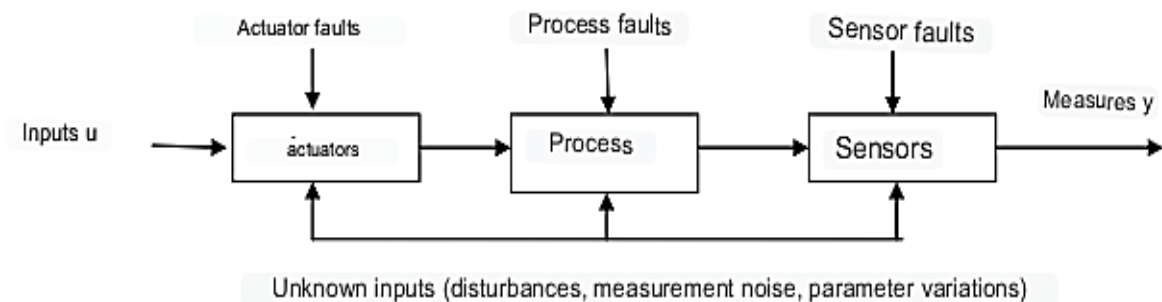
### II.2.8. Analytical symptom

A change in the dynamic behavior of the physical system caused by a fault.

## II.3 Types of faults

A fault is the difference between the value of a system and its estimated value. As shown in Figure (II.1), there are three types of defects: actuator fault, sensor defects, and process fault (or component fault).

Each of these faults and their influences on the process are briefly described in the paragraph below.



**Figure (II.1):** Types of defects in a physical system.

#### a. Sensor fault

Sensor defects refer to the system output (measured) that does not match the system's responses.

Mathematically, they are represented as follows [1]

$$y_i(t) = \begin{cases} x_i(t) & \forall t \geq t_0 \text{ sans défaut biais} \\ x_i(t) + b_i & b_i(t) = 0, b_i(t_f) \neq 0 \quad \forall t \geq t_f \text{ dérive} \\ x_i(t) + b_i(t) & |b_i(t)| = c_i(t), 0 < c_i \ll 1 \quad \forall t \geq t_f \text{ pert d'efficacité} \\ x_i(t) + b_i(t) & |b_i(t)| \leq \bar{b}_i, b_i(t) \in L^\infty \quad \forall t \geq t_f \text{ plocage} \\ x_i(t_{fi}) & 0 < \bar{k} \leq k_i(t) \leq 1 \quad \forall t \geq t_f \quad \forall t \geq t_f \text{ défaut de calibrage} \\ k_i(t)x_i & \end{cases}$$

With:

$t_{fi}$ : time of occurrence of a defect for the  $i^{th}$  sensor, and  $b_i$  determines it, where  $b_i \in [-\bar{b}_i, \bar{b}_i]$  with  $\bar{b}_i > 0$ . Additionally,  $k_i \in [\bar{k}_i, 1]$  with  $\bar{k}_i > 0$  indicates the efficiency of the sensor.

### b. Actuator defects

Actuator defects affect the system inputs that do not correspond to the command acting on the system.

The following expressions show the types of actuator defects:

$$u_a^i(t) = \begin{cases} u_c^i(t) & \text{flawless} \\ k_i(t)u_c^i(t) & 0 < \varepsilon_i \leq k_i(t) < 1, \forall t \geq t_{fi} \text{ loss of efficiency} \\ 0 & \forall t \geq t_{fi} \text{ oscillation} \\ u_c^i(t_{fi}) & \forall t \geq t_{fi} \text{ blockage} \\ u_{imin} \vee u_{imax} & \forall t \geq t_{fi} \text{ saturation} \end{cases}$$

With:

$u_a^i(t)$  output of the actuator;  $u_c^i(t)$  the command applied to the  $i$ th actuator;  $t_{fi}$  indicates the time of occurrence of the fault in the  $i$ th actuator;  $k_i$  is the efficiency of the actuator,  $\varepsilon_i > 0$  is

the minimum efficiency  $u_{i \max}$  and  $u_{i \min}$  are the respective output limits of the  $i$ th actuator.

### c. Component Faults

They directly affect the system. These faults occur when the system parameters change. They induce system instability.

Faults can be classified according to their temporal evolutions [2]

Abrupt: This type of fault is characterized by discontinuous temporal behavior. This evolution is due to a sudden failure of the element itself: total or partial disconnection. A mathematical representation of this fault is given by:

$$f(t - t_{f_i}) = \begin{cases} \delta & t > t_{f_i} \\ 0 & t < t_{f_i} \end{cases}$$

Where:  $f(t - t_{f_i})$  is the temporal signal of the defect and 0 is a constant threshold.

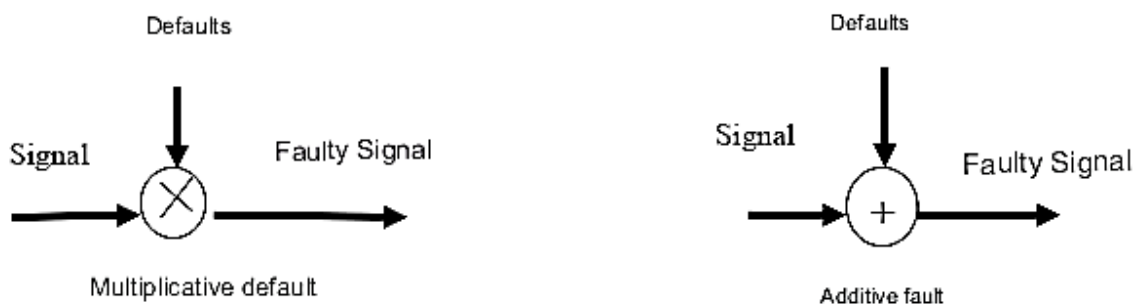
- Intermittent: It appears in a distinct interval, representing one of the types of abrupt defects.
- Gradual: It is characterized by degradation. It is not easily detectable because it varies over time.

The relationship below shows its temporal evolution.

$$f(t - t_{f_i}) = \begin{cases} \delta \left(1 - e^{-\alpha(t-t_{f_i})}\right) & t \geq t_{f_i} \\ 0 & t < t_{f_i} \end{cases}$$

Where:  $\delta$  and  $\alpha$  are two positive constants.

Defects are classified into two types, additive and multiplicative, according to their effects on the system's behavior (Figure (II.2)). Additive defects are noisy signals that accumulate at a point in the functional diagram. Sensor and actuator defects are considered additive defects, whereas component defects are specified as multiplicative defects, as well as changes in the system's dynamics characteristics.



**Figure (II.2):** Classification of fault: multiplicative and additive.

## II.4 Diagnostic Methods

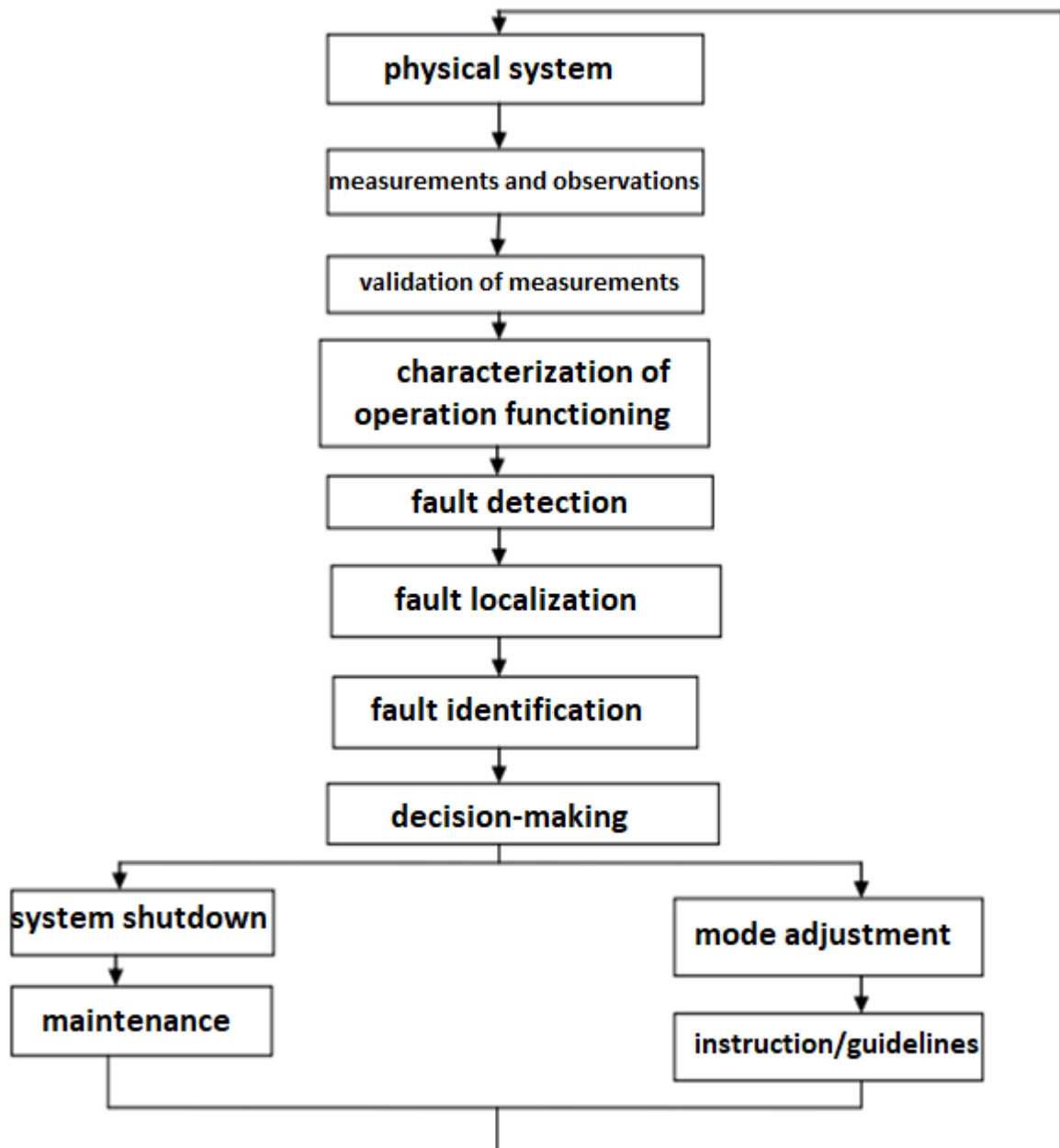
There are several fault diagnostic procedures that are used in different industrial settings. These procedures involve evaluating the data collected during the actual operation of the system, comparing it with the nominal operation or faulty operations of the system. The diagnostic methods are dependent on the form in which knowledge about the system is presented.

The diagnostic techniques are commonly known as Fault Detection and Isolation (FDI). The application of this approach to linear systems has been extensively studied.

FDI for nonlinear systems is still an important field of research. For certain specific nonlinear systems, authors [3] have employed linearization around operating points to apply linear FDI methods. However, in general, this approach is not always realistic due to strong nonlinearities (such as saturation effects or non-analytical behavior) or the impracticality of linearization.

Therefore, several approaches to FDI have been improved in order to also handle more general nonlinear systems. We illustrate the observer-based approach, the parity space approach, and parametric estimation. Fuzzy observers and artificial neural networks have also been considered as practically relevant tools for nonlinear systems. Recently, new approaches have been proposed for the class of nonlinear systems with affine inputs. Specifically, an observer-based FDI approach for nonlinear systems has been studied and developed [4]; [5];[6].

Based on our literature review, we observe that the diagnostic procedure for faults affecting industrial processes can be divided into the following steps (Figure II.3):



**Figure (II.3):** modules of a monitoring procedure.

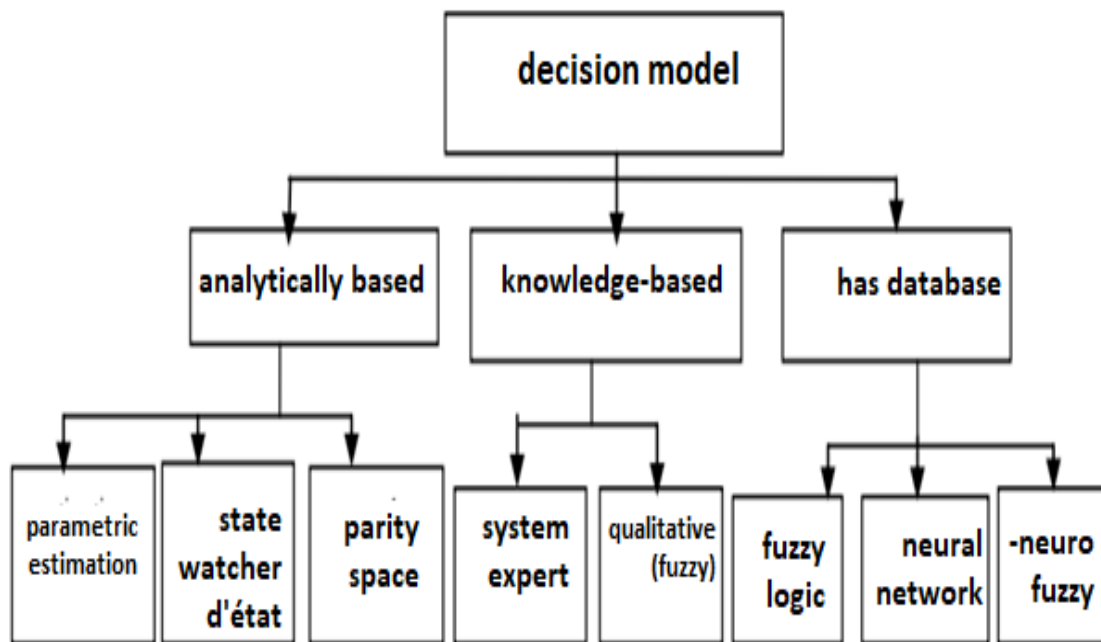
The classification of diagnostic methods for a given industrial system is done after enumerating the need for available knowledge. Many approaches have been developed to contribute to fault diagnosis (Figure (II.4)). We will present these different methods [7] by grouping them into three classes: functional and hardware modeling diagnostic methods or methods based on reasoning mode, physical modeling diagnostic methods, and external signature analysis diagnostic methods.

Model-based approaches rely on fundamental physical principles and quantitative or qualitative models that incorporate the structure of the system and the relationships between components [8]

Knowledge-based approaches are based on expert knowledge and reasoning [9][10][11].

Database-based approaches extract system characteristics from stored data [12].

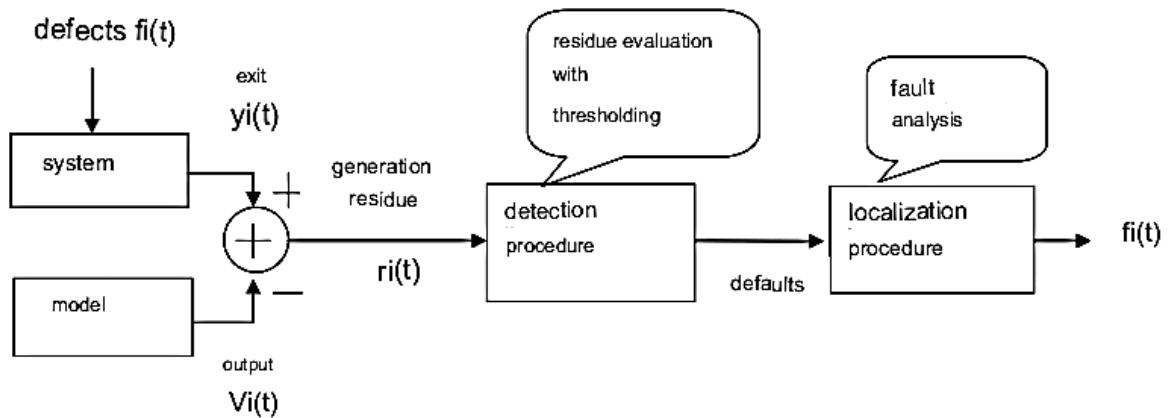
The study focuses on the direct construction of residues without building a model of the behavior of the system under investigation.



**Figure (II.4):** Different diagnostic methods.

### II.4.1 Model-based methods

Model-based diagnostic methods play a significant role in the literature. Their use, particularly in the context of critical applications such as energy systems, transportation systems, and heavy industry, has greatly expanded. Model-based diagnostics have been developed since the seventies. Methodological aspects are illustrated in [8][10][13][14], while [15] provides an overview of the industrial applications of this approach. As previously discussed, this FDI (Fault Detection and Isolation) approach involves techniques for generating residuals, fault detection, and fault localization. This approach is represented in Figure (II.5) [16].



**Figure (II.5):** Fault Detection and Isolation (FDI) Procedure

The first phase of diagnosis in a model-based system is to generate fault indicators that contain information about system malfunctions to be monitored. The principle is to measure the error between the measurements of process signals, such as sensors or actuators, and the theoretical value provided by the model under normal operation. Generating residuals is a crucial element to ensure the behavior of a diagnostic system. Therefore, the accuracy of detection and localization will depend on the performance of the given residual system.

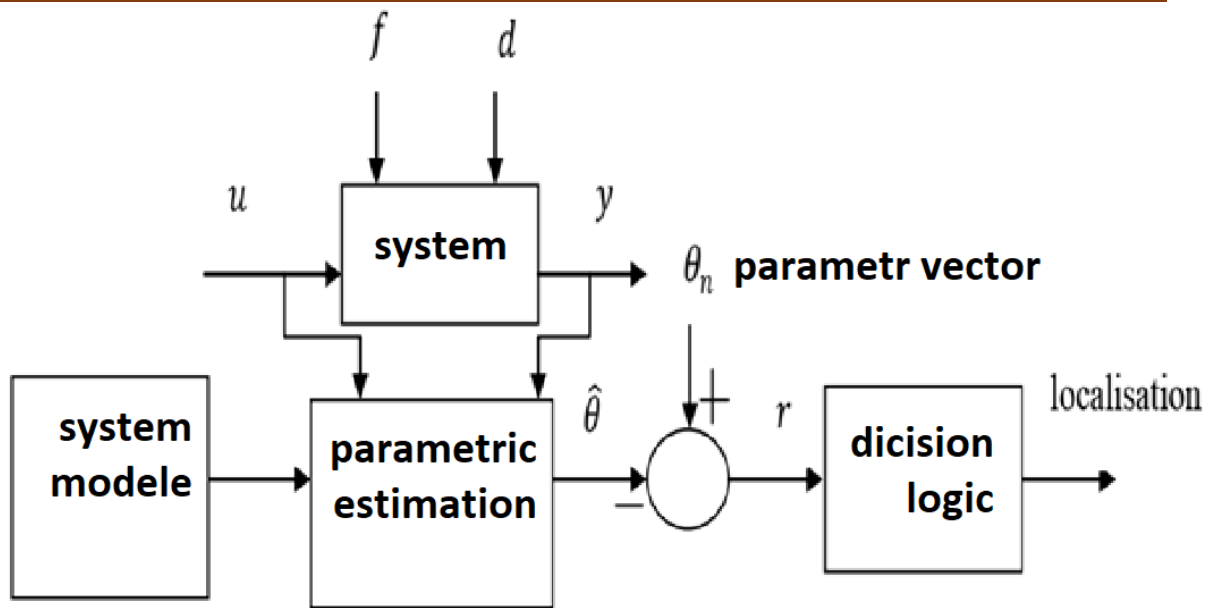
### a) Parametric Estimation

The mathematical model of a system, whether it is based on knowledge or representation, involves a set of parameters whose numerical values are generally unknown. Parametric estimation techniques allow defining the parameter vector used in the model based on a set of measurements obtained from the system.

The appearance of a fault within the system leads to a modification of its physical characteristics, resulting in a significant deviation of the parameters from their nominal values. In other words, any noticeable deviation of the parameters from their nominal values indicates a fault.

Therefore, the search for a parametric estimator to diagnose industrial systems is captivating. Thus, estimating the system parameters can be compared to the corresponding actual parameters.

The diagram in Figure (II.6) represents the generation of residuals from an estimation of the system parameters.  $\theta$  represents the estimated parameter vector, and  $\theta_n$  represents the corresponding actual parameter vectors.



**Figure (II.6):** Principle of residual generation through parametric estimation

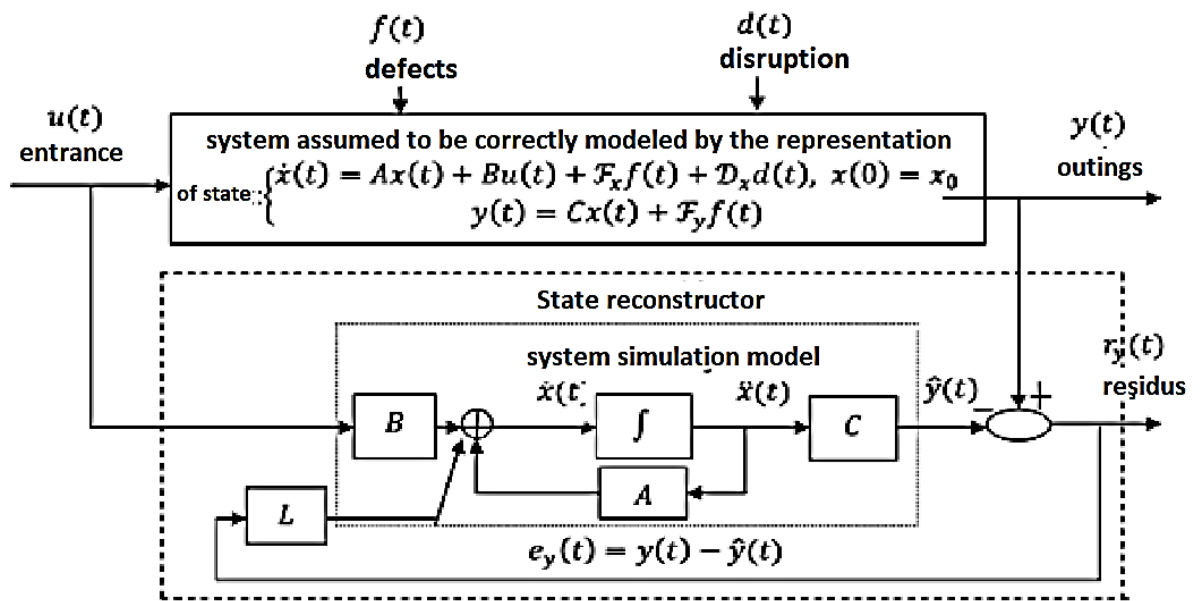
The choice of a system model structure is sufficient to generate an accurate fault indicator. However, to perform a more detailed fault analysis, a continuous-time knowledge model is used. Therefore, the parameters of a knowledge model have a direct physical meaning, as opposed to a representation model. Indeed, estimating such physical parameters will greatly facilitate fault detection and localization. However, we will particularly consider the problem of identifying the parameters of a knowledge model.

### b) State observation

The problem of state estimation for a system is significant, whether it is for implementing a control law or for diagnosis. Residual generation is based on observers that estimate the system's outputs based on measurable variables, namely the inputs and outputs. The residual is the difference between the estimated output and the measured output.

An observer, also known as an estimator, is a dynamic system that takes as inputs the inputs and outputs of the actual process, as well as the residual vector representing a diagnostic step.

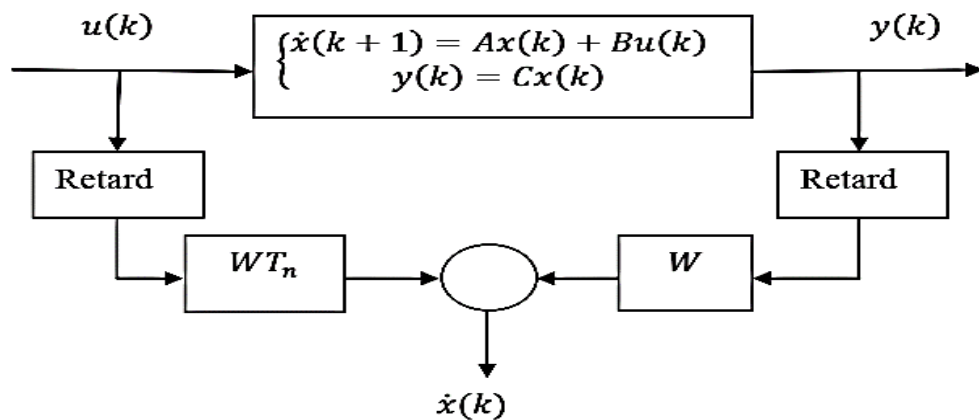
Figure (II.7) illustrates the general principle of an observer, which includes a state model of the system closed by the estimation error.



Where:  $A \in R^{n \times n}$  is the state or evolution matrix,  $B \in R^{n \times m}$  is the input vector,  $C \in R^{p \times n}$  is the output or observation vector,  $\mathcal{D}x$  represents the action of perturbations  $d(t)$ ,  $\mathcal{F}x$  and  $\mathcal{F}y$  are the fault action matrices  $f(t)$  to be detected, and  $L$  is the observer gain matrix.

**c) Parity space**

The model equations are projected into a specific space called the parity space, which allows for the elimination of unknowns through redundancies. The projected equations only involve measurable variables (system inputs and outputs) in an estimation part. These equations are referred to as analytical redundancy relations (ARR). The idea is to test the consistency of measurements with their estimations provided by the model (referred to as measurement consistency or parity) as shown in Figure (II.8) [16].



**Figure (II.8):** Parity space diagnostic.

## II.4.2 Knowledge-Based Methods

These methods are applied when it is not technically feasible to model the devices that link the causes of defects. They are based on test feedback. Among these methods, we can find pattern recognition, neural networks, fuzzy logic, and expert systems or knowledge-based systems.

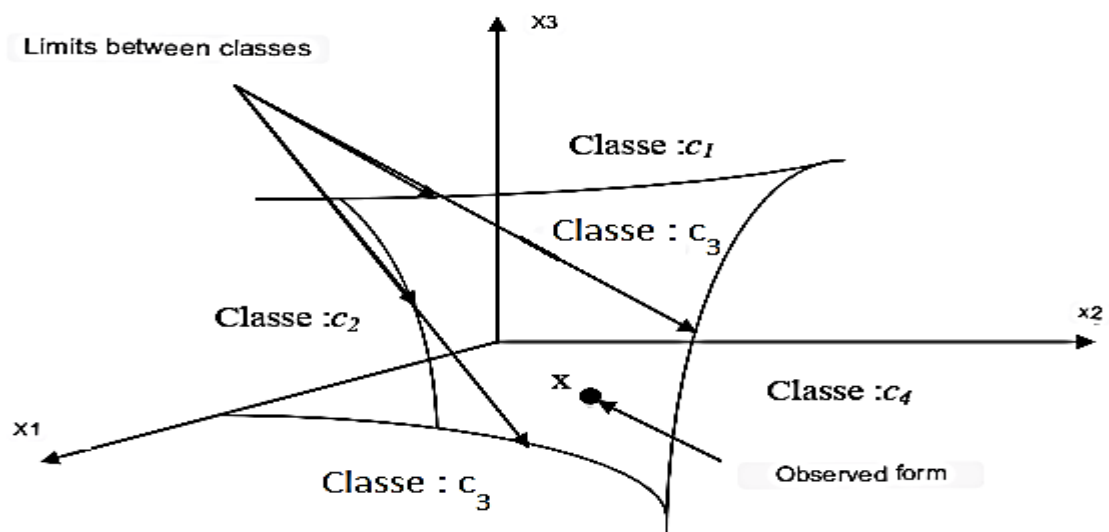
### a) Pattern Recognition

This technique combines methods that allow for the spontaneous classification of a shape based on its resemblance to a reference shape. In other words, it is necessary to decide to which class of known objects (shapes) the observed object, referred to as a shape, belongs. A shape is determined using  $q$  parameters, called features, which represent the components of a feature vector  $x$ .

The feature vector is represented as a point in a  $q$  dimensional space, called the representation space ( $x \in R^q, x^T = x_1 x_2 \dots x_q$ ).

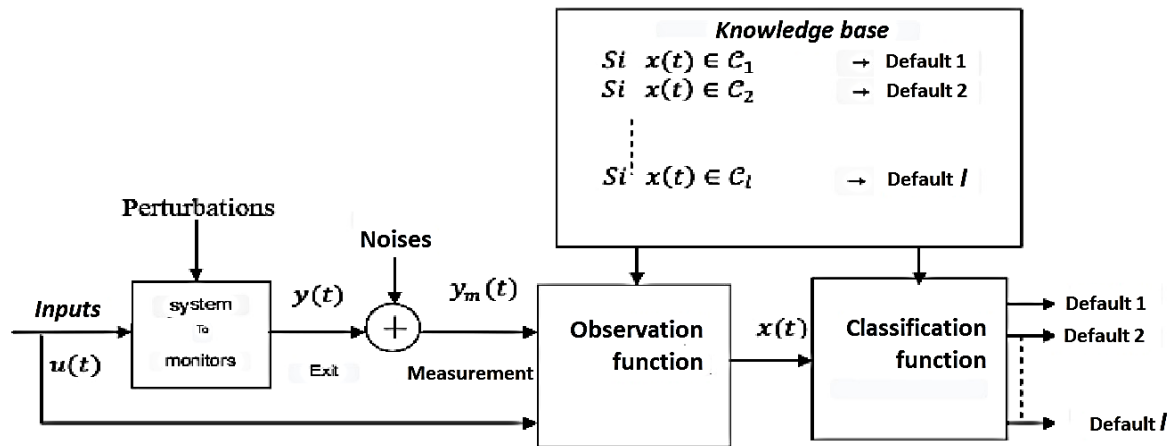
In the following, we will define  $C_1, C_2, \dots, C_l$  as the  $l$  mentioned various classes of a pattern recognition problem. The objective, therefore, is to decide, given a shape  $x$ , whether to assign it to class  $C_1$  or  $C_2, \dots, C_l$ . Each category uses a geometric part of the space  $R^q$ , and the problem is then to determine boundaries between classes.

As shown in Figure (II.9), knowing the boundaries between classes allows for assigning a new observation to one of them, which is the process of discrimination.



**Figure (II.9):** The observations  $x_i$  and their classes  $C_i$

Figure (II.10) illustrates a condensed combination of a pattern recognition-based diagnostic system. The observation function develops the shape vector from measurements and observations made on the system. The generated shape is then applied to the corresponding operating mode. This is only possible when there is a knowledge base that enables the selection of the most useful quantities to observe for diagnosis and the structuring of various operating modes into classes.



**Figure (II.10):** Pattern Recognition-Based Diagnostic System Diagram

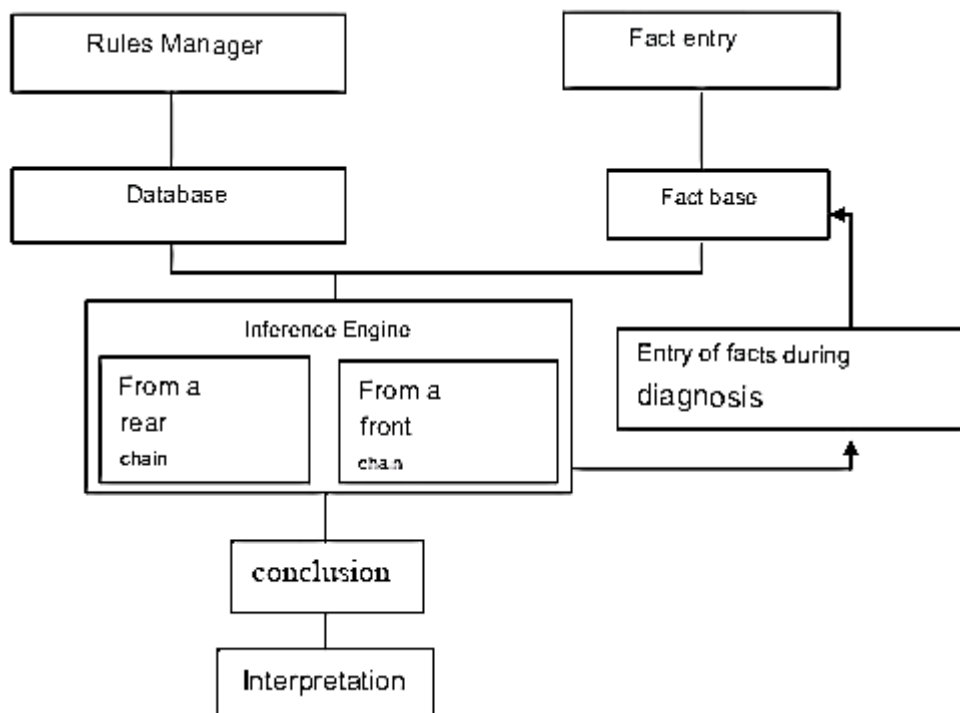
The selection of variables to be observed can be directly derived from expert knowledge and experience, but it can also result from a functional analysis followed by a dysfunctional analysis, which determines the variables to be monitored for the detection and localization of the most critical faults. As we will see, this dual functional/dysfunctional analysis also enables the determination of a rule base that connects the observable variables to the faults. However, this rule base can also be used to solve the classification problem. It should be noted that in all cases, this dual analysis is qualitative and relies on the knowledge and experience of human operators who are familiar with the system.

There are three main steps involved in developing a pattern recognition-based diagnostic method:

1. Creation of a training database.
2. Selection and parameterization of a classifier.
3. Effective utilization of the classifier during the operational phase.

## b) Expert system

An expert system is required to provide answers related to a given state, despite the difficulty of the studied domain which prevents all feasible aspects of the conditions. Therefore, a repair specialist performs their diagnosis based on a partial representation of the situation. Using the set of available signs, they demonstrate all possible conclusions, make new assumptions, and deepen their diagnosis by providing relevant additional information about the system to be diagnosed [7]. Figure (II.11) illustrates the fundamental components of an expert system.



**Figure (I.11):** General structure of a diagnostic expert system

- The knowledge base: which consists of a rule base that models the knowledge of the domain being considered.
- The fact base: Facts containing information about the case being handled.
- The inference engine: capable of reasoning based on the information held in the knowledge base, making deductions, etc.

### I.5 Diagnostic Steps

There are three steps involved in the diagnosis: residue generation, detection, localization, and identification[16].

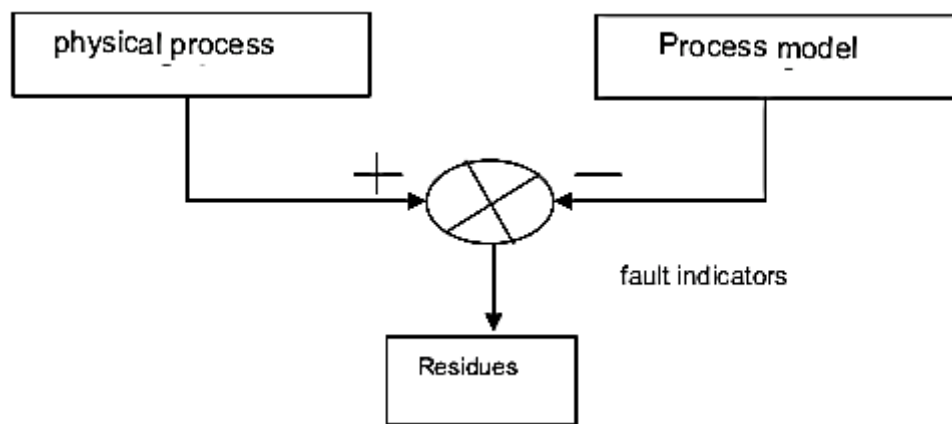
### a. Residue Generation

In order to detect and isolate faults, it is necessary to generate residues (Figure (II.12)). This residue is well defined and clearly indicates its usefulness.

Therefore, it is a sign of system malfunction. There are various methods for generating residues. It includes two essential approaches:

- Quantitative approach: Several techniques have been adopted, such as observer, Kalman filter, parity space, parameter estimation...

- Qualitative approach: This study employs fuzzy logic, neural networks, pattern recognition, expert systems...



**Figure (I.12):** The residue generation step.

### b. Fault Detection

This step enables the detection of the normal operating state of the system. A fault is deemed to have occurred when the residue is non-zero.

### c. Fault Localization

The localization step aims to determine the fault or faults by using statistically significant non-zero residues. It involves identifying the faulty elements.

The signature of a fault represents its effect on one or more residues. If we have the signature for each fault to be detected, it becomes possible to trace back from the effects (non-zero residues) to the causes (the faulty elements).

### d. Fault Identification

The objective of this phase is to identify the type of faulty parameter and indicate the time of occurrence and location of a fault. Additionally, the identification may involve a procedure aimed at determining the cause of the fault, in other words, its origin.

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## **I. 5 Conclusion**

We began this chapter by providing certain definitions and terminologies used in this field, and then explained the different diagnostic methods. The discussed diagnostic methods consist of three main steps: detection, localization, and identification.

The next chapter will be dedicated to introducing some techniques of artificial intelligence, as well as their use in the field of fault diagnosis. We will particularly focus on neural networks, which will subsequently be used in our contribution to diagnosis.

## **Chapter III**

### **III.1. Introduction**

For industrial PV systems, it is necessary to construct a mentoring system that allows detecting, isolating, and even figuring out any failures that could appear. Therefore, diagnosis of PV systems is an essential topic of research to enhance production and also to make the possibility of operating a predictive or a fast corrective maintenance after each breakdown issue ensures an improved usage of the installation and less interruptions of the service.

There are many faults which affect the performance of the PV panel, concerning these faults, environmental condition and panel degradation are some major causes. The faults that affect the production of the PV panel include diode bypass faults, series resistance augmentation and shading over the panel etc. Different techniques of fault diagnosis for PV systems were proposed in literature. For instance, in Ref. the authors suggested a technique based on artificial neural network (ANN). Two different algorithms have been used, the first one is based on thresholding method, while the second one is based on an ANN. In Ref. a Neuro-Fuzzy classifier (NFC) is used, by extraction the database from the simulation with MATLAB/Simulink software. The method based on NFC of three types of faults after using the threshold detection method. In Ref the authors applied a method that combines two algorithms, the ANN and fuzzy logic method for detecting short-circuited PV modules and disconnected strings. This paper aims to design a Fuzzy Logic Classifier in MATLAB/ Simulink software, where the designed model allows to the detection and classification and localization of eight types of faults occurring in: PV cells, series resistance, shunt resistance, and bypass diodes. For that, a model of diagnosis and detection faults will be shown. This model simulates both of the normal (healthy) and the faulty conditions of the PV panel. These operations will be followed by the presentation of the two methods are applied for the diagnosis of the PV panel. The proposed techniques are based on the analysis of several characteristic quantities of the PV such as the power, voltage, and current, our analysis is performed using two different Algorithms:[1]

- Model based method (residual)
- Signal based method (artificial intelligence)

### **III.2 Photovoltaic Panel Defects**

At this level, we will discuss several defects encountered in the DC part of a photovoltaic system.

These defects arise due to manufacturing flaws or weather conditions.

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## Chapter III Modeling and simulation of healthy and faulty PV systems and fault detection.

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There are four types of different loss categories in a photovoltaic system

- Extended defects with zero efficiency: Occur when there is a physical fault and the system is disconnected for a long duration.
- Short defects with zero efficiency: Occur during a momentary disconnection of the inverter, causing the system to be disconnected for a short duration.
- Shading defects: Occurs when there is a shadow passing over (cables, structures, trees, clouds, etc.).
- Defects with efficiency loss in the absence of shading: Occurs when there is an error in maximum power point tracking (MPPT) and other faults.[2]

### III.2.1 Increase in Series Resistance ( $R_s$ )

Generally, the increase in series resistance is caused by corrosion in the connection between two PV modules, a poorly tightened connection screw, corrosion at solder points between cells, etc. Under normal operation, this connection resistance is nearly zero. The value of this resistance can increase in several abnormal cases



*Figure (III.11): Increase in  $R_s$  Resistance Fault*

The increase in series resistance can cause a significant voltage loss, reaching a point where the group voltage becomes negative, leading the bypass diode to switch into a conducting state. This results in inflection points in the I(V) curve.

### III.2.2 Shading Fault

There are two types of shading faults: total shading and partial shading. Total shading occurs when all radiation is blocked from reaching the PV cells, while partial shading refers to the obstruction of radiation to only a part of the photovoltaic cell (e.g., passing clouds, tree leaves, cables).

#### III.2.2.1 Partial Shading

In urban environments, partial shading is often unavoidable since it is difficult to ensure homogeneous sunlight exposure across the PV system. Factors such as partial shading on the PV array, birds, clouds, and shadows on individual cells

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contribute to this fault [Pet,09]. It is generally considered a defect observed in a photovoltaic panel, reducing its power output. The generator exhibits multiple maximums due to this fault. Specifically, this occurs when the bypass diodes of PV cells conduct.

Consequently, an unstable behavior arises in the PV system when one or more cells receive different illumination compared to their neighbors. Cells with lower energy levels need to dissipate the excess current supplied by the more illuminated cells, leading to overheating if the module is not protected. To prevent cell overheating, connection boxes are equipped with bypass diodes to limit the reverse voltage of shaded cells and control temperature. However, when the bypass diodes do not function correctly, shaded cells may overheat, potentially resulting in the loss of a portion of the PV generator if the fault persists. These phenomena directly affect the delivered energy production of the generator, causing a decrease compared to the power generated under consistent irradiation. In conclusion, to avoid damaging the PV generator, it is necessary to mitigate this fault, which is why protective diodes (bypass diodes) are installed in high-power PV generators. However, these protection measures can be costly.

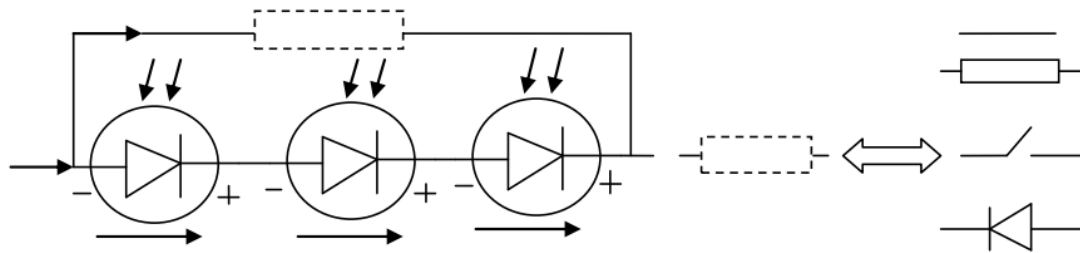


**Figure (III.12):** Partial Shading Fault Diagram

### **III.2.3 Bypass Diode and Anti-Reverse Diode Faults**

The bypass diode is used to protect the cells from partial shading. Typically, this diode is connected in parallel with a branch of a certain number of cells. Various manufacturing defects can be observed in these diodes. In a PV panel, one can identify a disconnected diode, a diode equivalent to an arbitrary impedance, a short-circuited diode, or a reversed diode [Cro,12]. Similarly to the bypass diode, the anti-reverse diode faces the same types of faults: short circuit, arbitrary impedance, open circuit, and reversed diode [Chi,16], [Mel,13].

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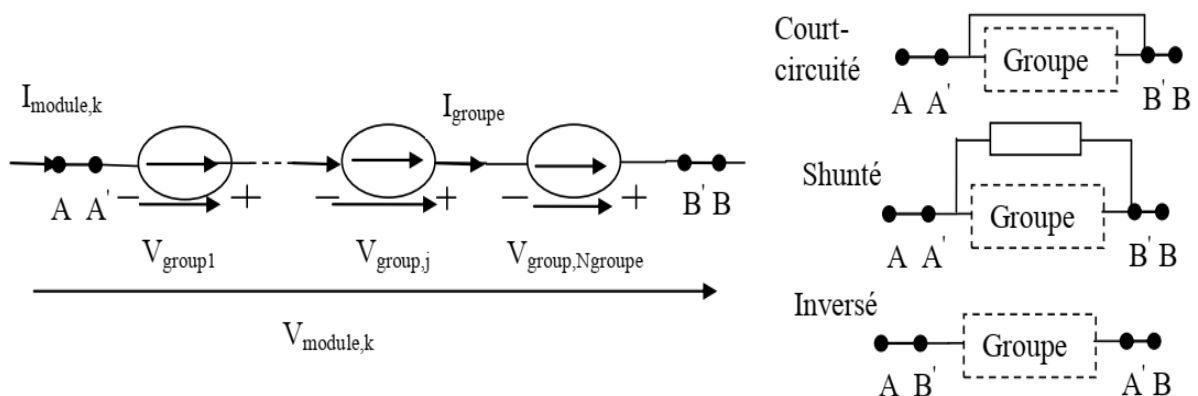


*Figure (III.13): Bypass Diode Fault Configuration.*

### III.2.4 Module Fault

The module fault encompasses all electrical faults associated with the connection of a module in a PV string. These electrical faults include a short-circuited module, a module connected in parallel with an impedance, and a polarity inversion of the module.

Figure (III.14) represents the fault that affects all electrical faults related to the connection of a PV module.



*Figure (III.14): Module Fault Configuration*

### III.2.5 Connection Fault

The connection fault is related to the problem of increased resistance in the connection between two PV modules. Under normal conditions, this connection resistance is nearly zero. However, its value can increase in several abnormal cases, such as corrosion in the connection, poorly tightened screws, etc. In extreme cases, an infinite resistance can be used to represent a module that is disconnected from the PV string [Chi,15], [Cho,10], [Ali,17].

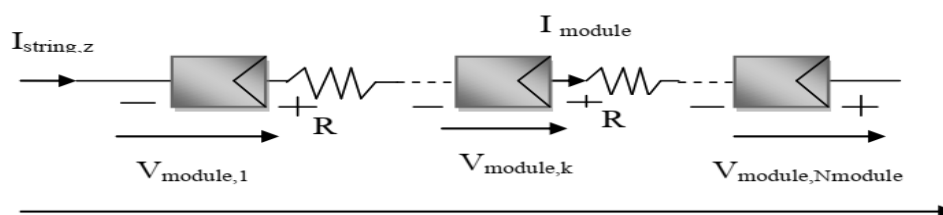


Figure (III.15): PV String Configuration with Non-Zero Connection Resistance

### III.2.6 Anti-Reverse Diode Fault

Similarly, to the bypass diode, there are four types of faults associated with the anti-reverse diode: short circuit, arbitrary impedance, open circuit, and reversed polarity.

Figure (III.16): Schematic of a PV array where the anti-reverse diode is replaced by an element that can exhibit one of the faulty states of the diode.

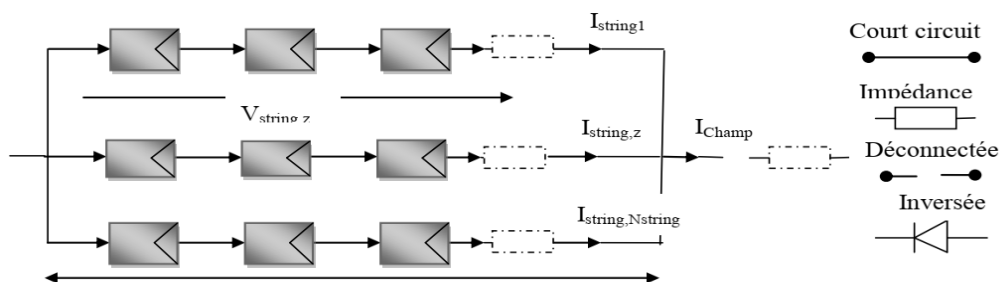


Figure (III-16): Installation of a PV field with a faulty reverse diode.

### III.3 Classification of Photovoltaic Generator Faults

Previously, we mentioned four types of faults based on their impact on performance: extended faults with zero efficiency, short faults with zero efficiency, shading faults, and non-shading faults with non-zero efficiency. In this section, we will classify the faults into their respective categories.

Faults	Description	Category
<ul style="list-style-type: none"> <li>Component fault.</li> <li>System disconnected (long duration).</li> <li>Temporary disconnection of the inverter.</li> </ul>	<p>In case of component failures, the electricity production becomes zero.</p> <p>In the event of isolation (disconnection) of the PV system, the production stops.</p>	<p>Extended faults with zero efficiency.</p>

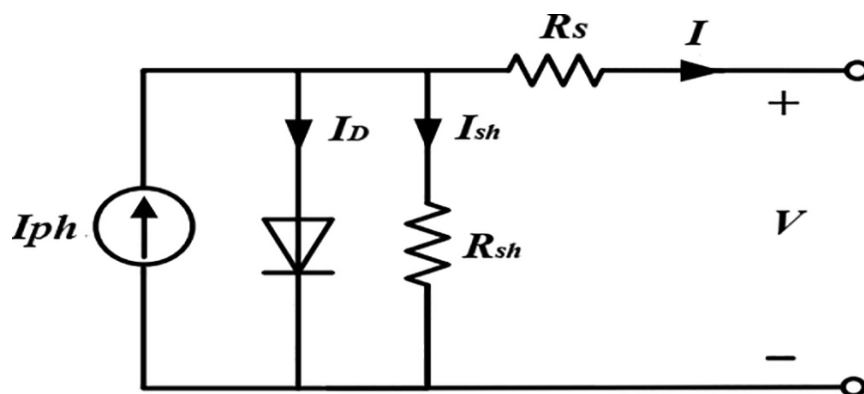
**Chapter III** Modeling and simulation of healthy and faulty PV systems and fault detection.

<ul style="list-style-type: none"> <li>System disconnected (short duration).</li> </ul>	<p>In the event of a disconnection between the PV string and the inverter, electricity production is zero.</p> <p>When there is isolation (disconnection) of the PV system, production is halted.</p>	<p>Short faults with zero efficiency.</p>
<p>Shading faults MPPT errors.</p>	<p>Solar radiation is blocked by external shading objects such as buildings and trees.</p>	<p>Shading Fault.</p>
	<p>The variation in the I-V characteristics affects the power curve characteristic.</p>	<p>Fault with non-zero efficiency (no shading).</p>

**III.4 Modeling and simulation**

**III.4.1. Photovoltaic module modeling**

To evaluate the performance of photovoltaic panels under different operating conditions, the single diode model is generally



*Fig. 1. Solar cell equivalent circuit.*

considered as the most used model for describe the electrical behavior of PV cell as shown in Fig. 1.

This model contains  $I_{ph}$  current source which represents the current generated due to photon interaction. The  $R_s$  series resistor represents the interconnection

between cells. The parallel resistance  $R_{sh}$  represents the leakage current. The current generated by the cell is expressed by:

$$I = I_{ph} - I_d - I_{sh} \quad (1)$$

The current flowing through the diode  $I_d$  is given by:

$$I_d = I_0 \cdot \left[ \exp\left(\frac{V+R_S \cdot I}{V_t}\right) - 1 \right] \quad (2)$$

The current flowing through the  $R_{sh}$  is expressed by:

$$I_{sh} = \frac{V+R_S \cdot I}{R_{sh}} \quad (3)$$

$R_{sh}$  Replacing Eq. (2) and (3) in Eq. the characteristic equation becomes:

$$I = I_{ph} - I_0 \cdot \left[ \exp\left(\frac{V+R_S \cdot I}{V_t \cdot a}\right) - 1 \right] - \frac{V+R_S \cdot I}{R_{sh}} \quad (4)$$

where  $V_t$  is defined by:

$$V_t = \frac{N_S K T}{q} \quad (5)$$

where:

$I_{ph}$ : Photo-current [A].

$I_0$ : Saturation current [A].

$V$ : Cell voltage [V].

$V_t$ : Thermal voltage.

$N_S$  : The total number of cells connected in series.

$T$ : Cell temperature [K].

$q$ : Electron's charge  $e = 1.6 * 10^{-19}$  C.

$K$ : Boltzmann constant ( $1.3854 * 10^{-23}$  JK<sup>-1</sup>).

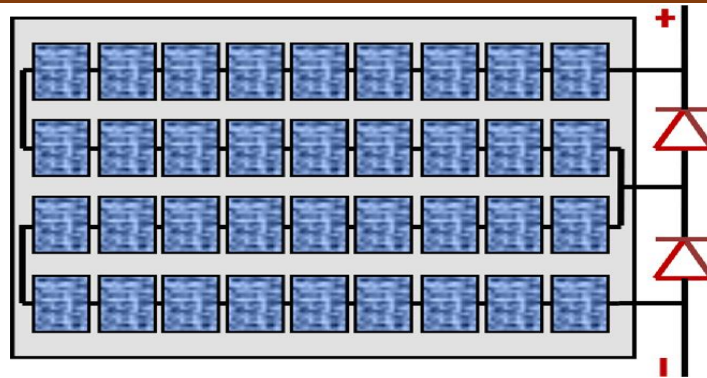
$a$ : Ideality factor of the junction.

### **III.4.2. PV module characteristics**

The PV panel used in this work is a SUNTECH PV module, composed of 36 PV cells and two bypass diodes as shown in Fig. 2, with power 54W of type poly crystalline silicon and its electrical characteristics are presented in Table 1.

Under standard test conditions (STC) (30 C and  $1000 W/m^2$ ). The electrical characteristics  $I(V)$  and  $P(V)$  curve of PV panel are appeared in Fig. 3 and Fig. 4 using Simulink/MATLAB.

---



**Fig. 2.** Schema of photovoltaic module

Electrical characteristics of the SUNTECH PV module.

Electrical characteristics

$P_{max}$ : Maximum power 54 W

$V_{mp}$ : Voltage at Maximum power 7.4V

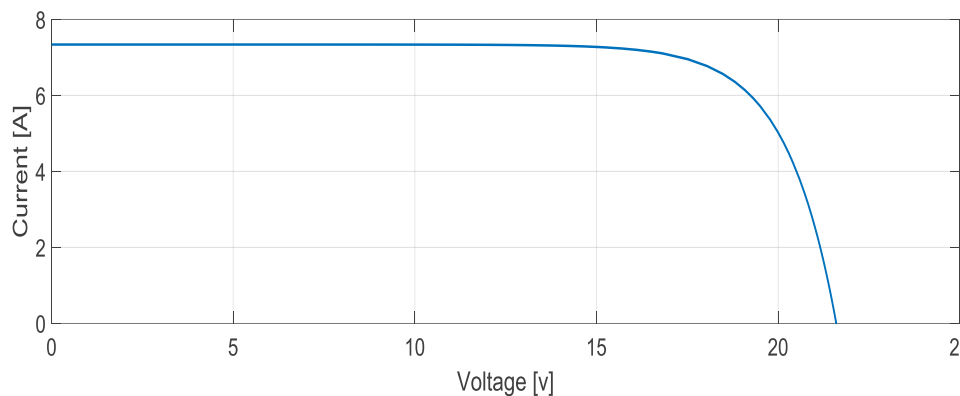
$I_{mp}$ : Current at Maximum power 7.4 A

$V_{oc}$ : Open Circuit Voltage 21.8 V

$I_{sc}$ : Short Circuit Current 3.13 A

The total number of cells connected in series 36

Number of bypass diodes 2



**Fig. 3.** I-V Characteristic of a PV module under STC (30 C and 1000 W/m<sup>2</sup>)

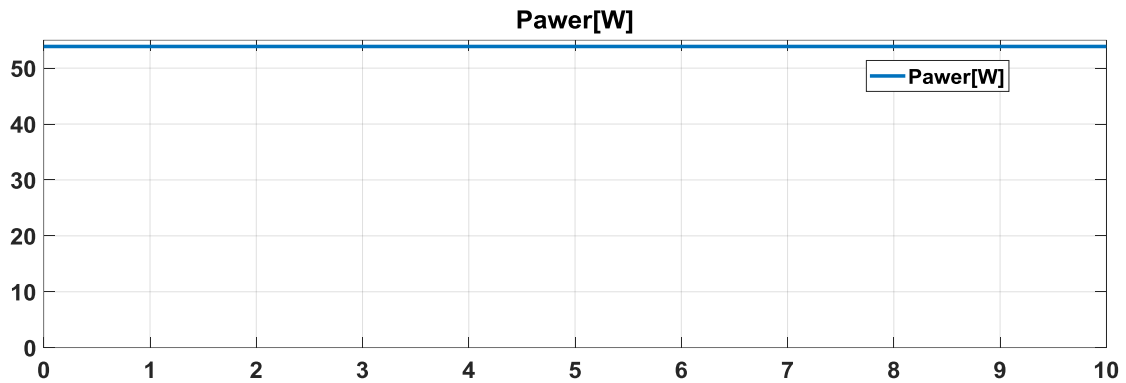
### III.4.3. PV module faults

Although it is desirable to maintain a regular solar radiation over the panel with each cell performing at its Maximum Power Point (MPP). In reality, PV panels often experience several abnormal conditions that negatively affect their efficiency and the total output power. In this study, eight faults on PV module are chosen to be achieved as listed.

### III.4.4. Fault Diagnosis PV System

## Chapter III Modeling and simulation of healthy and faulty PV systems and fault detection.

The simulated diagnosis PV system is composed of two SUNTECH PV modules, these modules consist of 36 cells and two bypass diodes each. As a first step we simulate the normal PV panel (healthy) which used as a reference module and the faulty PV panel.



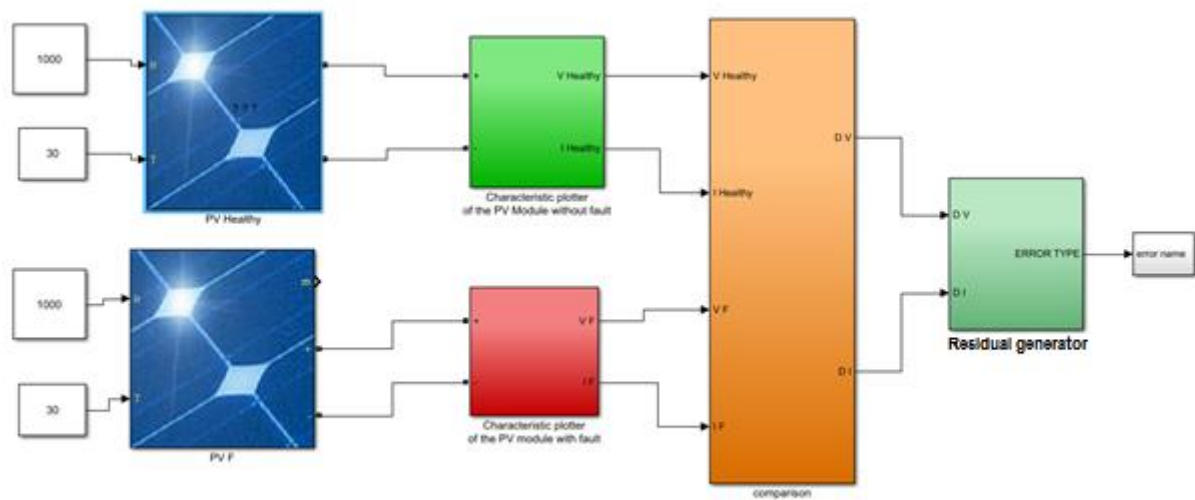
*Fig. 4. P Characteristic of a PV module under STC (30C and 1000 W/m<sup>2</sup>).*

Different type of faults chosen for the diagnosis.

- **F1:** By-pass diode disconnected.
- **F2:** Shading of one cell in submodule of the panel at 50%.
- **F3:** Shading of one cell in submodule of the panel at 100%.
- **F4:** Increase the Serie resistors ( $R_s = 0.9 \Omega$ ) module.
- **F5:** Decrease the shunt resistors ( $R_p = 5 \Omega$ ) module.
- **F6:** By-pass diode disconnected.
- **F7:** Shading of a cell of the submodule 1 and another of the submodule 2 of the panel at 50%
- **F8:** Shading of a cell of the submodule 1 and another of the submodule 2 of the panel at 100%

as a tested module for different chosen faults. In the second step, for each I-V curve three parameters ( $P_{max}$ ,  $V_{oc}$ ,  $I_{sc}$ ) are extracted, and in the third step, a diagnosis algorithm is used to detect and classify PV module faults into two groups:

## Chapter III Modeling and simulation of healthy and faulty PV systems and fault detection.



*Fig. 5. Diagnosis PV system.*

### III .4.5 Model-based methods:

Model-based methods and signal-based methods are two different approaches used in various fields, including artificial intelligence and signal processing. Let's explore each method in more detail: Model-based Method (Residual):

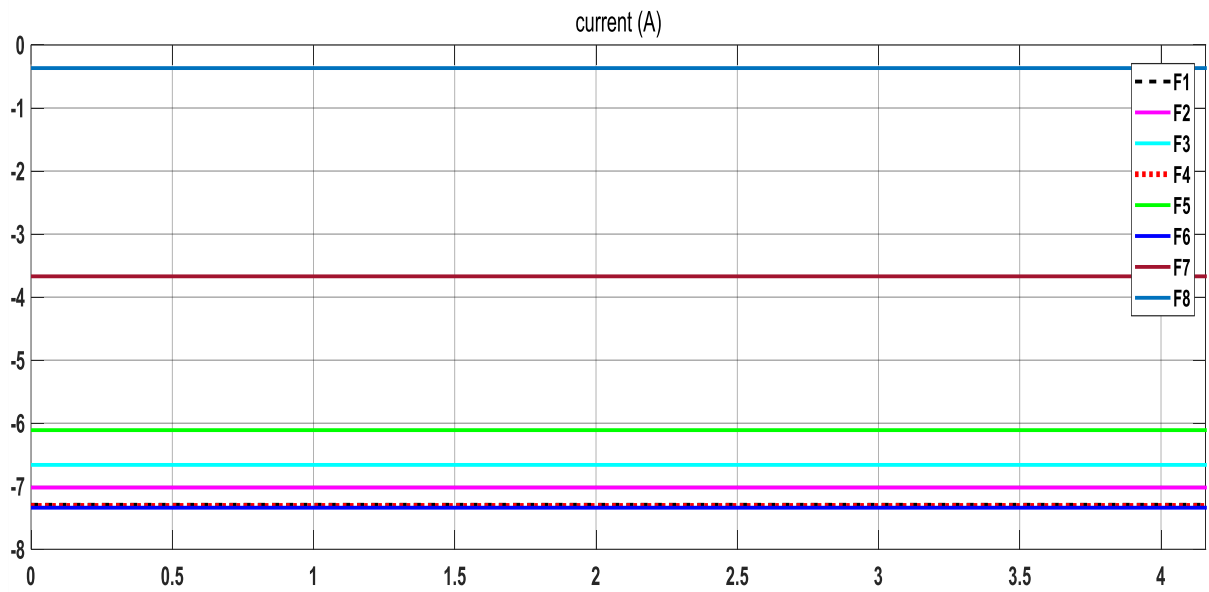
Model-based methods rely on creating mathematical models or simulations to represent the underlying system or phenomenon being studied. These models are developed based on existing knowledge, theories, or empirical data and are used to make predictions or infer information about the system.

In the context of artificial intelligence, a model-based method with residuals refers to a technique where a model is trained to predict the expected output, and the difference between the predicted output and the actual output is captured as residuals. These residuals can then be used to refine the model or detect anomalies or errors in the data. By analyzing the residuals, insights can be gained into the quality of the model and the underlying system.

For example, in regression analysis, residuals represent the differences between the observed data points and the predicted values from the regression

### Chapter III Modeling and simulation of healthy and faulty PV systems and fault detection.

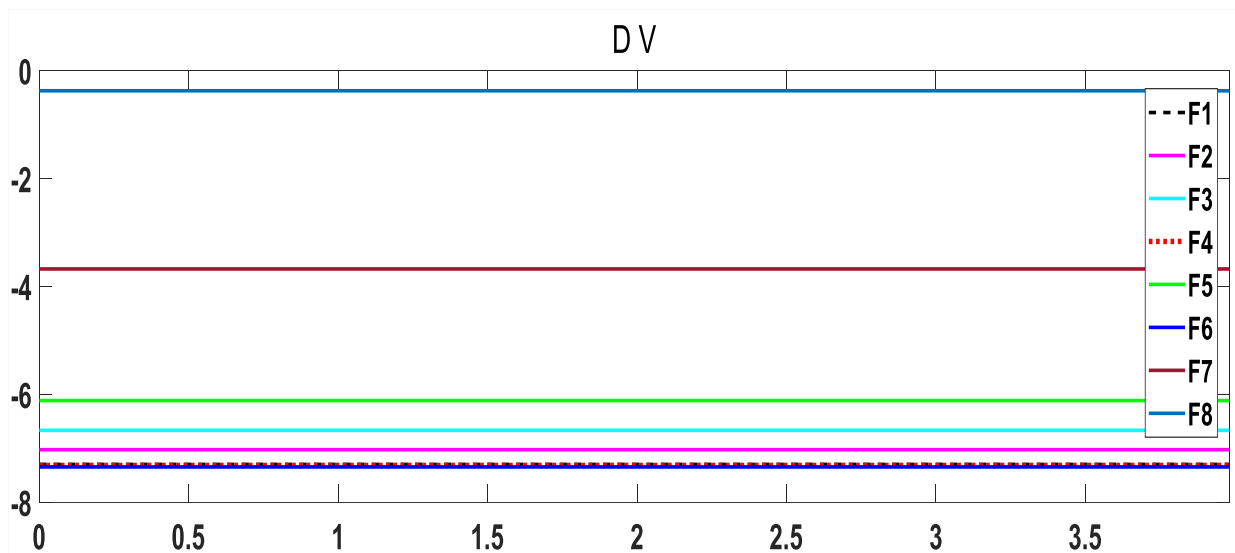
model. Analyzing the residuals helps assess the accuracy of the model and



identify any patterns or trends that the model might have missed.

*Fig.III.12. The difference in the current.*

The previous figure illustrates the difference between the current in the proper condition of photovoltaic panels and the condition of each fault as shown in the previous arrangement.



*Fig.III.13. The difference in the tension.*

The previous figure illustrates the difference between the tension in the proper condition of photovoltaic panels and the condition of each fault as shown in the previous arrangement.

### **III.5 Conclusion**

This chapter provided explanations and fundamental principles of converting solar energy into electrical energy. We also defined the various components associated with the PV system. Furthermore, we discussed the different equivalent electrical models of a PV cell and the various types of faults affecting photovoltaic systems.

By understanding the basic concepts presented in this chapter, one can gain insights into the operation and performance of PV systems. Additionally, recognizing the different types of faults helps in diagnosing and troubleshooting issues that may arise in photovoltaic installations.

Overall, this chapter serves as a foundation for further exploration and study of solar energy conversion and the analysis of photovoltaic systems. It lays the groundwork for understanding the complexities and challenges involved in harnessing solar power for electricity generation.

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## **Chapter IV**

### **IV.1. Introduction**

In the previous chapters, we have developed the necessary steps to achieve our goal and facilitate the implementation of our electronic device, "solar regulator based on a microcontroller for maximum power control and output voltage regulation." The system implementation is based on the sizing and technical characteristics of the components available in the laboratory of the Faculty of Science and Applied Sciences at Eloued. In this chapter, we will study two experimental setups of a complete PV system: (PV array + Detection Device+ load).

### **IV.2. Equipment Used**

#### **IV.2.1. The Microcontroller**

##### **IV.2.1.1. Definition**

The Arduino NodeMCU (LoLin) is a development board based on the ESP8266 Wi-Fi module. It combines the capabilities of an Arduino microcontroller with built-in Wi-Fi functionality, making it ideal for IoT (Internet of Things) projects. The NodeMCU board provides a convenient platform for prototyping and programming projects that require wireless communication and connectivity. It is compatible with the Arduino IDE (Integrated Development Environment) and can be programmed using the Arduino programming language. The NodeMCU board offers a range of GPU IO pins, analog inputs, and various communication interfaces, making it versatile for a wide range of projects.

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**Figure IV.1.** The Arduino Uno board.

#### **IV.2.1.2. Advantages**

If there is an Arduino Lilon board, here are some potential advantages it might offer:

1. **Compatibility with Lilon batteries:** The board may be specifically designed to work seamlessly with Lilon (Lithium Ion) batteries. This compatibility can provide efficient power management and charging capabilities, allowing for longer battery life and optimized performance.
2. **Versatility:** The Arduino Lilon board might be versatile, offering various input/output options and compatibility with different sensors, actuators, and modules. This versatility would enable users to create a wide range of projects and applications.
3. **Simplified integration:** The board could provide easy integration with the Arduino ecosystem, including the Arduino IDE (Integrated Development Environment) and libraries. This simplifies the development process and allows users to leverage the vast Arduino community for support and resources.
4. **Power management features:** The Arduino Lilon board might incorporate power management features such as voltage regulation, power monitoring, and energy-saving mechanisms.

These features can help optimize power usage and prolong battery life.

5. **Safety features:** The board may include safety mechanisms to protect the battery and the connected devices from overcharging, over-discharging, and short circuits. These safety features ensure reliable and secure operation.
6. **Documentation and community support:** Arduino products typically come with extensive documentation, tutorials, and a vibrant community. If the Arduino Lilon board exists, users would likely benefit from the available resources, making it easier to get started and troubleshoot any issues that may arise.

Please note that the advantages mentioned above are speculative and based on typical features and benefits associated with Arduino boards. As there is no specific information available about the Arduino Lilon board, these advantages may or may not be applicable to it.

### **IV.2.1.3. Characteristics**

Since there is no specific information available about the "Arduino Lilon" board as of my knowledge cutoff in September 2021, I cannot provide specific characteristics for that board. However, I can outline some general characteristics that are common to Arduino boards:

1. **Microcontroller:** Arduino boards are typically based on microcontrollers from the Atmel AVR or ARM family. The microcontroller is the brain of the board and controls its operations.
  2. **Input/output (I/O) Pins:** Arduino boards feature a number of digital and analog input/output pins. These pins allow you to connect sensors, actuators, and other electronic components to interact with the board.
  3. **Power Supply:** Arduino boards can be powered through various sources, including USB connection, batteries, or external power supplies. They typically have built-in voltage regulators to handle different power supply options.
-

4. **Programming Interface:** Arduino boards use a simple and easy-to-learn programming language based on C/C++. They are programmed using the Arduino IDE (Integrated Development Environment) or other compatible software.
5. **Prototyping Platform:** Arduino boards are widely used for prototyping and experimenting with electronic projects. They provide a platform to connect and control various components, allowing you to build and test your ideas quickly.
6. **Expandability:** Arduino boards are designed to be expandable through shields and modules. Shields are add-on boards that provide additional functionalities, while modules enable connectivity options such as Wi-Fi, Bluetooth, or Ethernet.
7. **Compatibility:** Arduino boards are compatible with a wide range of sensors, actuators, and electronic components. They support different communication protocols such as I2C, SPI, UART, and more, allowing you to interface with various devices.
8. **Community Support:** Arduino has a large and active community of users, makers, and developers. This community provides extensive support, documentation, tutorials, and example projects, making it easier to get started and find assistance for your Arduino-based projects.

These characteristics represent the general features and capabilities of Arduino boards. If you have specific details about the "Arduino Lilon" board, it may have unique characteristics tailored to its design or specific use cases.

### **IV.2.1.4. The software interfaces**

The Arduino software interface refers to the integrated development environment (IDE) used for programming Arduino boards. The Arduino IDE provides a user-friendly interface for writing, compiling, and uploading programs to Arduino boards.

Here are some common characteristics of the Arduino software interface:

## Chapter IV Experimental validation of the detection fault method

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1. **Code editor:** The Arduino IDE includes a code editor where you can write your program. It offers features like syntax highlighting, automatic indentation, and code suggestions to facilitate programming.
2. **Compilation tools:** The Arduino IDE has built-in compilation tools that convert your code into machine language understandable by the Arduino board. You can verify your code for any syntax errors before uploading it to the board.
3. **Libraries:** The Arduino IDE provides easy access to a vast library of pre-written code called "libraries." These libraries contain functions and code examples ready to use for different functionalities, making Arduino project development easier.
4. **Board management:** The Arduino IDE offers board management functionality where you can select the Arduino board model you are using. This allows the IDE to configure the appropriate compilation settings for the selected board.
5. **Uploading:** Once you have written and verified your program, you can upload it to the Arduino board through the IDE's interface. This sends the compiled code to the board, which then executes it.
6. **Serial Monitor:** The Arduino IDE has a Serial Monitor feature that displays debugging messages, errors, or other information during program execution. This can be useful for understanding your program's behavior and troubleshooting issues.
7. **Debugging Tools:** The Arduino IDE also provides debugging tools that allow you to monitor the values of input/output pins, variables, or other information in real-time during program execution.

The Arduino software interface is designed to be user-friendly and accessible to beginners while offering advanced features for experienced users. It is compatible with different operating systems such as Windows, macOS, and Linux, making it accessible to a wide range of users.

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### IV.2.2. The solar panel

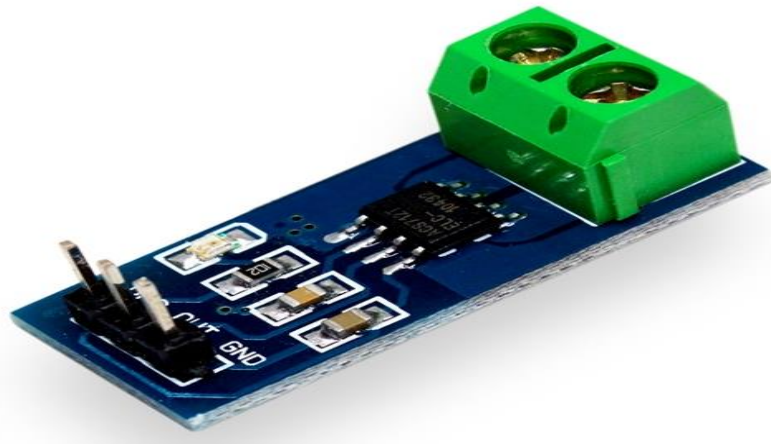
We used the 7.4V, 54W laboratory bench solar panel, which is illustrated in Figure (IV.3).



Figure IV.2 Characteristics the PV array

#### IV.2.2.1 Current Sensor

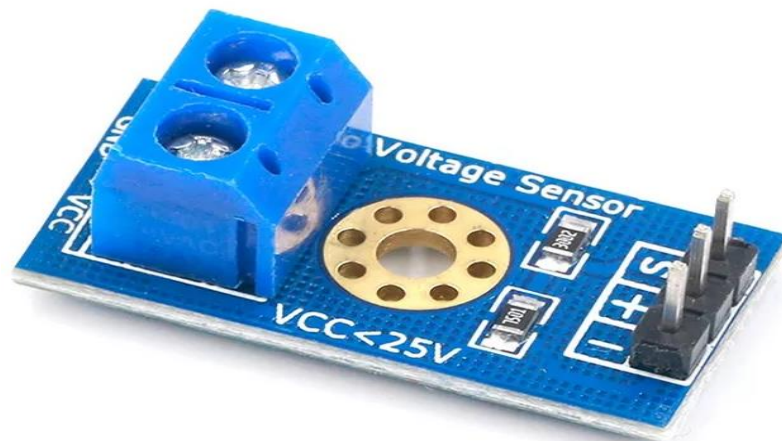
The ACS712s sensor is based on the Hall effect to accurately measure AC or DC current signals. It can support a maximum current of 5A. The current signal can be read through an analog port.



**Figure IV.3** for the ACS712s current sensor.

#### IV.2.2.2. Voltage Sensor

A voltage sensor with 3 pins (VCC, GND, SIGNAL). It can handle up to 25V. This module is based on the principle of resistance point pressure, and it can reduce the input power voltage from the red terminal by 5 times.



**Figure IV.4.** Voltage Sensor.

### IV.2.2.3. Photoresistor

A photoresistor, also known as a light-dependent resistor (LDR), is a type of electronic component that exhibits a change in resistance based on the intensity of light it is exposed to. It is made from a semiconductor material whose conductivity varies with light. When light falls on the photoresistor, the photons in the light excite the electrons in the material, causing a decrease in resistance.

The resistance of a photoresistor decreases when exposed to bright light and increases in the absence or presence of low light. This property makes photoresistors useful in various applications such as light sensors, cameras, automatic lighting systems, and other devices that require light detection or control



Figure IV.5. Photoresistor.

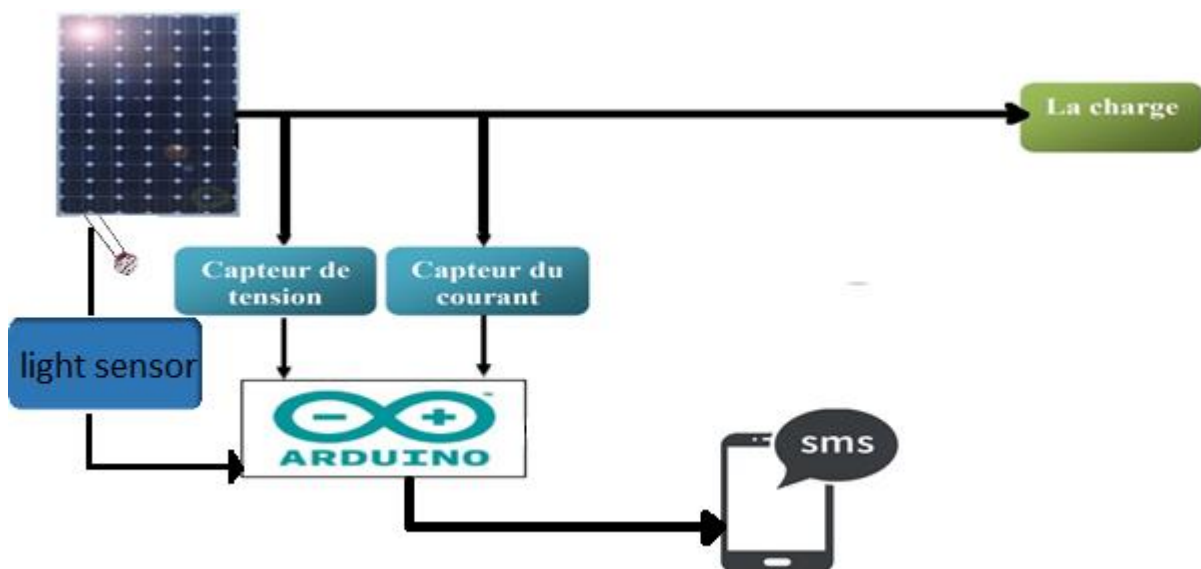


Figure IV.3 Implementation of the control system in Arduino

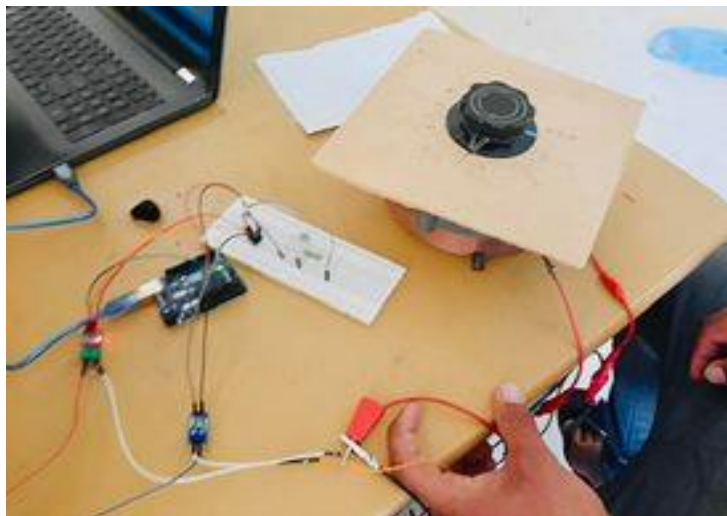
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**A**



**B**



**C**

*Figure IV.4. A.B.C. Explain during the invention of the device*

## **Conclusion Générale**

In this simulation work, Model-based method (residual) and Signal-based method (artificial intelligence) techniques were used to diagnose and detect eight types of faults in a solar panel. The different power, voltage, and current characteristics of the normal and faulty (I-V) solar panel were compared. The resulting parameters were then compared with three energy, voltage, and current thresholds synchronized with light to obtain output values for three in series, which were presented along with the type of fault. After analyzing the simulation results, it can be observed that this technique is suitable for diagnosing solar power units. The obtained results demonstrate the detection of all discernible faults. As a future outlook for this work, we will focus on improving the diagnostic capability for as many faults as possible and conducting experimental verification of the technique.

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