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Stand –Alone Household Electrification, Water Pumping and Outdoor Lighting PV Systems

Spécialité

Production Electrique et Energie Renouvelables

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Abstract

This dissertation provides the exact calculations and the right methods to design and build some of the mainly solar systems applications.

The huge growth of solar energy industry in the past 30 years, led to a wild range of its applications, mentioning household electrification, water pumping and street lights systems. These systems give a variety of its components, from solar modules, inverters, batteries, pumps…etc. Also shows different system structure from one to another, in addition to geographical locations that plays a major role in the system.

Numerical and analytical methods are applied to a real case study to fulfill a client’s energy needs to its different applications.

The final design reveals the necessity of solar energy applications for the modern day life, in all sorts of domains and fields due to its moderate and long efficiency along with its cheap cost in a long term.

Resumé

Ce document fournit les calculs exacts et les bonnes méthodes pour concevoir et construire certaines applications de systèmes solaires.

L’énorme croissance de l'industrie de l'énergie solaire au cours des 30 dernières années a conduit à une large gamme d'applications, notamment l'électrification des ménages, le pompage de l'eau et les systèmes d'éclairage public. Ces systèmes sont composés d'une grande variété de composants, tels que des modules solaires, des onduleurs, des batteries, des pompes, etc.

Les méthodes numériques et analytiques sont appliquées à une étude de cas réel pour répondre aux besoins énergétiques d'un client et à ses différentes applications.

La conception finale révèle la nécessité des applications de l'énergie solaire pour la vie moderne, dans toutes sortes de domaines et de secteurs, en raison de son efficacité modérée et longue ainsi que de son prix récupérable à long terme.

ملخص

تقدم هذه المذكرة الحسابات الدقيقة والطرق الصحيحة لتصميم وبناء بعض تطبيقات أنظمة الطاقة الشمسية بشكل أساسي.

أدى النمو الهائل لصناعة الطاقة الشمسية في الثلاثين عامًا الماضية إلى مجموعة واسعة من تطبيقاتها ، مع ذكر كهربة المنازل ، وضخ المياه ، وأنظمة إنارة الشوارع ، حيث توفر هذه الأنظمة مجموعة متنوعة من مكوناتها ، من الوحدات الشمسية ، والعاكسات ، والبطاريات ، والمضخات ...إلخ. يعرض أيضًا بنية نظام مختلفة من واحد إلى آخر ، بالإضافة إلى المواقع الجغرافية التي تلعب دورًا رئيسيًا في النظام.

يتم تطبيق الأساليب العددية والتحليلية على دراسة حالة حقيقية لتلبية احتياجات الطاقة للعميل لتطبيقاته المختلفة.

يكشف التصميم النهائي عن ضرورة تطبيقات الطاقة الشمسية لحياة اليوم الحديث، في جميع أنواع المجالات والمجالات نظرًا لكفاءتها المعتدلة والطويلة جنبًا إلى جنب مع تكلفتها الرخيصة على المدى الطويل.

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INTRODUCTION

Solar energy is by far the most important form of energy discovered on planet Earth. Due to its permanence and periodicity, this perceptible energy is employed to generate electricity, heating and others. The most common way to covert this energy to electricity is by using a Photovoltaic converting system.

Photovoltaic is inextricably linked with the development of quantum mechanics. Solar cells respond to light particles or *quanta*, although the wave-particle duality of light cannot be overlooked in cell design.

Sunlight itself approximates ideal blackbody radiation outside the earth's atmosphere. The inability to explain such blackbody radiation by classical theory was itself responsible for the development of quantum mechanics, which in turn was needed to understand solar cell operation. As well as reflecting light from the sun, the earth itself emits radiation similar to that of a blackbody, but centered at much greater wavelengths because of its lower temperature.

This study is about an off-grid (stand-alone) photovoltaic (PV) system for electrification of a single residential household in the city of Annaba, Algeria (36.54°N, 7.44°E, 121 (m). The system has been designed keeping in view the required household load and energy available from the sun. The complete model for the sizing of complete PV system has been presented to determine the required PV power rating, battery storage capacity, size of charge controller and inverter to fulfill the required load. Using this model, the peak power and area of PV modules, capacity of battery backup, size of charge controller and inverter was calculated to be 2000 Wp, 9650Wh, 82.93A and 2594 W, respectively.

Another application of photovoltaic (PVs) has been increasingly popular, especially in remote areas, where power from a utility is not available or is too costly to install. PV-powered water pumping is frequently used for agriculture and in households. Among many available schemes, the system under study consists of a PV array, a variable-frequency inverter, an induction motor, and a water pump. The inverter feeds the induction motor, which drives the water pump. To seek the optimum power output of the PV array, the inverter is operated at variable frequency, to vary the output of the water pump.

Solar-powered street lighting is a means of getting light from a sustainable energy source. In this dissertation, we addressed the importance of urban sustainable energy projects in the world by lighting roads using solar energy to provide some of the municipality's energy needs, given its role in improving the quality of life of the population, providing a decentralized source of street lighting (a system independent of the network), ensuring street lighting and providing energy to respond to other needs. In order to access the electricity that is being consumed by light poles, the electrical light poles have been confined within the city, and we have been able to calculate the energy we can save by replacing these poles with solar light poles.

The climate data and the intensity of solar radiation of Annaba are used on the basis of the average monthly day, and the calculation of the number of night hours from sunset to sunrise and brightness on a solar panel tilt for each month, we have also selected the appropriate storage batteries to meet energy requirements after sunset. Avoided CO_2 emissions have also been calculated to save the environment if solar street lighting is used.

Chapter 1

Solar Energy Potential

1.1.Solar Energy

1.1.1.The Sun

The sun is, without doubt, the largest object in the solar system, it represents more than 99.8% of its total mass. It is a combination of two gases: Hydrogen and Helium (91% and 8.9% by number of atoms, 70.6% and 27.4% by mass) [1].

According to NASA, the sun's enormous mass is held together by gravitational attraction, producing immense pressure and temperature at its core. It has six regions: the core, the radiation zone, and the convective zone in the interior; the visible surface, called the photosphere; the chromosphere; and the outermost region, the corona.

This hot sphere of gas whose internal temperatures reach over 20 million °K due to nuclear fusion reactions at the sun's core, converts hydrogen to helium and release radiations according to (1.1):

$$H_2 \Rightarrow He + \gamma \rightsquigarrow \tag{1.1}$$

H_2: Hydrogen gaz ; He: Helium gaz; γ: Gamma rays

This Gamma rays travels out toward the surface, the energy is continuously absorbed and re-emitted at lower and lower temperatures so that by the time it reaches the surface, it is primarily visible light. For the last 20% of the way to the surface the energy is carried more by convection than by radiation [2].

1.1.2.Solar radiation in space [3]

At a temperature of 5800 °K, the sun's surface luminosity (H_{sun}) is estimated at $64x10^6$ W/m^2 multiplied by its surface area, the sun's total power output is valued up to $3.9x10^{26}$ W. Considering an object in the space away from the sun by a certain distance D, and measuring the sun's luminosity at any point of the surface of this object, a decrease in value is observed. This new value is called the solar irradiation H_0, defined as in (1.2):

$$H_0 = \frac{R^2}{D^2} H_{sun} \tag{1.2}$$

H_{sun}: Power density at the sun's surface (W/m2) as determined by Stefan-Boltzmann's blackbody equation; R: Radius of the sun (m); D: Distance from the sun (m); H_0: Solar irradiation, the solar radiation intensity, sun light intensity (W/m^2).

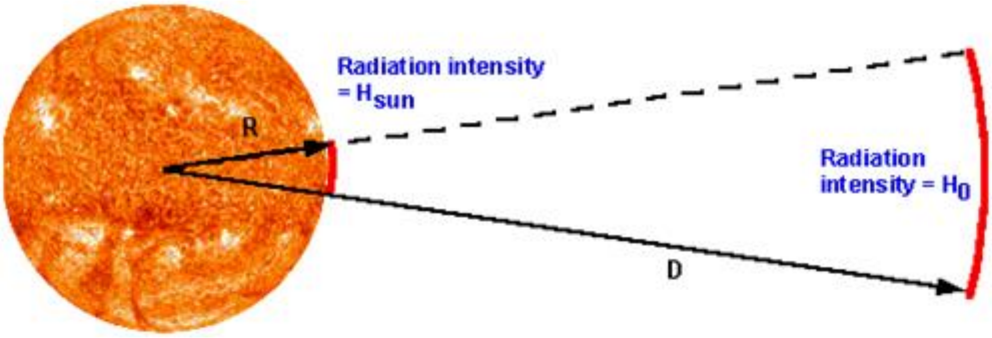


Fig. 1.1: Demonstration of solar irradiation formula

1.2.Terrestrial Solar Radiation

1.2.1.Solar radiation outside the earth's atmosphere [3]

Applying the formula in (1.3) with D=150x10^9 ±1.7% m, the distance between the sun and the surface of the earth, the amount of solar intensity that the earth theoretically receives is H_0=1373.33 ±3 W/m^2, yet, this value slightly differs according to the days of the year, due to earth-sun distance changes, (the earth moves in its elliptical orbit around the sun).

$$\frac{H}{H_{cst}} = 1 + 0.033\cos(\frac{360n}{365}) \tag{1.3}$$

H: Radiant power density outside the earth's atmosphere (in W/m^2); H_{cst}: Value of the solar constant, 1353 W/m^2 (1357 W/m^2 by NASA).

For photovoltaic applications, the value of solar constant and it's spectrum have been defined as a standard value called air mass zero (AM0) and takes a value of 1366 W/m^2.

1.2.2.Atmospheric Effects

The straight falling energy to the earth from the atmosphere is assumed to be equal in value as the solar constant, yet, it is not. The solar constant energy as it falls from the atmosphere experience and go through some modifications as the Fig1.2 shows.

The atmosphere contains Nitrogen and Oxygen (respectively 78 and 21%), along with Argon, CO_2, steam, the famous nitrogen layer of the stratosphere, whose filtering the hardest UV rays. Dust and clouds are also important in the scattering of solar radiation.

All those factors cause an enormous impact on the quality and amount of solar radiation at the earth surface. The highly considerate impacts on photovoltaic applications are the following:

- a reduction in the power of the solar radiation due to absorption, scattering and reflection in the atmosphere;
- a change in the spectral content of the solar radiation due to greater absorption or scattering of some wavelengths;
- the introduction of a diffuse or indirect component into the solar radiation;
- local variations in the atmosphere (such as water vapor, clouds and pollution) which have additional effects on the incident power, spectrum and directionality [3].

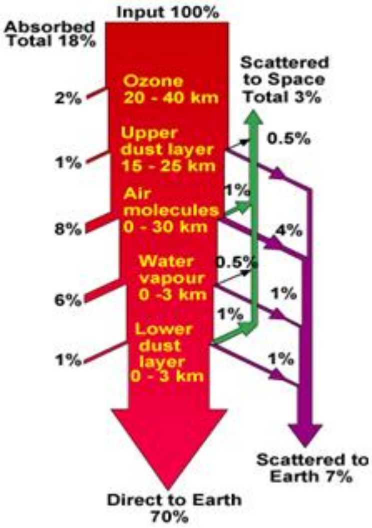


Fig. 1.2: Atmospheric Effects

1.2.3.Air Mass

The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead). The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The Air Mass is defined as in (1.4)[3]:

$$AM = \frac{Y}{X} = \frac{1}{\cos\theta} \tag{1.4}$$

If: $\theta=0$ → AM= 1 Unit

Or:

$$AM = \frac{1}{\sin\alpha} \tag{1.5}$$

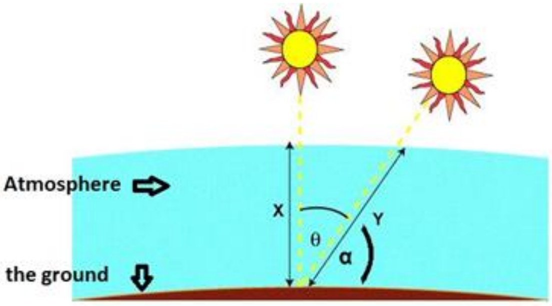


Fig. 1.3: Air Mass calculating method

- Different Air Masses [5]
  - AM0: The extraterrestrial solar spectrum.
  - AM1: The sun at the zenith.
  - AM1.5: The sun at 41.8° (chosen as a reference for photovoltaic applications).
  - AM2: The sun at 30°

Another way to calculate the Air Mass:

$$AM = \sqrt{1 + (\frac{s}{h})^2} \tag{1.6}$$

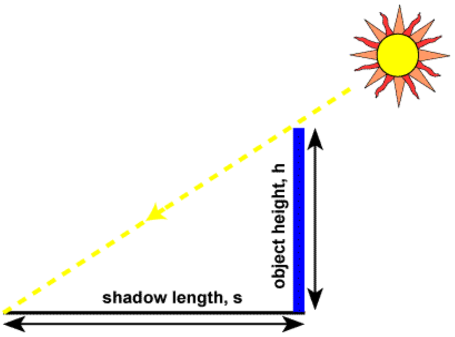


Fig. 1.4: Air Mass determination by shading method

1.2.4.The Earth's Motion

Out of general knowledge, the earth takes 365 days 5h 48mn 46s to complete a cycle around the sun, and takes 24 hours (a day) to rotate around itself.

The axe of rotation is tilted relatively to the earth's orbit around the sun, instead of being perpendicular, it is tilted 23.27° [5]. During its rotation around the sun, it follows a nearly circular path with small elliptical eccentricity with the sun not in the center of this ellipse.

When the northern hemisphere is towards the sun, it receives more sunlight during the day which makes the day longer then the night. This is the summer solstice (June 21st), meanwhile, the sun is directly overhead the Tropic of Cancer providing it with intense heating during that period, conversely of the southern hemisphere experience winter. Furthermore, in winter solstice (December 22nd), the complete opposite is noticed, the northern hemisphere is experiencing winter where the night is longer than the day, and the southern hemisphere experiencing summer time, the sunlight is perpendicular on the Tropic of Capricorn. For the Equinoxes (Mars 21st, September 23rd), the day and night are equal in length in every point of the planet, the sun is perpendicular to the equator [6].

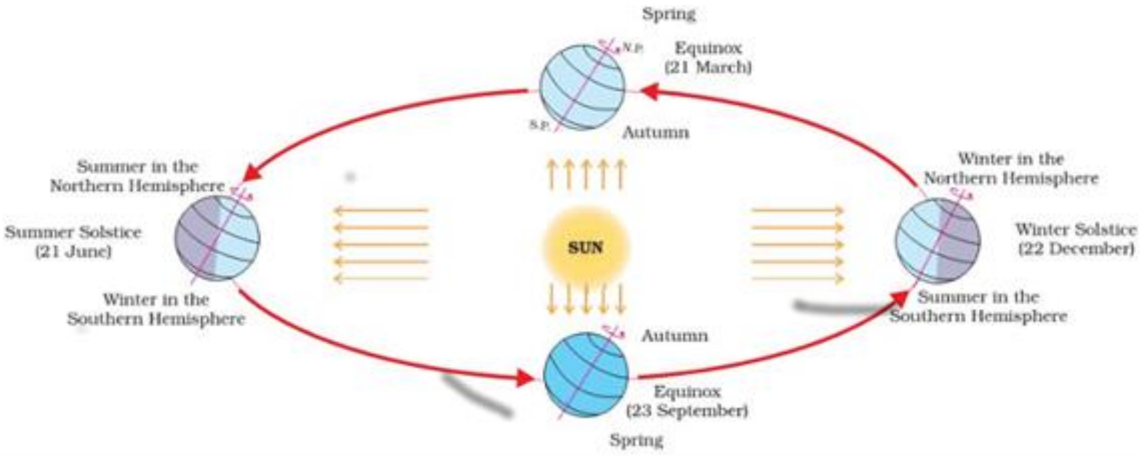


Fig. 1.5: The Earth's Motion

1.2.5.The Sun's Trajectory and Position

In order to determine the sun's apparent trajectory, for a sited observatory on the Earth surface, some data must be collected first such as:

1.2.5.1.The Latitude

Latitude φ: measurement of distance north or south of the Equator. It is measured with 180 imaginary lines that form circles around the Earth east-west, parallel to the Equator. These lines are known as parallels. A circle of latitude is an imaginary ring linking all points sharing a parallel [7].

1.2.5.2.The Longitude

Longitude is the measurement east or west from the Greenwich meridian. Longitude is measured by imaginary lines that run around the Earth vertically (up and down) and meet at the North and South Poles. These lines are known as meridians. The meridian that runs through Greenwich, England, is internationally accepted as reference (0° longitude).

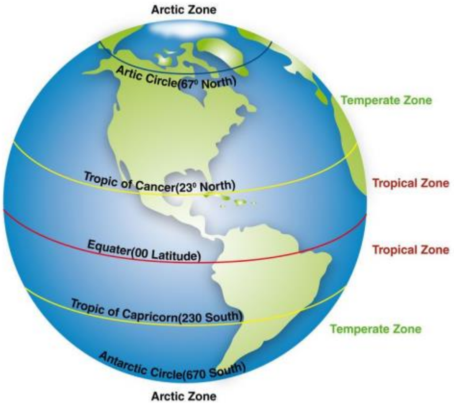


Fig.. 1.6: Main Latitude Circles

Maps are often marked with parallels and meridians, creating a grid. The point in the grid where parallels and meridians intersect is called a coordinate. Coordinates can be used to locate any point on Earth [7].

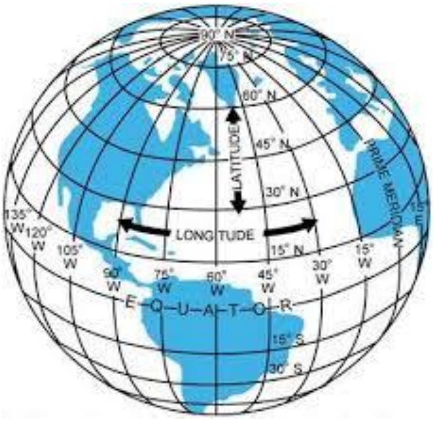


Fig. 1.7: Parallels and Meridians

In addition of the Latitude and Longitude, where every single place on earth has a different sun's trajectory then another, the sun's trajectory and position depends also on the months of the year (where each month draws its own trajectory).

1.2.5.3.Declination Angle [3]

As a result of the Earth's rotation around the Sun and its tilt on its rotation axes, the declination angle, noted δ, is known as angle between the equator and the sun-earth line. It varies seasonally, with an interval varies from δ=-23.45° (Winter solstice) to δ=23.45° (Summer solstice). When δ=0° means we're on the Fall or Spring equinoxes.

$$\delta = 23.45\, sin\left(360\,\frac{284+n}{365}\right) \tag{1.7}$$

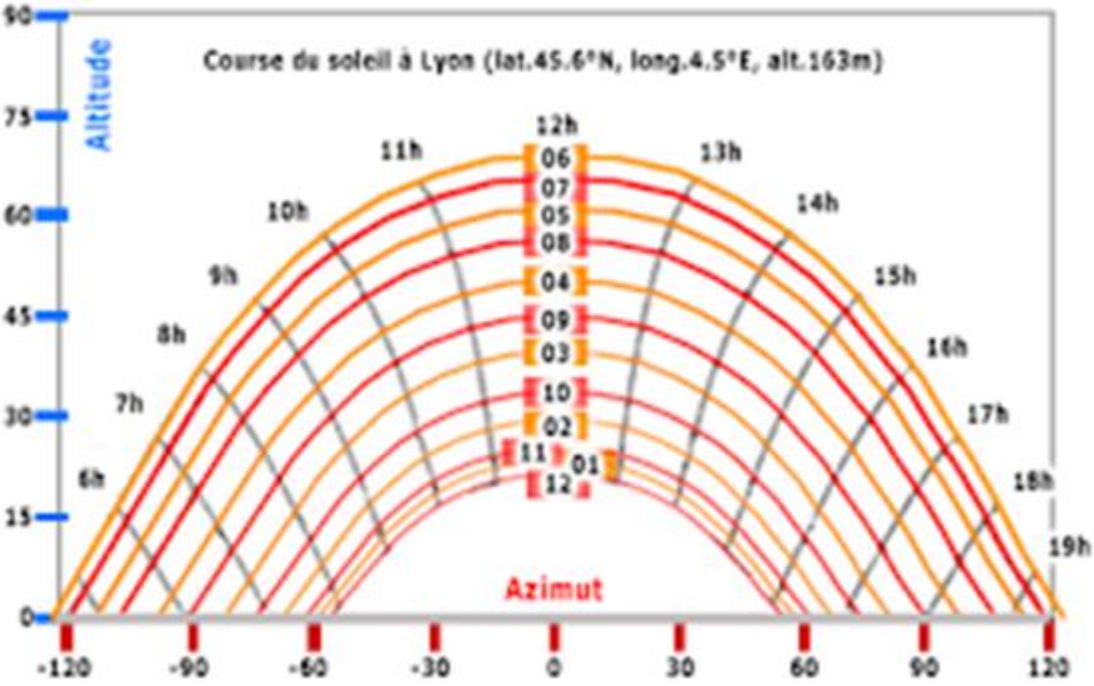


Fig. 1.8: Sun's Trajectory in Lyon

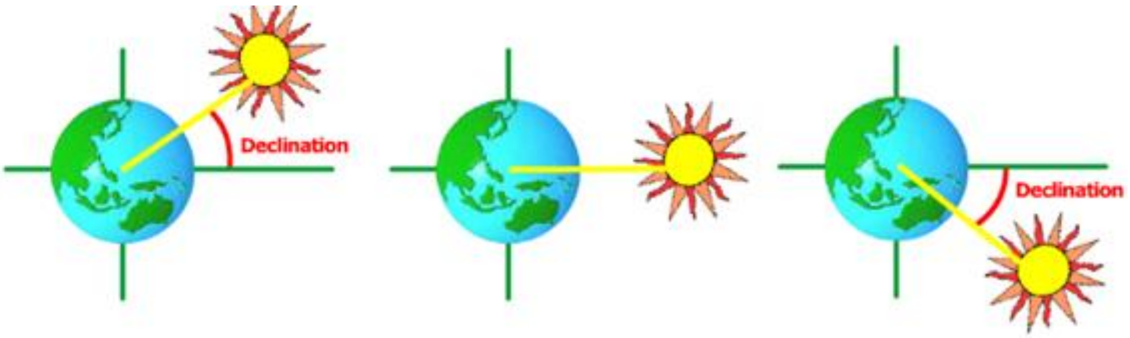


Fig. 1.9: Declination Angle

1.2.5.4. Elevation Angle [3]

Elevation angle or Altitude α describes the height of an object in meters above the sea level. For photovoltaic application, the elevation angle is the angular height of the sun in the sky compared to the horizon. At sunrise α=0°, and the maximum elevation angle occurs at noon: α=90°, and for sunset: α=0°.

In general, the elevation angle changes throughout the day in function of the day itself and the latitude.

$$\alpha = 90 + \varphi - \delta \tag{1.8}$$

Zenith angle: Zenith angle is the angle between the sun and the vertical line on the earth.

$$\zeta = 90 - \alpha \tag{1.9}$$

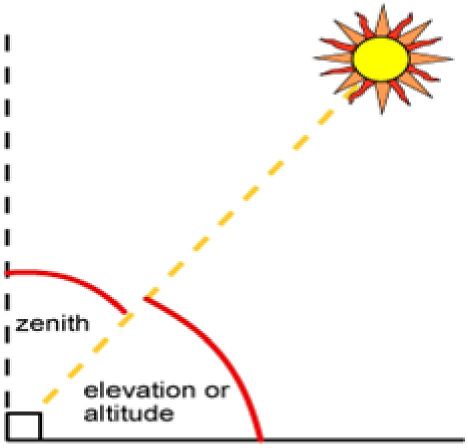


Fig. 1.10: Elevation and Zenith Angles

1.2.5.5.Azimuth Angle [3]

The azimuth angle Z is the direction from which the sunlight is coming. At solar noon, the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere.

At noon: Z=0° while at sunrise: Z=90° and at sunset: Z=270° or Z=-90°. Every moment during day time, Z takes different value then it's previous one, drawing the sun's trajectory of that particular day.

$$Z = \cos^{-1}((\sin\delta\cos\varphi - \cos\delta\sin\varphi\cos H)/\cos\alpha) \tag{1.10}$$

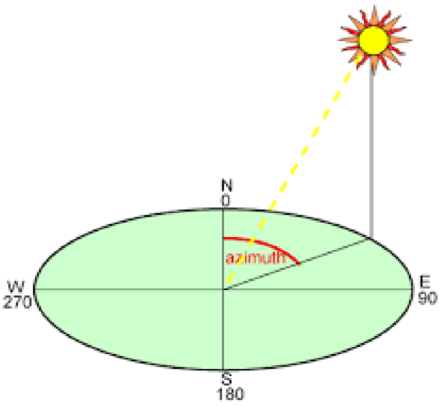


Fig. 1.11: Azimuth Angle.

1.3.Sunlight Properties

1.3.1. Definition of Sunlight

Sunlight or Sunshine is the emanated light from the sun that we see everyday, characterized by its enormous speed and wave-particle duality [5]. Sunlight is a form of "electromagnetic radiation" and the visible light that we see is a small subset of the electromagnetic spectrum.

- **Electromagnetic spectrum:** The electromagnetic spectrum describes light as a wave. Einstein and Planck defined light as "packets" or particles of energy, called photons [3]. This is the wave-particle duality. Quantum-mechanics explains both the observations of the wave nature and the particle nature of light: the photon [3].

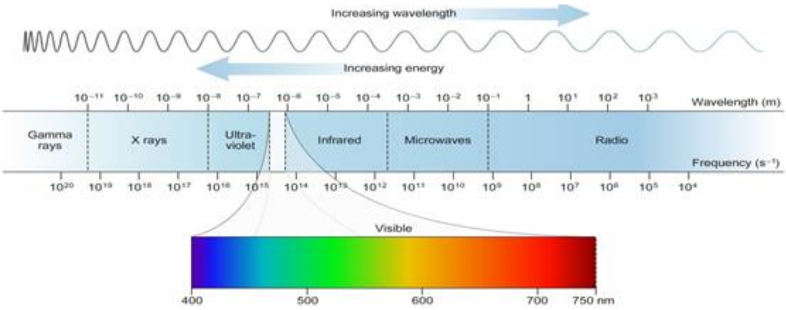


Fig. 1.12: Electromagnetic Spectrum

1.3.2.Photon's Energy [3]

A photon is characterized by either a wavelength, denoted by λ or equivalently energy, denoted by *E*. There is an inverse relationship between *E* and λ given by the equation (1.11):

$$E = \frac{hc}{\lambda} \tag{1.11}$$

$h = 6.626 \times 10^{-34}$ (J·s) is Planck's constant; *c* is the speed of light c=2.998 × 10^{8} (m/s)

Unit of energy commonly used is the electron-volt (eV) rather than the joule (J). Knowing that e=1.6*10^{-19} C, we arrive at a commonly used expression which relates the energy and wavelength of a photon, as shown in (1.12):

$$E(eV) = \frac{1.24}{\lambda\ [\mu m]} \tag{1.12}$$

1.3.3.Atmospheric Interaction

The most important source of electromagnetic radiation is the sun. All along its path till the earth's surface, three primary interaction mechanisms occurs: Scattering, Absorption and Transmission.

1.3.3.1.Scattering [8]

This phenomenon happens when sun's energy hits an object and bounces off in all direction unpredictably. The amount of scattering depends on several parameters. The more the wave is short in length (ex: blue), longer path, more scattering occurs in addition to the size and abundance of the atmospheric particles (bigger size and more dense leads to more scattering). There are 3 types of scattering:

1.3.3.1.1.Rayleigh Scattering

Rayleigh scattering (Molecular scattering) happens when the radiation impinges only with atmospheric molecules or other tiny particles smaller than the wavelength's itself.

1.3.3.1.2.Mie Scattering

Occurs when the radiation hits particle such as dust, water vapor, smoke...etc, equal in diameter as the wavelength. Longer visible waves or over cast with high humidity days cause a significant amount of scattering.

1.3.3.1.3.Non Selective Scattering

It appears when the particles or molecules diameter is bigger than of the wavelength. These particles are: water droplets, volcanic dust, clouds...etc. In this type of scattering, all wavelengths scatter equally.

1.3.3.2.Absorption [8]

Is the process by which incident radiation energy is retained by a substance the result is an irreversible transformation of radiation into another form of energy. The medium will only absorbs a portion of the total energy, the other energy will be reflected, refracted or scattered.

1.3.3.3.Transmission [8]

Some energy is transmitted through the atmosphere in the wave length from 0 to 22µm called "Atmospheric Windows". Without this, remote sensing process would not be possible.

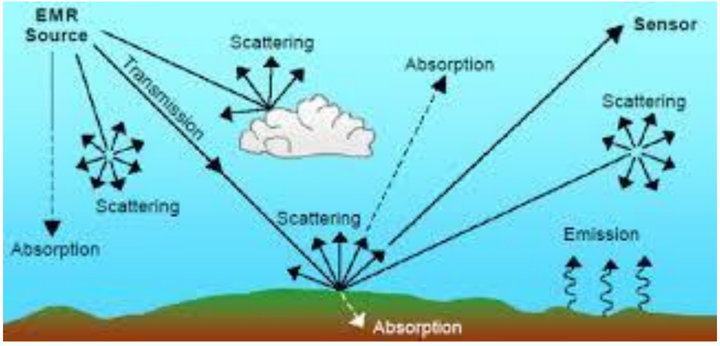


Fig. 1.13: Atmospheric interaction

1.3.4.Solar radiation spectrum [3]

As solar radiation passes through the atmosphere, gasses, dust and aerosols absorb the incident photons. Specific gasses, notably ozone (O_3), carbon dioxide (CO_2), and water vapor (H_2O), have very high absorption of photons that have energies close to the bond energies of these atmospheric gases. This absorption yields deep troughs in the spectral radiation curve. For example, much of the far infrared light above 2 µm is absorbed by water vapor and carbon dioxide. Similarly, most of the ultraviolet light below 0.3 µm is absorbed by ozone.

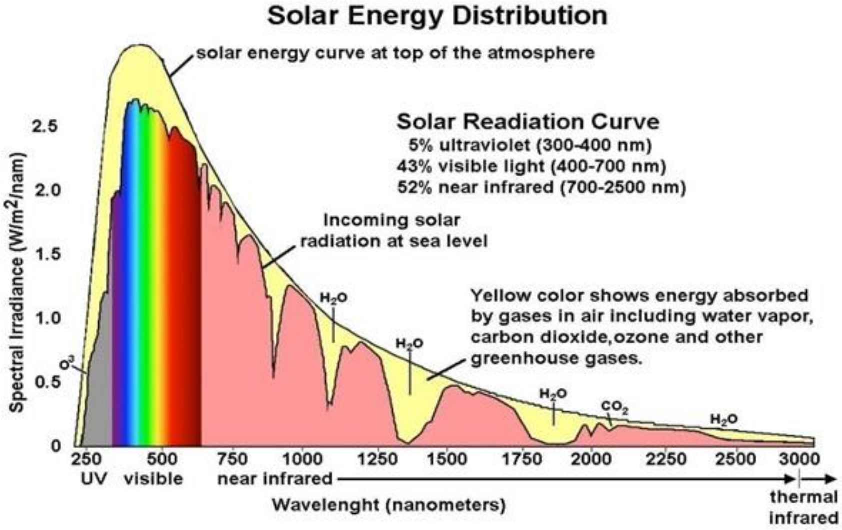


Fig. 1.14: Solar energy spectrum

1.4.Solar Radiation on a Flat and Tilted Surface [3]

The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and the sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (the power density is always be at its maximum when the PV module is perpendicular to the sun). However, as this incident angle is continually changing, the power density on a fixed PV module is less than that of the incident sunlight.

The amount of solar radiation incident on a tilted module surface is its component which is perpendicular to the module surface. The following figure shows how to calculate the radiation incident on a tilted surface (S_{module}) given either the solar radiation measured on horizontal surface (S_{horiz}) or the solar radiation measured perpendicular to the sun ($S_{incident}$).

The tilt angle has a major impact on the solar radiation incident on a surface. For a fixed tilt angle, the maximum power over the course of a year is obtained when the tilt angle is equal to the latitude of the location. However, steeper tilt angles are optimized for large winter loads, while lower title angles use a greater fraction of light in the summer.

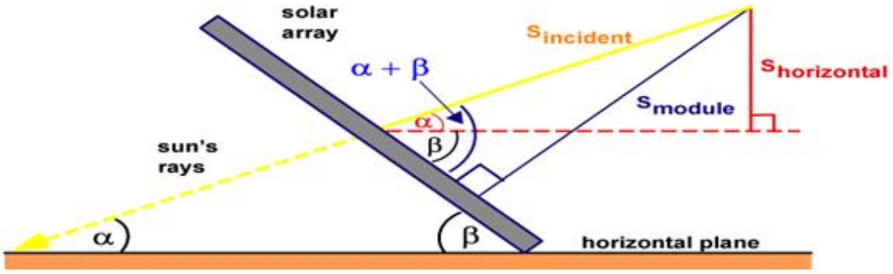


Fig. 1.15: Solar Radiation on a Tilted Surface

Chapter 2

Photovoltaic Effect

2.1. Solid-state materials

2.1.1. Band theory [1]

Band theory is a quantum model in solid state physics which gives the possible energies for electrons in a solid and gives an understanding of electrical conductivity. It comes from the theory of molecular orbital.

In a solid the allowed energy levels are confined to a band of which the width, of the order of an electron volt, depends on the crystal and the overlap of the atomic orbital.

Solids have a band structure: there are allowed energy bands and forbidden energy bands.

2.1.1.1.Valence Band [2][3]

The band of energy where all of the valence electrons reside and are involved in the highest energy molecular orbital. It is the band made up of the occupied molecular orbital. It is lower in energy than the so-called conduction band. When heated, electrons from this band jump out of the band across the band gap and into the conduction band.

2.1.1.2.Conduction Band

The band energy where positive or negative mobile charges carriers exist. Negative mobile charge carriers are simply electrons that had enough energy to escape the valence band and jump to the conduction band. Here, they move freely throughout the crystal lattice and are directly involved in the conductivity of semiconductors. Positive mobile charge carriers are also referred to as holes or to the lack of an electron [2][3].

2.1.1.3. Fermi Level

This level refers to the highest occupied molecular orbital in valence band at absolute zero. It is usually found at the center between the valence and conduction bands. Therefore the Fermi-Level is located in the band gap [2][3].

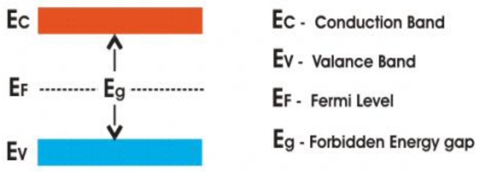


Fig. 2.1: different energy band

2.1.2.Classification of Solid-state materials [4]

Solid-state materials can be classified into 3 groups: insulators, semiconductors and conductors.

- Insulators are materials having an electrical conductivity : $\sigma < 10^{-8}$ [s/cm]
- semiconductors have a conductivity : $10^{-3} < \sigma < 10^{3}$ [s/cm]
- at last conductors are materials with high conductivities : $\sigma > 10^{3}$ [s/cm]

The electrical properties of a given material depend on the electronic populations of the different allowed bands. A material with fully occupied or empty energy bands is then an insulator. This is the case when the gap energy exceeds ~5 eV.

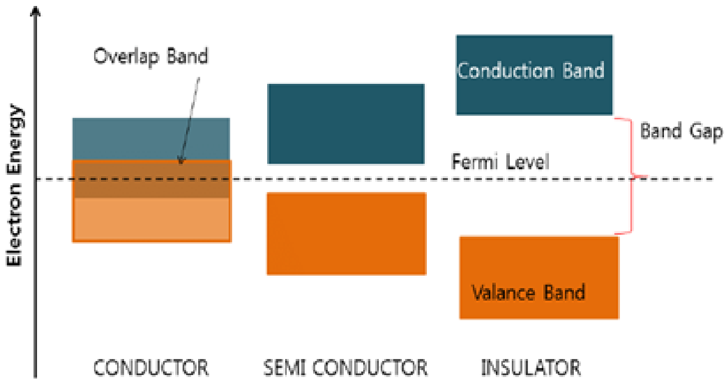


Fig. 2.2: energy bands model

2.1.3.The difference between solid-state materials [4]

Table 2.1 : the difference between solid-state materials

Basis of comparison	**Conductors**	**Semiconductors**	**Insulators**
Conductivity	More than (10^{-7} S/m)	10^{-7} to 10^{-13} S /m	< 10^{-13} S/m
Resistivity	Less than (10^{-5} Ω.m)	10^{-5} to 10^{5} Ω .m	> 10^{5} Ω.m
Temperature coefficient	Positive	Negative	Negative
Current flow	Caused by the presence of free electrons	Caused by free electrons and holes	Negligible
Forbidden gap : Eg	No forbidden gap Eg=0 eV	Small forbidden gap Eg < 2 eV	Large forbidden gap Eg > 5 eV

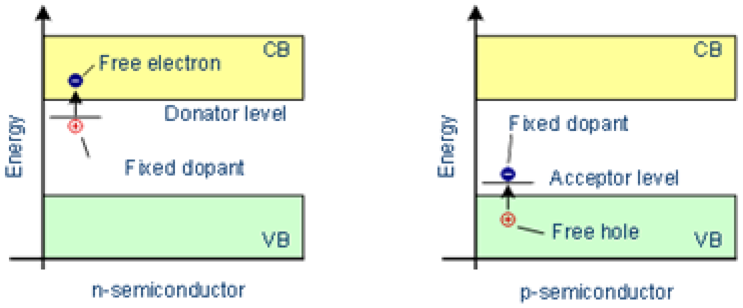


Fig. 2.3: Band model of doped semiconductors

A special case with the semiconductors is their tendency to be doped. As known, semiconductors have 4 electrons in their valance layer. In order to increase the number of electrons n the semiconductor is doped by the N-type, meanwhile the P-type doped is used to increase the holes number. Among the wide applications of doping, power generation solar cell based is the largest industry that uses this technology.

2.2. P-N junction

A P-N junction diode is a piece of silicon that has 2 terminals. One of the terminals is doped with P-type material and the other with N-type material. The P-N junction is the basic element for semiconductor diodes. A Semiconductor diode facilitates the flow of electrons completely in one direction only – which is the main function of semiconductor diode. There are two operating regions: P-type and N-type. And based on the applied voltage, there are three possible "biasing" conditions for the P-N Junction Diode, which are as follows:

2.2.1.Zero Biased Condition

In this case, no external voltage is applied to the P-N junction diode; and therefore, the electrons diffuse to the P-side and simultaneously holes diffuse towards the N-side through the junction, and then combine with each other. Thus an electric field is generated by these charge carriers. The electric field opposes further diffusion of charged carriers so that there is no movement in the middle region. This region is known as depletion width or space charge.

2.2.2.Forward Bias

In the forward bias condition, the negative terminal of the battery is connected to the N-type material and the positive terminal of the battery is connected to the P-Type material. This

connection is also called as giving positive voltage. Electrons from the N-region cross the junction and enter the P-region. Due to the attractive force that is generated in the P-region the electrons are attracted and move towards the positive terminal. Simultaneously the holes are attracted to the negative terminal of the battery. By the movement of electrons and holes the current flows. In this condition, the width of the depletion region decreases due to the reduction in the number of positive and negative ions.
The amount of energy required by the electrons and holes for crossing the junction is equal to the barrier potential (0.3V for Ge; 0.7V for Si; 1.2V for GaAs). It is a voltage drop across the diode due to internal resistance. This can be observed in the below graph.

2.2.3. Reverse Bias

In the forward bias condition, the negative terminal of the battery is connected to the N-type material and the positive terminal of the battery is connected to the P-type material. Hence, the electric fields due to both the voltage and depletion layer are in the same direction. This makes the electric field stronger than before. Due to this strong electric field, electrons and holes want more energy to cross the junction so they cannot diffuse to the opposite region. Hence, there is no current flow due to the lack of movement of electrons and holes.

Due to thermal energy in crystal minority carriers are produced. Minority carriers mean a hole in N-type material and electrons in P-type material. These minority carriers are the electrons and holes pushed towards P-N junction by the negative terminal and positive terminal, respectively. Due to this movement, a very little current (nA) flows. This current is called as reverse saturation current.

When the reverse voltage is increased beyond the limit the reverse current increases drastically. This particular voltage that causes the drastic change in reverse current is called reverse breakdown voltage.

$$I = Is * (e^{\frac{qV}{K_B T}}\text{-}1) \tag{2.1}$$

With: $K_BT/q \approx 0.026V$ at ambient temperature; $Is \approx 10^{-17}$ to $10^{-13}A$

Therefore, (2.1) can be written as(2.2):

$$I = Is * (e^{(V/0.026)} - 1) \tag{2.2}$$

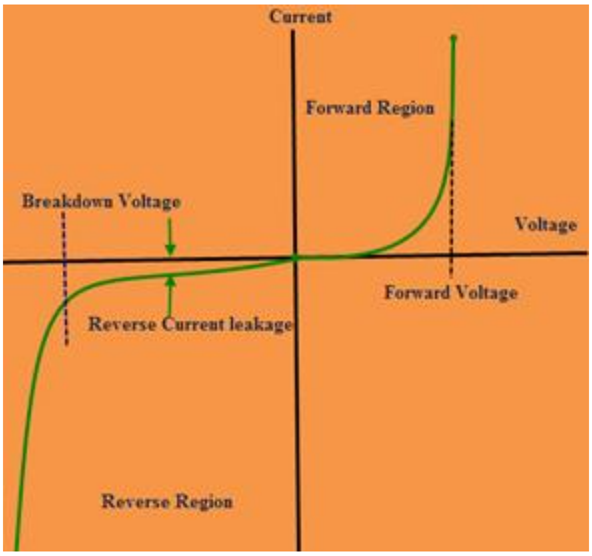


Fig. 2.4: Characteristics of P-N junction semiconductor (diode)

N.B: The graph changes according to different semiconductor materials used in the construction of a P-N junction diode.

2.3. Solar Cell

2.3.1. Solar Cell Construction [5][6]

Solar cell is the basic unit of solar energy generation system where electrical energy is extracted directly from light energy without any intermediate process. The working of a solar cell solely depends upon its photovoltaic effect, hence a solar cell also known as PV cell.

A solar cell is basically a semiconductor p-n junction device. It is formed by joining p-type and n-type semiconductor material. When sunlight falls on the solar cell, photons with energy greater than band gap of the semiconductor are absorbed by the cell and generate electron-hole (e-h) pair. These e-h pairs migrate respectively to n- and p- side of the p-n junction due to electrostatic force of the field across the junction. In this way a potential difference is established between 2 sides of the cell.

Typically a solar or PV cell has negative front contact and positive back contact. A semiconductor p-n junction is in the middle of these two contacts like a battery. If these two sides are connected by an external circuit, current will start flowing from positive to negative terminal of the solar cell. This is basic working principle of a solar cell. For silicon, the band gap at room temperature is Eg = 1.12 eV and the diffusion potential is U_D = 0.5 to 0.7 V.

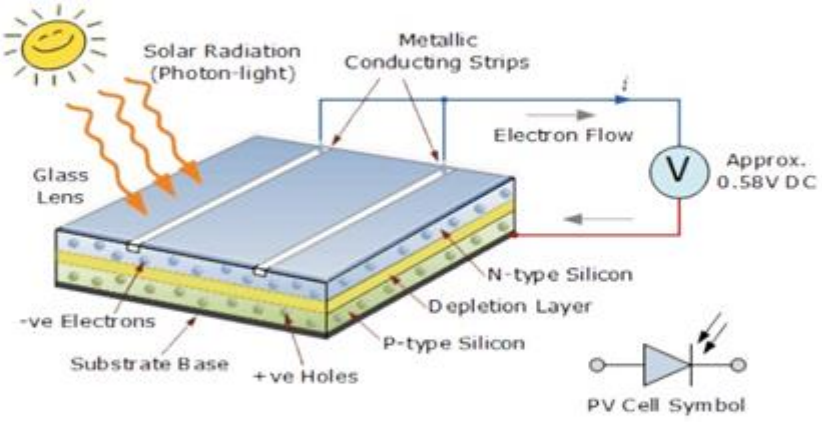


Fig. 2.5: Construction of a Si solar cell

2.3.2. Characteristics of PV Cell [5][6]

- The short-circuit current I_{SC} is the current through the solar cell when it is short circuited. We obtain this case when the two electrodes of the module are connected together without any load. So the voltage is zero and consequently the current is corresponding to the value on the current axis. Approximately, the short-circuit current and the light-generated current are identical. Therefore, I_{SC} is the largest current which may be drawn from the solar cell.

- The open-circuit voltage, V_{OC}, is produced by the module when it is no loaded. So the current is zero and consequently the voltage is corresponding to the value on the voltage axis. Therefore, V_{OC} is the largest voltage which may be drawn from the solar cell.

- The "fill factor" (FF) is defined as the ratio of the maximum power from the solar P_{max} cell to the product of V_{OC} and I_{SC}.

$$FF = Pmax/(Voc * Isc) \tag{2.3}$$

- The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell, the efficiency depends on the spectrum, incident sunlight intensity and solar cell temperature.

$$\eta = \frac{Pout}{Pin} = \frac{P_{max}}{H\,S} \tag{2.4}$$

S: solar cell surface; H: solar radiation.

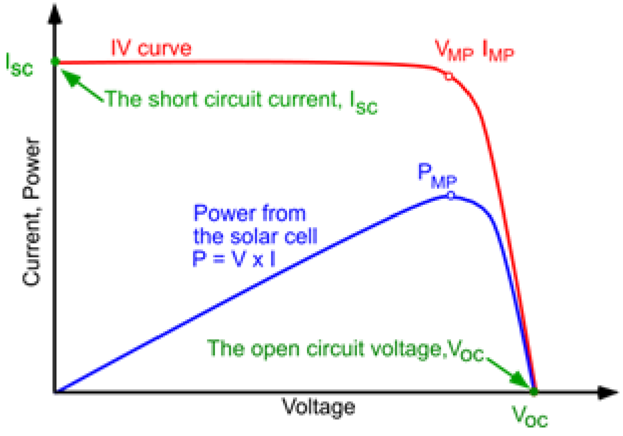


Fig. 2.6: I-V and P-V characteristics at STC

Standard Test Conditions (STC) are the industry standard for the conditions under which a solar panel is tested. By using STC conditions, all solar panels can be more accurately compared and rated against each other. There are three STC which are: - Temperature of the cell: 25°C; Solar irradiance: 1000 W/m²; Air Mass: 1.5.

2.3.3.Temperature and irradiance effect I-V curves [5][6]

There are several factors that can influence the performance of solar PV modules, including temperature and irradiance. V_{OC} varies with cell temperature. As the temperature increases, due to environmental changes or heat generated by internal power dissipation during energy production, V_{OC} decreases. This in turn reduces the power output. The design of a solar PV system must take into account the PV module temperature coefficient, comparing the expected average cell temperature in its operational environment, against the STC data used to calculate the module output.

In the same way, irradiance will also affect module performance, with a reduction of sunlight resulting primarily in a reduction in current and consequentially a reduced power output.

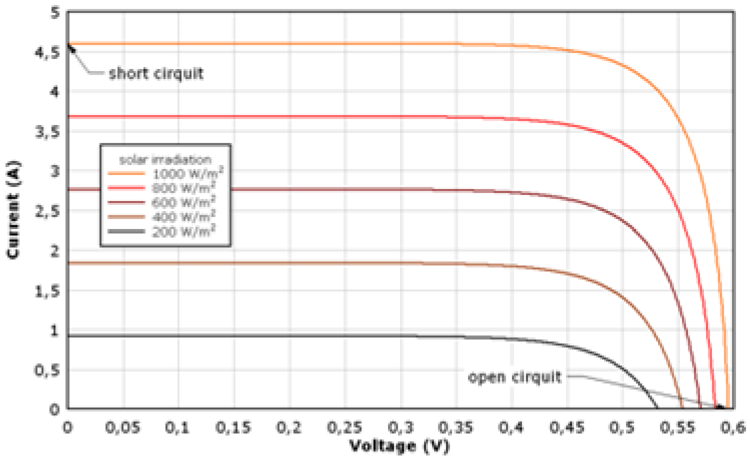


Fig. 2.7: Solar cell I-V characteristics for different irradiation values

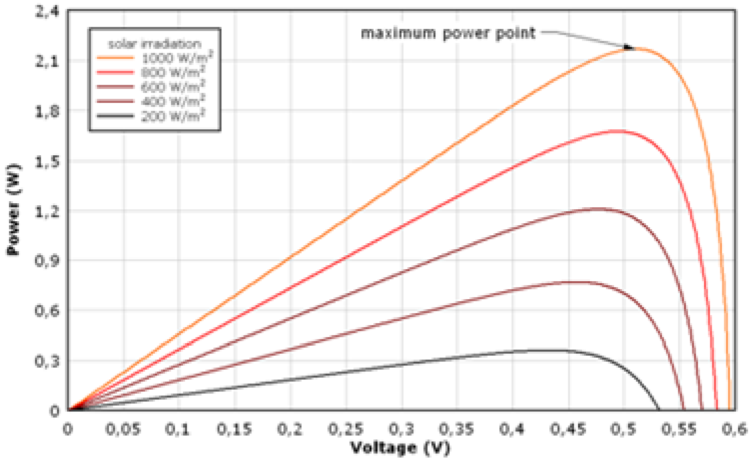


Fig. 2.7: Solar cell power characteristics for different irradiation values

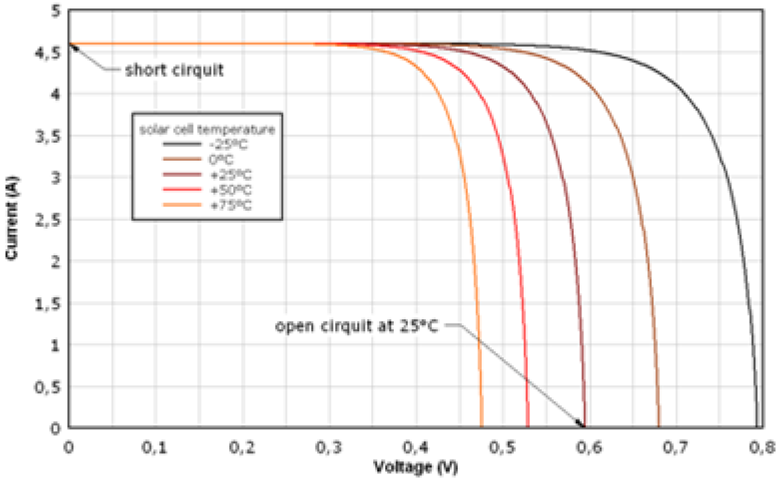


Fig. 2.8: Solar cell I-V characteristics temperature dependency

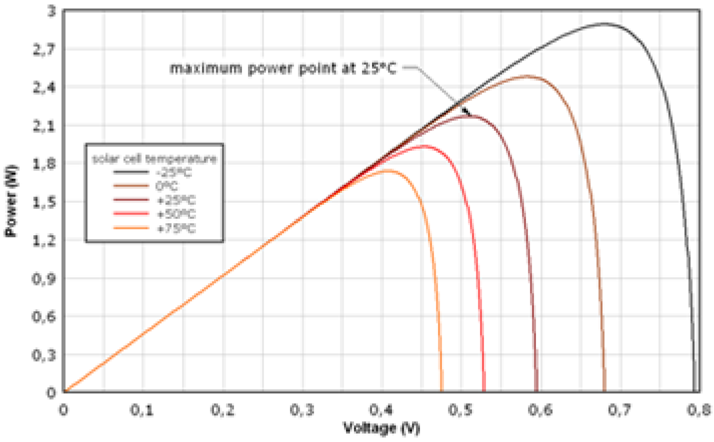


Fig. 2.9: Solar cell power characteristics temperature dependency

2.3.4. Solar Cell Model [5][6]

A general mathematical description of I-V output characteristics for a PV cell has been studied for over the pass four decades .Such an equivalent circuit-based model is mainly used for the MPPT technologies. The equivalent circuit of the general model which consists of a photo current, a diode, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow, is shown in (Fig 2.10):

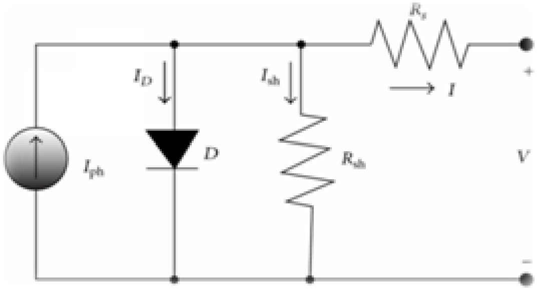


Fig. 2.10: Solar Cell Model

The voltage-current characteristic equation of a solar cell is given as (2.5):

$$I = I_{ph} - I_s\left[e^{\left(q\frac{V+IRs}{KT_CA}\right)} - 1\right] - \frac{V+IRs}{Rsh} \tag{2.5}$$

The photocurrent mainly depends on the solar insulation and cell's working temperature which is described as in (2.6) :

$$I_{ph} = H * [I_{sc} + K_1(T_C - T_{ref})] \tag{2.6}$$

Where Isc is the cell’s short-circuit current at a 25°C and 1000W/m².

K_1: the cell short-circuit current temperature coefficient; T_{ref}: the cell reference temperature.

On the other hand, the cell saturation current varies with the cell temperature as in (2.7):

$$I_S = I_{ref}(\frac{Tc}{Tref})^3 e^{qE_gkA(\frac{1}{Tref}-\frac{1}{Tc})} \tag{2.7}$$

I_{ref} : the cell reverse saturation current at a reference temperature and a solar radiation; E_g: the bang-gap energy of the semiconductor used in the cell; A: The diode ideal factor.

However, there are some limitations to develop expressions for the V-I curve parameters subject to the implicit and nonlinear nature of the model. Therefore, this model is rarely used in the subsequent literatures and is not taken into consideration for the generalized PV model.

The shunt resistance R_{sh} is inversely related with shunt leakage current to the ground. In general, the PV efficiency is insensitive to variation in R_{sh} which can be assumed to approach infinity without leakage current to ground. On the other hand, a small variation in the series resistance R_S will significantly affect the PV output power. The appropriate model of PV solar cell with suitable complexity can be rewritten as in (2.8) :

$$I = I_{ph} - I_s[e^{\left(\frac{qV+IR_S}{KT_cA}\right)} - 1] \tag{2.8}$$

For an ideal PV cell, there is no series loss and no leakage to ground, i.e., R_s=0 and R_{sh}=∞. Thus the above equivalent circuit of PV solar cell can be simplified to be (2.9):

$$I = I_{ph} - I_s[e^{\left(\frac{qV}{KT_cA}\right)} - 1] \tag{2.9}$$

2.4. Classification of PV cells [7]

Several types of PV technologies are developed and can be classified as follows:

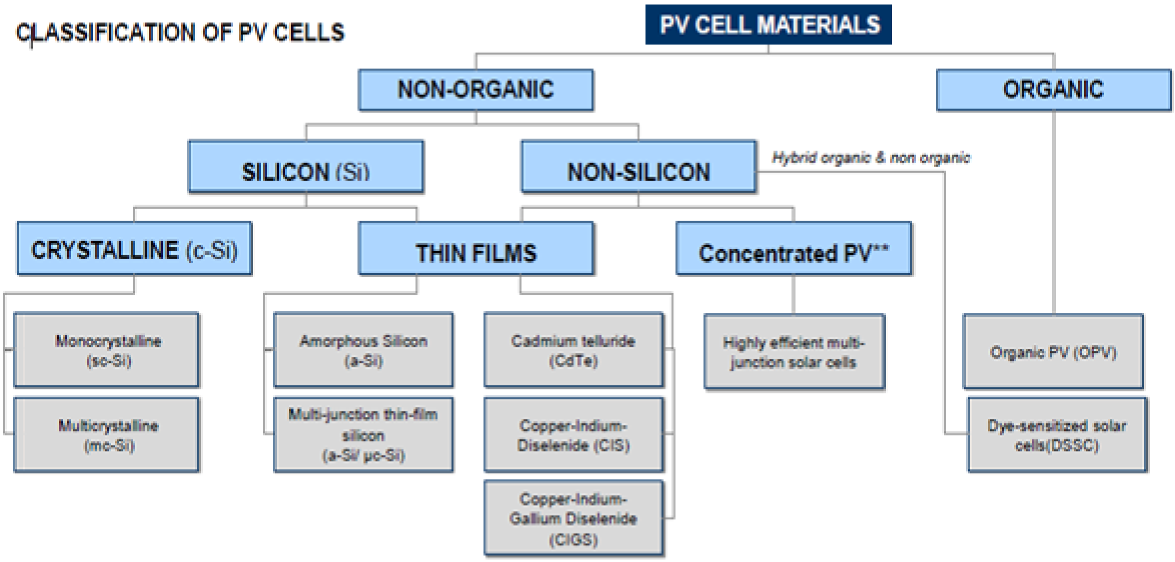


Fig. 2.11: Classification of PV cell

2.4.1. Crystalline silicon cells

This technology uses the wafer-based crystalline silicon (c-Si) technology, either single (mono) crystalline (sc-Si) or multi-crystalline (mc-Si). Crystalline silicon cells may be mounted into framed or frameless panels suitable for roof or façade integration. Highest cell efficiency for commercial mono crystalline cells is for the moment 22.5% and the multi crystalline cells have about 18%.

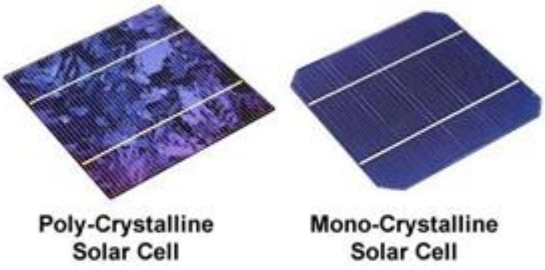
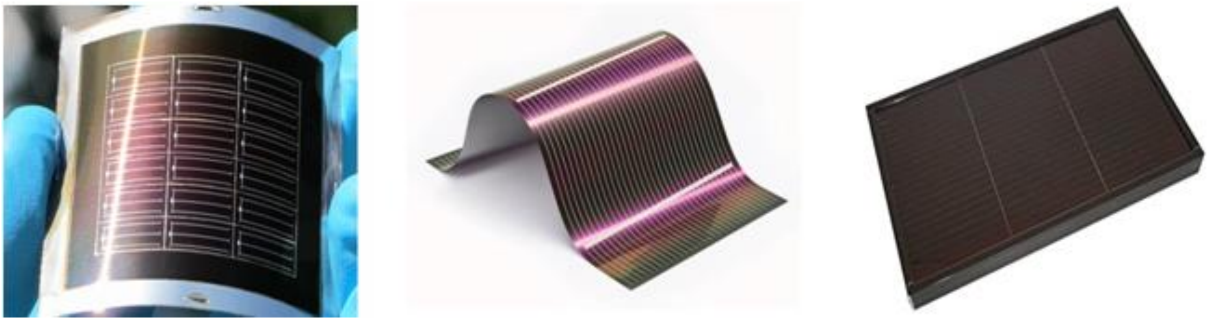


Fig. 2.12: Crystalline silicon cells

2.4.2. Thin-film cells

The thin-film technology reduces the amount of material required in creating the active material of solar cells. Most thin-film solar cells are sandwiched between two panes of glass to make a frameless module. Since silicon solar panels only use one pane of glass, thin-film panels are approximately twice as heavy as crystalline silicon panels. The majority of thin-film panels have 2% to 3% lower conversion efficiencies than silicon. Cadmium telluride

(CdTe), copper indium gallium selenium (CIGS) and amorphous silicon (A-Si) are three thin-film technologies. The highest efficiency reach is about 20 % with Cadmium telluride (CdTe) and CIGS. The market share of thin films PV is around 11% of all manufactured PVs.



CdTe solar call CIGs solar cell Amorphous silicon

Fig. 2.13: Thin-film cells

2.4.3. Organic Photovoltaic (OPV)

An organic solar cell or plastic solar cell is a type of polymer solar cell that uses organic semiconductors. The plastic used in organic solar cells has low production costs in high volumes. Combined with the flexibility of organic molecules, organic solar cells are potentially cost-effective for PV applications. The main disadvantages associated with organic PV cells are low efficiency, low stability and low strength compared to inorganic PV cells. At the moment, organic PV uses three key technologies: OPV oligomers, OPV polymers and OPV DSSC (dye-sensitized solar cells; hybrid technology).

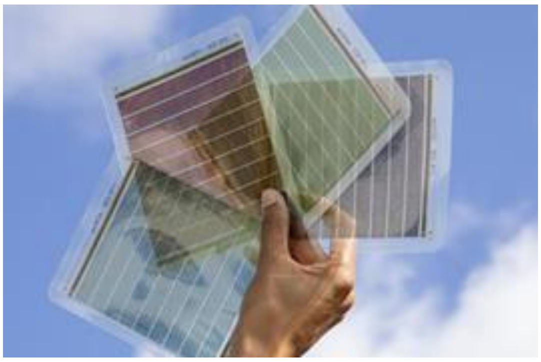


Fig. 2.14: Organic Photovoltaic cell

2.5. Layers of solar panels

Solar modules consist of multiple layers. Besides the power producing layer of solar cells, the structure of solar modules also has to allow for stability and corrosion protection**.** Here are the different layers of a photovoltaic solar module:

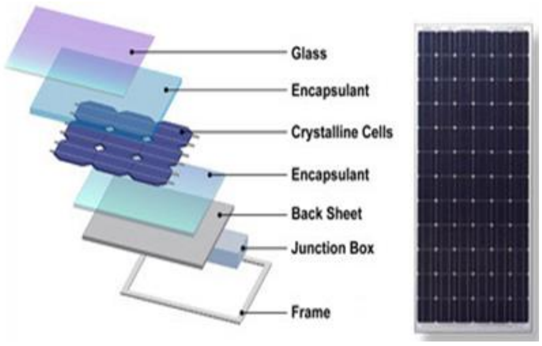


Fig. 2.15: layers of solar panels

2.5.1. Face-plate (ESG)

The first layer is a 4mm thick ESG glass plate (safety glass), which is not only impact pressure and temperature resistant, but also shock proof. Applying an anti-reflective coating to the cover glass will reduce reflections and increase the module's output power.

2.5.2. Encapsulating film (EVA)

Two plastic layers made from EVA (ethylene vinyl acetate) or a cast resin layers are inserted, one as upper and the other as lower, moisture barrier. The plastic films are welded (laminated) onto the solar cells at temperatures around 150°C forming a water-proof corrosion protection.

2.5.3. Solar cells

Single solar cells, interconnected with each other, produce electric power.

2.5.4. Tedlar laminated film

A plastic layer made from polyvinyl fluoride, better known under the trade name Tedlar and icosolar, or a glass plate is used as finish on the back side.

2.5.5. Frame

To give stability to the different layers and to facilitate the assembly, the module is enclosed in an aluminum frame.

Chapter 3

Household electrification, Water Pumping and Public Lighting System Components

3.1. Household Electrification System Components

3.1.1.Solar Panels

3.1.1.1.Solar Module Structure

A PV module consists of a number of interconnected solar cells encapsulated into a single, long-lasting, stable unit. The encapsulating protects the cells and their interconnecting wires from the typically harsh environment [1].

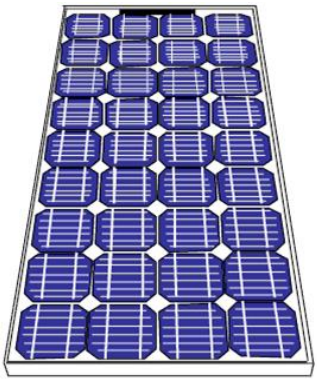


Fig. 3.1: A Bulk Silicon PV Module

A bulk PV module consists of multiple individual solar cells connected, nearly always in series, to increase the power and voltage above that from a single solar cell. The voltage of a PV module is usually chosen to be compatible with a 12V battery. An individual silicon solar cell has a voltage at the maximum power point around 0.5V under 25°C and AM1.5 illumination. Taking into account an expected reduction in PV module voltage due to temperature and the fact that a battery may require voltages of 15V or more to charge, most modules contain 36 cells in series. This gives an open-circuit voltage of about 21V under STC, and an operating voltage at maximum power and operating temperature of about 17V or 18V. The remaining excess voltage is included to account for voltage drops caused by other elements of the PV system, including operation away from maximum power point and reductions in light intensity.

In order to obtain a certain PV module characteristics and to fulfill the market demands of more efficient PV module with less power losses , different cells interconnection structure are applied to achieve this expectations.

- **Series Interconnection**

As shown in Fig 3.3, a certain number of PV cells are interconnected in a way that the negative pole of a cell in connected to the positive pole to the following cell. In the end only one pair of positive-negative wires are extracted from the module.

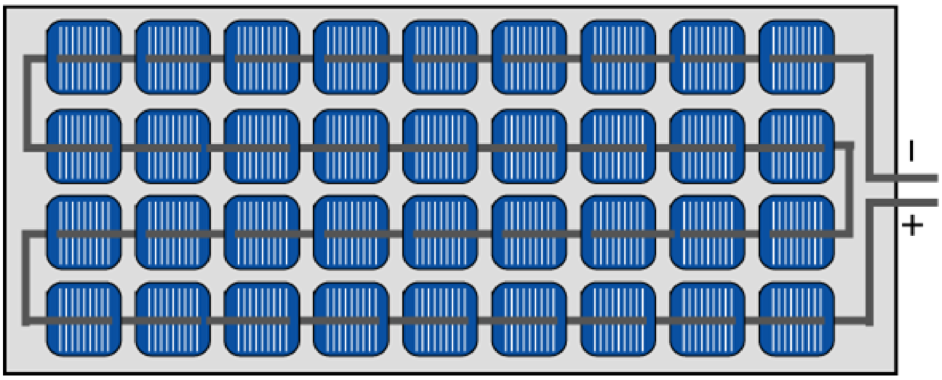


Fig. 3.2: A Typical 36 cells in series Module

Considering the cell voltage V_c, the voltage of the module is (3.1) :

$$V_{m} = n * V_{c} \tag{3.1}$$

n : the number of the PV cells; V_m: the module total voltage

- **Parallel Interconnection**

In the parallel interconnection is used to increase the current. The negative poles of all the calls are connected to each others as well as for the positive poles. One pair of positive-negative wires are extracted from the module.

$$I_{m} = n * I_{c} \tag{3.2}$$

I_m: the module total current; n: the number of the PV cells; I_c: The individual cell current

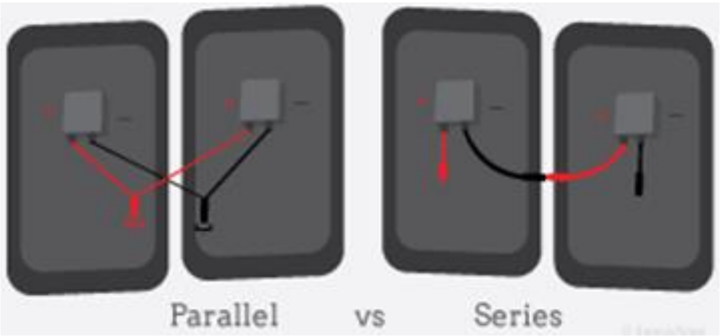


Fig. 3.3: Parallel and series Interconnection

- **Mix Interconnection**

Series and parallel interconnection are combined. Number of cells assembled together and connected in series and this group is connected in parallel to another group of series cells. This method increases both the voltage and current at the same time. One pair of negative-positive wires is extracted at the end.

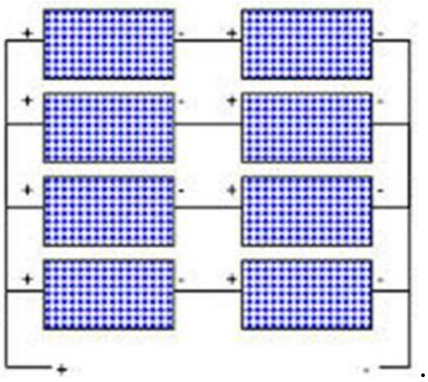


Fig. 3.4: Mix Connection

$$I_m = n_p * I_c \tag{3.3}$$

$$V_m = n_s * V_c \tag{3.4}$$

$$P_m = I_m * V_m \tag{3.5}$$

I_m: the module total current; n_s: the number of the PV cells in series; I_c: The individual cell current; n_p: the number of the PV cells in parallel; V_m: the module total voltage; V_c: the individual cell voltage; P_m: the module total Power.

3.1.1.2.Solar Array Structure

Starting from a cell to a module ending with an array, this procedure is necessary to generate enough power and fulfill the consummation demands. As for the structure, it is similar to the module assembling structure (series, parallel, mix).

3.1.1.3.Solar Panel inside protection

A solar panel or module is like any other devise that needs to protect itself from damaging it components as individuals or the panel as a whole, bypass diode and non return diode are integrated shield in the structure.

- **Non return diode**

A non return diode is simply the normal basic diode; semiconductor based material, it's placed to protect a full string of interconnected solar cell from the reversed current in the system. in which it may damage the sell and cause the malfunction of the whole system.

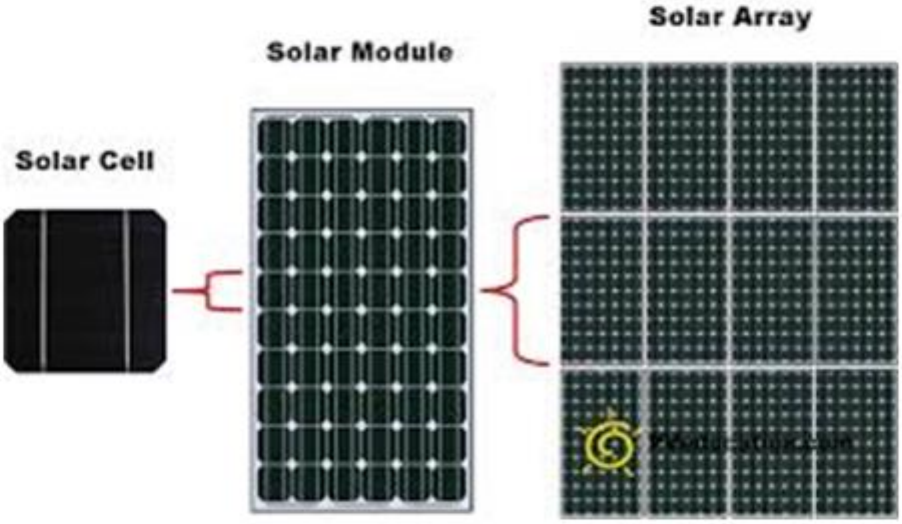


Fig. 3.5: From a Cell to an Array

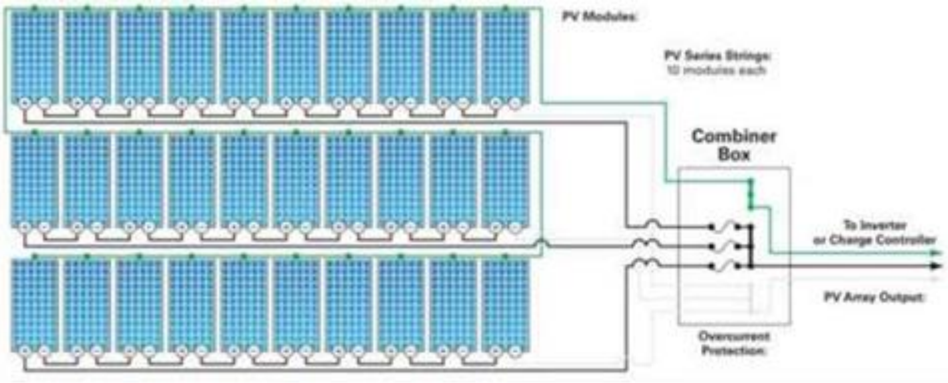


Fig. 3.6: Solar Array

- **Bypass diode**

Bypass diode take place to protect the other cells when a certain one or some cells doesn't function properly, whether the malfunction is caused by shading or cells distortion, where the cell temperature is dramatically increased and would lead to damaging the module.

Schottky diode is used for its low forward voltage drop (0.3-0.5 V) which dissipate less power and generate less heat.

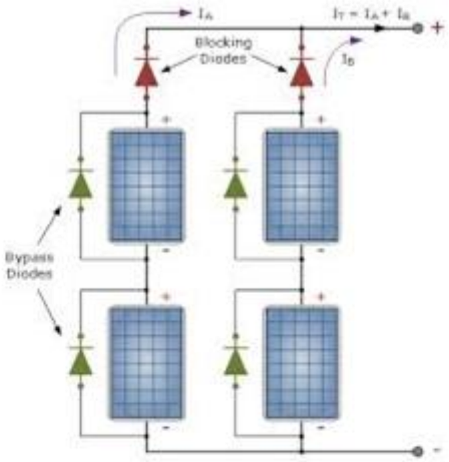


Fig. 3.7: Bypass and Non Return Diode in a Module

3.1.1.4.Shading

The output of a cell declines when shaded by a tree branch, building or module dust. The output declines proportionally to the amount of shading. For completely opaque objects such as a leaf, the decline in current output of the cell is proportional to the amount of the cell that is obscured. Since the cells in a module are all connected in series, shading a single cell causes the current in the string of cells to fall to the level of the shaded cell.

3.1.2.Solar Mounting System

A solar mounting system is a component that secures solar panels to your roof, ground or pole and holds them in place. There are different solar racking systems available and it's yours the choice of the right mounting system suitable for your solar installation.

There are 3 main mounting systems, which are: -Rooftop mounting; -Ground mounting; -Pole mounting.

3.1.3.Electric Wires and Connectors [2]

Electrical wires are used to carry electrical current from the power source to the user device. There are three different styles of wires. Bare wire is just what the name states, non-insulated. Insulated solid wire is a solid piece of wire that is coated and encased in a plastic coating. The last is insulated stranded wire. This has many smaller sized strands of copper and is also wrapped in a protective plastic coating.

Choosing the right wire sizes in PV system is important for both performance and safety reasons. If the wires are undersized, there will be a significant voltage drop in the wires resulting in excess power loss. In addition, there is a risk that the wires may heat up to the point in which a fire may result. If your electrical wires are not large enough or if the cable is longer than needed, then the resistance is higher resulting in less watts going to either your battery bank or the grid.

The chart below shows the capacity of various wire gauge sizes and their typical amp rating and application for both residential and solar applications.

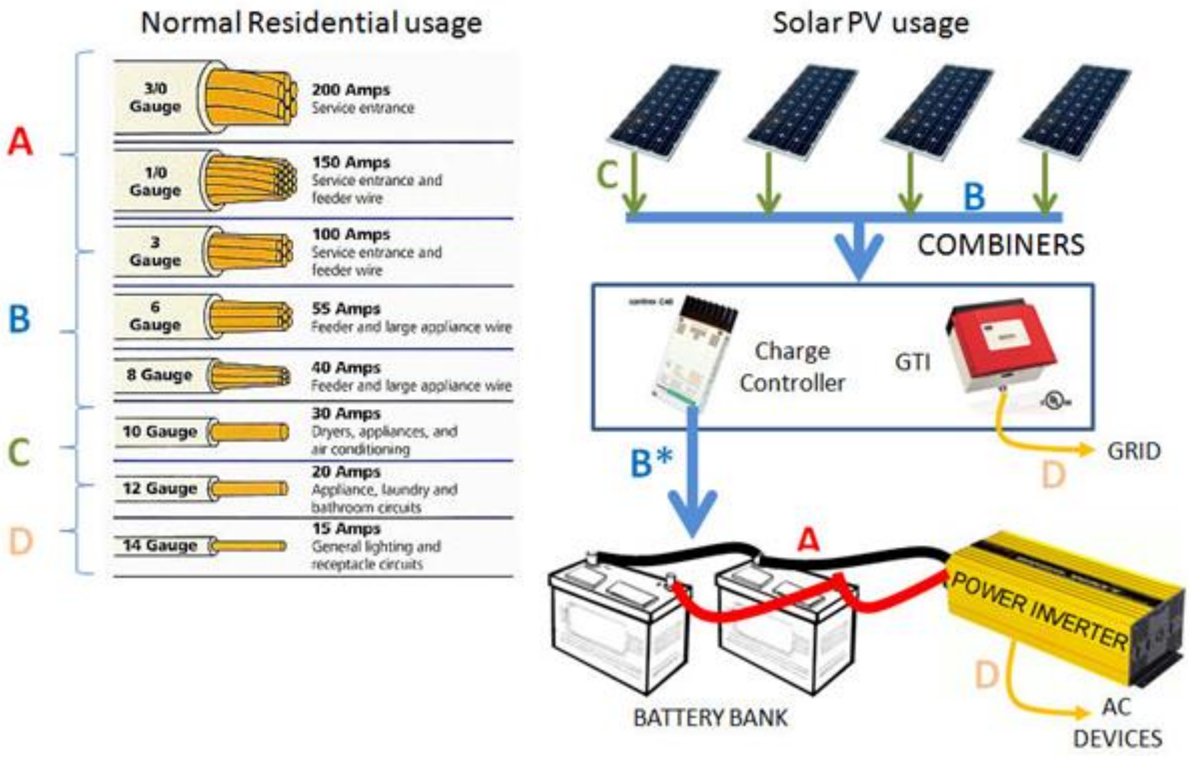


Fig. 3.8: Wire pick a for PV System

Commercial solar PV panels over 50W or so use 10 gauge (AWG) wires. This allows up to 30A of current to flow from a single panel. If multiple panels are combined in parallel, then a three to eight AWG “combiner” wire set is generally needed to safely transfer the power to a charge controller or GTI.

The wires from the charge controller to the battery bank can generally be the same or larger gauge than the main set from the PV array. The exception is when the Charge Controller is of the type that can operate a 12 or 24V battery bank even when the PV array is operating at higher voltages, such as 48 Vdc and larger. These Charge Controllers have large transformers that lower the voltage but in the process they increase the current going to the battery bank.

Refer to the installation material for the charge controller you chose when selecting the correct wire size to use.

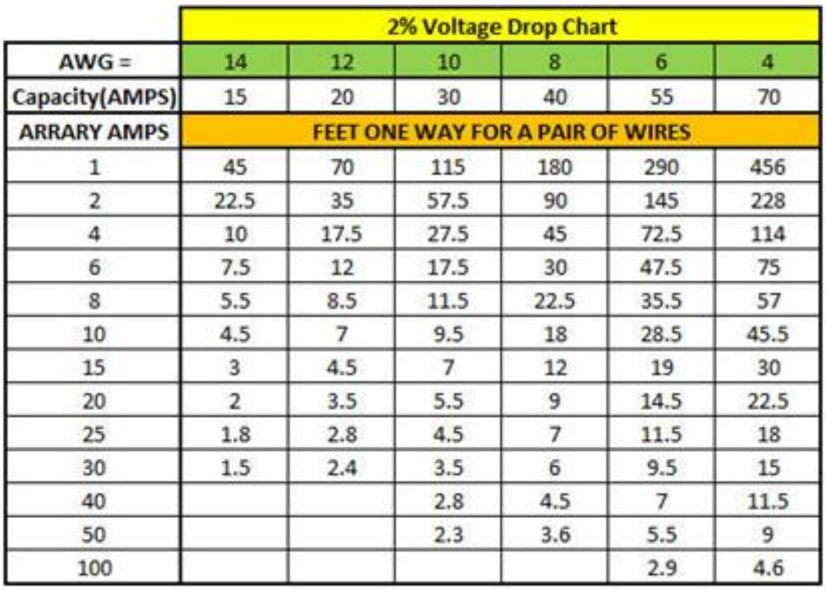
The wires between batteries in a battery bank tend to be the largest in the system since they are used in conjunction with a power inverter that can at times demand more current than that the PV system can supply on its own. These same wires will also have to carry current used simultaneously for charging and for power inversion. A typical battery bank wire size is 1/0 or “one-ought.”

It is very important to match the gauge and the wire lengths when combining batteries in a battery bank. If this is not done, then the battery bank’s life can be shortened and certain safety issues can result.

Usually the longest wire run is from the PV array to the location where the charge controller or GTI is located. Since all of the combined PV power flows through this wire set, we really need to choose it correctly to maximize performance and to assure safety.

The general rule-of-thumb is to stay below 2% voltage drop on this run. Using the known resistance of the various wire gauges, it is possible to calculate the maximum length for a wire-pair for each wire gauge size.

Here is what that calculation looks like for a 12V PV system. You can double the length for a 24V system, or quadruple it for a 48V system.



	2% Voltage Drop Chart					
AWG =	14	12	10	8	6	4
Capacity(AMPS)	15	20	30	40	55	70
ARRARY AMPS	FEET ONE WAY FOR A PAIR OF WIRES					
1	45	70	115	180	290	456
2	22.5	35	57.5	90	145	228
4	10	17.5	27.5	45	72.5	114
6	7.5	12	17.5	30	47.5	75
8	5.5	8.5	11.5	22.5	35.5	57
10	4.5	7	9.5	18	28.5	45.5
15	3	4.5	7	12	19	30
20	2	3.5	5.5	9	14.5	22.5
25	1.8	2.8	4.5	7	11.5	18
30	1.5	2.4	3.5	6	9.5	15
40			2.8	4.5	7	11.5
50			2.3	3.6	5.5	9
100					2.9	4.6

Fig. 3.9: Wire Run Lengths

3.1.4.Charge Controller [3]

A solar charge controller is fundamentally a voltage or current controller to charge the battery and keep electric cells from overcharging. Generally, electric storage devices require around 14 to 14.5V to get completely charged. The range of charge controllers is from 4.5A and up to 60 to 80A [3].

3.1.4.1.Types of Charge Controllers

There are 3 different types:

3.1.4.1.1.Simple 1 or 2 stage controllers

Which rely on relays or shunt transistors to control the voltage in one or two steps. These essentially just short or disconnect the solar panel when a certain voltage is reached. Their only real claim to fame is their reliability. They have so few components.

3.1.4.1.2.PWM (pulse width modulation)

PWM solar charge controllers (or 3 stages controllers) are the standard type of charge controller available to solar shoppers. They are simpler than MPPT controllers, and thus generally less expensive. PWM controllers work by slowly reducing the amount of power going into your battery as it approaches capacity. When your battery is full, PWM controllers maintain a state of “trickle”, which means they supply a tiny amount of power constantly to keep the battery topped off.

With a PWM controller, your solar panel system and your home battery need to have matching voltages. In larger solar panel systems designed to power your whole home, panel and battery voltage aren’t typically the same. As a result, PWM controllers are more suited for small solar systems with a couple of low voltage panels and a small battery.

3.1.4.1.3.Maximum power point tracking (MPPT)

MPPT solar charge controllers are a more expensive and complex charge controller option. They provide the same switch-like protection that a PWM controller does, and will reduce the power flowing to your home battery as it nears capacity.

Unlike PWM controllers, MPPT charge controllers can pair non-matching voltages from panels and batteries. MPPT controllers adjust their input to bring in the maximum power possible from your solar array, and can also vary their output power to match the attached battery. This means that MPPT charge controllers are more efficient than PWM controllers, and more effectively utilize the full power of your solar panels to charge a home battery system.

3.1.4.2.Features of Solar Charge Controller [3]

- Protects the battery (12V) from overcharging;
- Reduces system maintenance and increases battery lifetime;
- Auto charged indication;
- Reliability is high;
- 10A to 40A of charging current;
- Monitors the reverse current flow;

3.1.4.3.The function of the Solar Charge Controller [3]

The most essential charge controller basically controls the device voltage and opens the circuit, halting the charging, when the battery voltage ascents to a certain level. More charge controllers utilized a mechanical relay to open or shut the circuit, halting or beginning power heading off to the electric storage devices.

Generally, solar power systems utilize 12V of batteries. Solar panels can convey much more voltage than is obliged to charge the battery. The charge voltage could be kept at the best level while the time needed to completely charge the electric storage devices is lessened. This permits the solar systems to work optimally constantly. By running higher voltage in the wires from the solar panels to the charge controller, power dissipation in the wires is diminished fundamentally.

The solar charge controllers can also control the reverse power flow. The charge controllers can distinguish when no power is originating from the solar panels and open the circuit separating the solar panels from the battery devices and halting the reverse current flow.

3.1.5.DC/AC inverter [4]

The main objective of static power converters is to produce an AC output waveform from a DC power supply. For sinusoidal AC outputs, the magnitude, frequency, and phase should be controllable.

Static power converters, specifically inverters, are constructed from power switches and the AC output waveforms are therefore made up of discrete values. This leads to the generation of waveforms that feature fast transitions rather than smooth ones.

3.1.5.1.Autonomous Inverter [4]

A stand-alone inverter is a static converter DC-AC providing from a DC current source a voltage or current wave of variable frequency.

- A voltage switch is an inverter whose voltage wave is imposed on the load.
- A current switch is an inverter whose current wave is imposed on the load.

An inverter is supported, if the frequency and voltage are imposed by the grid, in this case we'll be able to adjust the frequency and voltage, so the inverter will be self-contained.

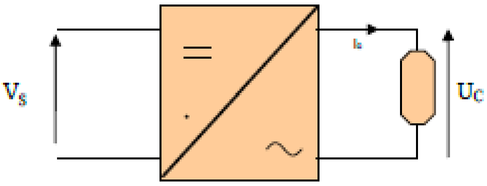


Fig. 3.10: DC/AC Stand-Alone Inverter Structure

3.1.5.2. Inverter with two electronic switches [4]

3.1.5.2.1.Resistive load

Two power supplies delivering 2 voltages, continuous and equal, supply a resistive load by via 2 switches H1 and H2 which can be transistors or thyristors, controlled unidirectional electronic components. If the one is open, the other is necessarily closed and vice versa.

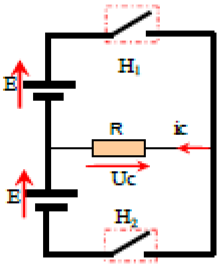


Fig. 3.11: Two Switches Inverter (Resistive Load)

3.1.5.2.2.Resistive and Inductive Load

For a highly inductive load, this component requires the addition of 2 diodes mounted in anti parallel on the switches. They allow the coil, to release the stored energy, when the switches are opened, allowing the current not to experience any discontinuity.

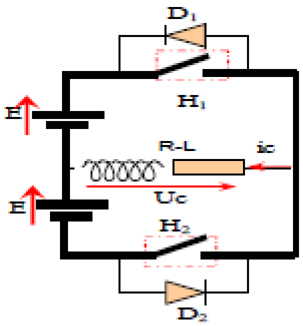


Fig. 3.12: Two Switches Inverter (Resistive and Inductive Load)

Table 3.1: Passing and Non Passing Components (R Load)

Time	Current i_c	Voltage U_c	Controlled Switches	Passing Elements
$0<t<t_1$	$i_c<0$	$U_c>0$, $U_c= E$	H_1 :closed	D_1 : Passing
t1<t<T/2	$i_c>0$	$U_c>0$, $U_c= E$	H_1 :closed	H_1 : Passing
$T/2<t<t_2$	$i_c>0$	$U_c<0$, $U_c= -E$	H_2 :closed	D_2 : Passing
$t_2 <t<T$	$i_c<0$	$U_c<0$, $U_c= -E$	H_2 :closed	H_2 : Passing

3.1.5.3.Inverter with four electronic switches (Bridge Inverter) [4]

This type of inverter has four diodes mounted in antiparallel on four switches. The output voltage adjustable value by shifting the ignition angle of the static switches.

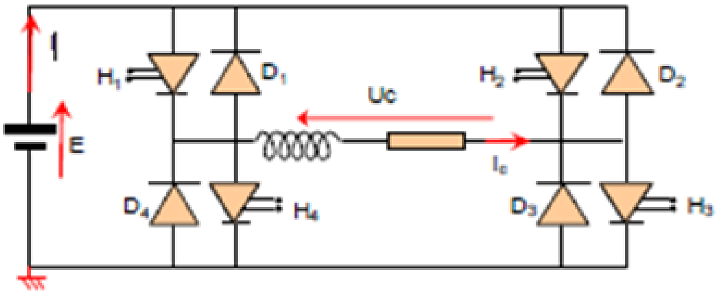


Fig. 3.13: Inverter with four electronic switches

3.1.5.3.1 Symmetrical control

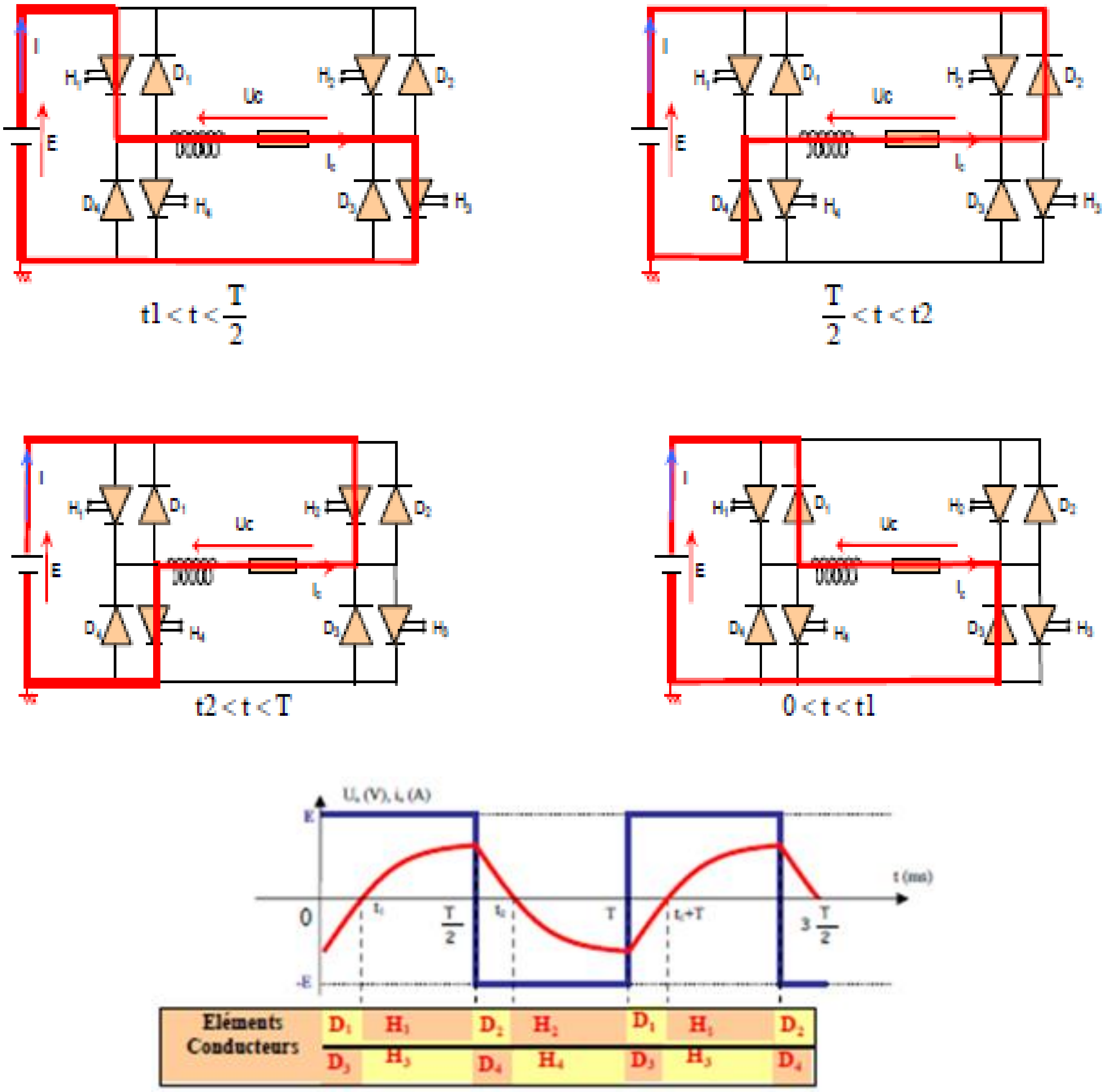
The bridge control is symmetrical H1 and H3 are closed simultaneously for half of the period. The rest of the period sees the closing of switches H2 and H4. When H1 and H3 are closed, the other two switches are necessarily open.

The voltage Uc can therefore only take the two following values :

H1 and H3 closed	H2 and H4 open	U = E.
H2 and H4 closed	H1 and H3 open	U = - E.

Table 3.2: Passing and Non Passing Components (RL Load)

Time	Current i_c	Voltage U_c	Controlled Switches	Passing Elements
$t1<t<T/2$	$i_c>0$	$U_c>0$	H_1, H_3 :closed	H_1, H_3 : Passing
$T/2<t<t_2$	$i_c>0$	$U_c<0$	H_2 , H_4:closed	D_2, D_4 : Passing
$t_2 <t<T$	$i_c<0$	$U_c<0$	H_2, H_4 :closed	H_2, H_4: Passing
$0<t<t_1$	$i_c<0$	$U_c>0$	H_1, H_3:closed	D_1, D_3: Passing



$t1 < t < \frac{T}{2}$

$\frac{T}{2} < t < t2$

$t2 < t < T$

$0 < t < t1$

Fig. 3.14: Four Switches Inverter Chronogram

3.1.5.3.2.Offset control

The bridge control is no longer symmetrical H1 and H3 are not necessarily closed in. At the same time, the same applies to H2 and H4. During the first half period H1 and H3 are closed simultaneously and then it is the turn of H3 and H4 to be closed together. During the second half period H4 remains closed with H2, then returns H1 with H2.

Table 3.3: Passing and Non Passing Components (Offset Control)

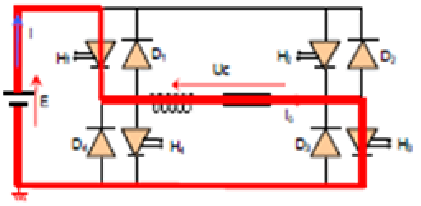
Time	Current i_c	Voltage U_c	Controlled Switches	Passing Elements
$t_a<t<t_1$	$i_c>0$	$U_c>0$	H_1, H_3 :closed	H_1, H_3 : Passing
$t_1<t<T/2$	$i_c>0$	$U_c=0$	H_3, H_4:closed	H_3, D_4 : Passing
$T/2<t<t_b$	$i_c>0$	$U_c<0$	H_2, H_4 :closed	D_2, D_4 : Passing
$t_b<t<t_2$	$i_c<0$	$U_c<0$	H_2, H_4:closed	H_2, H_4: Passing
$t_2<t<T$	$i_c<0$	$U_c=0$	H_1, H_2:closed	H_2, D_1 : Passing
$0<t<t_a$	$i_c<0$	$U_c>0$	H_1, H_3:closed	D_1, D_3: Passing

- Study of the functioning :

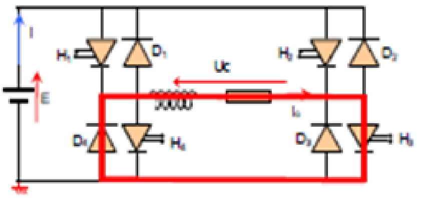
When Ucic >0: the load receives electrical energy.

When Ucic <0: the load restores electrical energy (recovery phase).

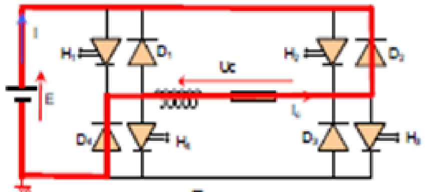
When Uc=0: the load restores electrical energy to itself. (free wheeling phase).



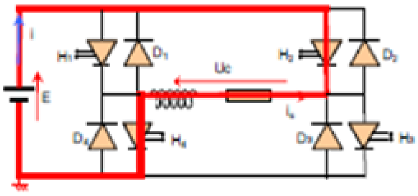
$-t_a < t < t_1$



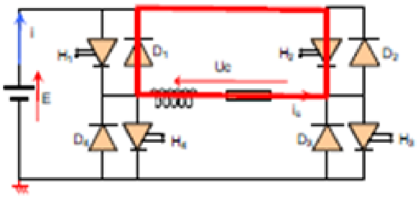
$t_1 < t < \frac{T}{2}$



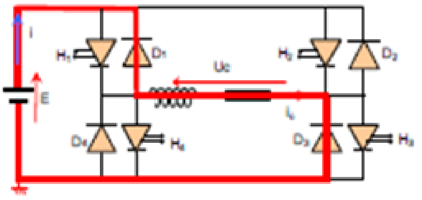
$\frac{T}{2} < t < t_b$



$t_b < t < t_2$



$t_2 < t < T$



$0 < t < t_a$

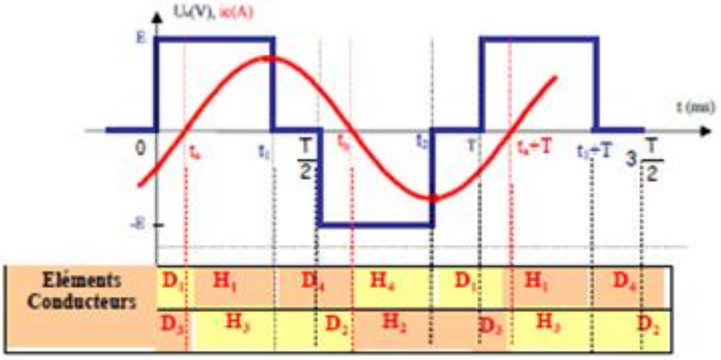


Fig. 3.15: Offset Inverter Chronogram

With inductive load, the current Ic is sinusoidal but delayed. The voltage at the load is:

The mean value of Uc is:

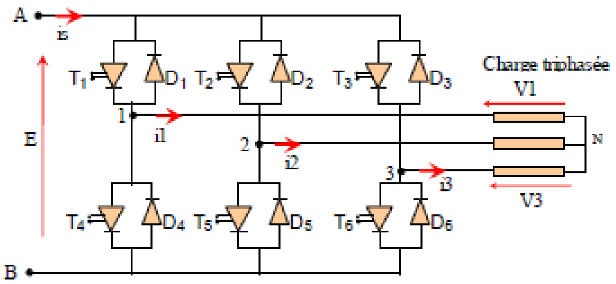
$$\overline{\mathrm{Uc}} = 0\mathrm{V} \tag{3.6}$$

The RMS value of Uc is:

$$\mathrm{Uc} = \mathrm{E}\sqrt{2\frac{\mathrm{t}}{\mathrm{T}}} \tag{3.7}$$

3.1.5.4.Three-phase voltage inverter [4]

We are only interested in the structure of the three-arm switch-mode inverter in series.



The load is assumed to be balanced. We immediately have the following relationships at the load level:

$$\begin{Bmatrix} \mathrm{i}_1 + \mathrm{i}_2 + \mathrm{i}_3 = 0 \\ \mathrm{V}_1 + \mathrm{V}_2 + \mathrm{V}_3 = 0 \end{Bmatrix} \quad \text{et} \quad \begin{Bmatrix} \mathrm{U}_{12} = \mathrm{V}_1 - \mathrm{V}_2 & \rightarrow (1) \\ \mathrm{U}_{23} = \mathrm{V}_2 - \mathrm{V}_3 & \rightarrow (2) \\ \mathrm{U}_{31} = \mathrm{V}_3 - \mathrm{V}_1 & \rightarrow (3) \end{Bmatrix} \tag{3.8}$$

By performing member to member the difference between equations (1) and (3), we obtain:

$$\mathrm{U}_{12} - \mathrm{U}_{31} = 2\mathrm{V}_1 - \mathrm{V}_3 - \mathrm{V}_2 = 3\mathrm{V}_1 \tag{3.9}$$

We thus arrive at the expression of the simple voltage:

$$\mathrm{V}_1 = \frac{1}{3}(\mathrm{U}_{12} - \mathrm{U}_{31}) \tag{3.10}$$

And by circular permutation of the indices 1,2,3, we can establish the expressions of the other two simple tensions indices:

$$V_2 = \frac{1}{3}(U_{23} - U_{12}) \qquad (3.11)$$

$$V_3 = \frac{1}{3}(U_{31} - U_{23}) \qquad (3.12)$$

Let's represent the different paces of the graphs of the simple voltages v1 and v2 that we will build from the compounded voltages.

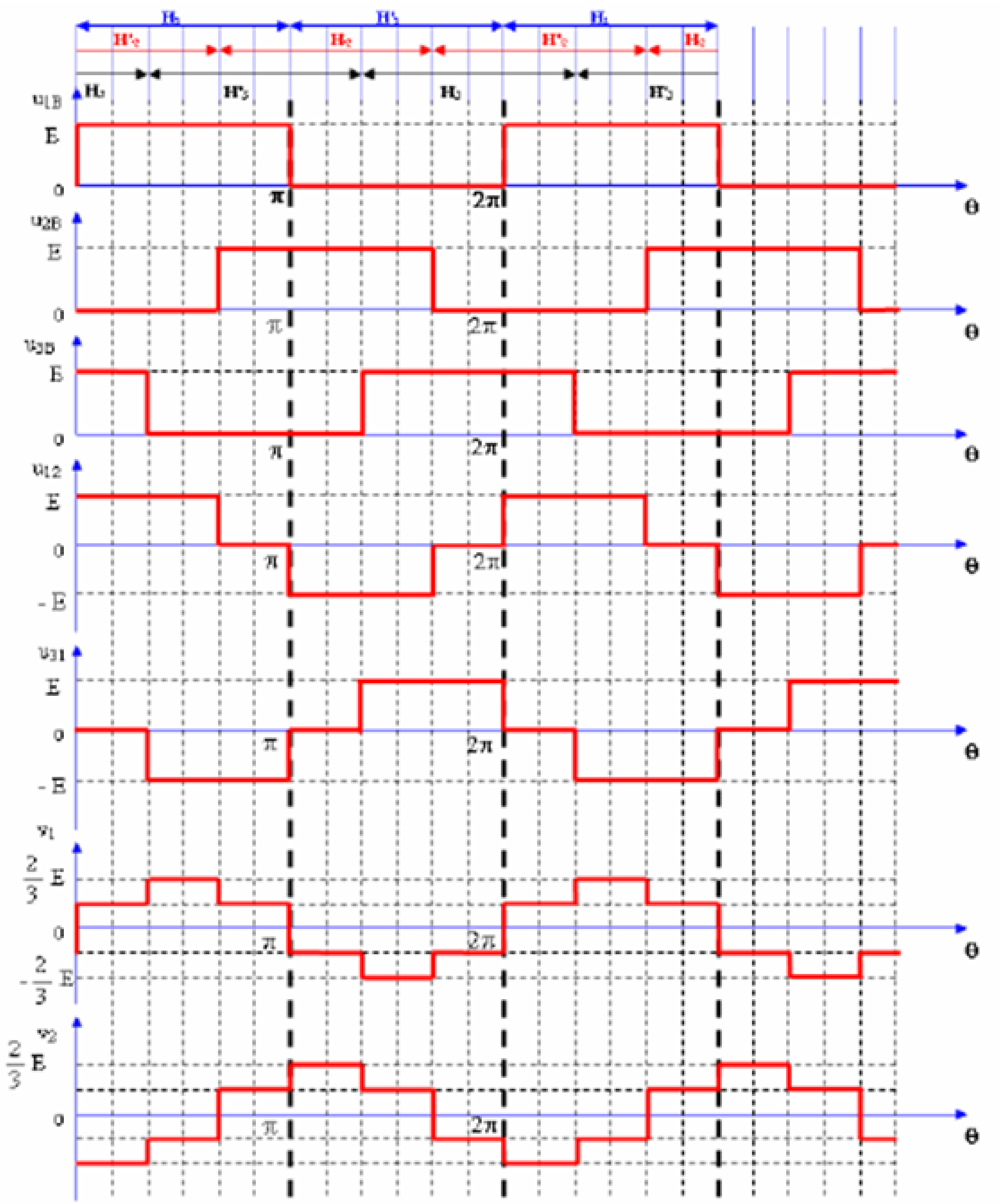


Fig. 3.16: Three-Phased Inverter Chronogram

3.1.6.DC/DC inverters [4]

DC/DC inverters are direct converters of direct-to-direct type. Their principle is based on the regular opening and closing of a switch static (thyristor or transistor). The relative setting of the opening and closing times and switch closure allows the control of the energy exchange.

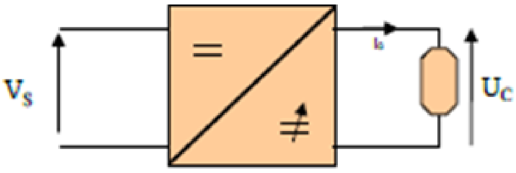


Fig. 3.17: DC/DC Inverter Structure

3.1.6.1.Inverter Series (Buck) [4]

It's also called a voltage depressor, buck converter. This Inverter controls the flow of a voltage generator Vs, in a current receiver.

3.1.6.1.1.Resistive load

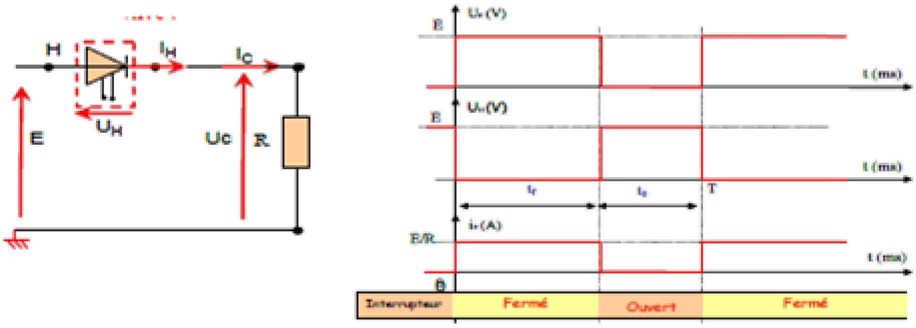


Fig. 3.18: Diagram and Chronogram of a Inverter Series for R Load

Duty cycle: The duty cycle is the ratio between the conduction time of the switch, and, the period of the signal. It is a dimensionless number, noted, between 0 and 1. (tf: closing time; to: opening time). The duty cycle is defined as follows:

$$\alpha = \frac{tf}{T} = \frac{switch\!-\!on\ time}{Signal\ period} \qquad (3.13)$$

State 0: H open $i_c = 0$

State 1: H closed $i_c = E/R$

The average voltage and the average current are respectively:

$$\overline{U_c} = \alpha * E \qquad (3.14)$$

$$\overline{i_c} = \frac{\overline{U_c}}{R} = \alpha \frac{E}{R} \qquad (3.15)$$

3.1.6.1.2.RL Load

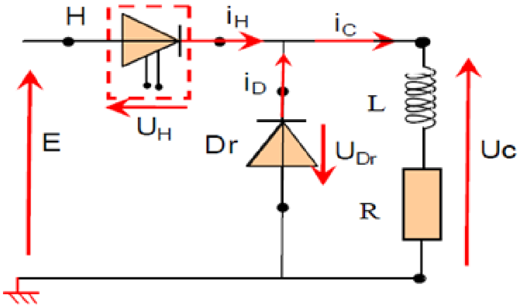


Fig. 3.19: Inverter Series For RL Load

-Operation:

We close H current in the load (energy storage). H inductance discharge through the diode (freewheeling period).

$$U_c = Ri_c + L\frac{di_c}{dt} = E \tag{3.16}$$

After the transient state is gone, the load current is plotted in the steady state. permanent and it is assumed at t=0 , ic(0)=Imin and at t=tf, Ic(tf)=Imax.

$$i_c(t) = A * e^{-\frac{t}{\tau}} + \frac{E}{R} \quad \text{avec} \quad \tau = \frac{L}{R} \tag{3.17}$$

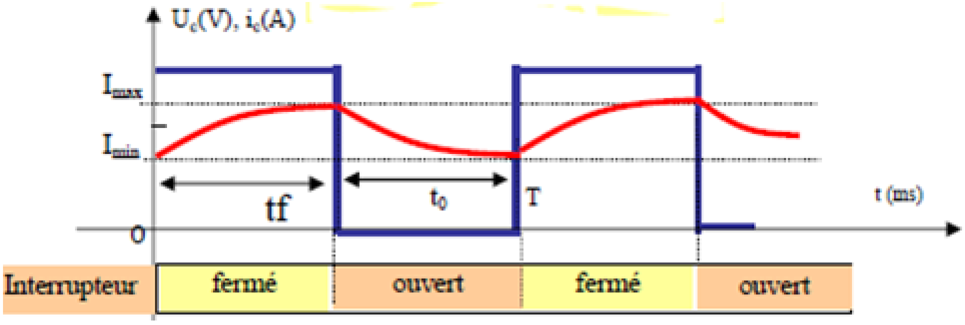


Fig. 3.20: Current and Voltage Chronogram for R Load

3.1.6.1.3.Linearization of the current ic

When x is large we approximate e^{-x} by a straight line and therefore the function ic(t) in each phase tends to become affine (rectilinear). From this observation, we will make an approximation to each phase of the operation replacing the term R.ic with the term $R.\overline{I_c}$.

It should be noted that:

$$E_c + R\overline{I_c} = \overline{U_c} = \alpha E \tag{3.18}$$

$$\begin{cases} H\ closed \Rightarrow E = E_c + R\overline{I_c} + L\frac{di_c}{dt} \Rightarrow E = \alpha E + L\frac{di_c}{dt} \\ H\ open \Rightarrow 0 = E_c + R\overline{I_c} + L\frac{di_c}{dt} \Rightarrow 0 = \alpha E + L\frac{di_c}{dt} \end{cases} \tag{3.19}$$

H closed: $L\frac{di_c}{dt} = (1-\alpha)E \Rightarrow \frac{di_c}{dt} = E\frac{1-\alpha}{L} = cst \Rightarrow ic(t) = E\left(\frac{1-\alpha}{L}\right)t + I_{max}$

(at t=0, ic=I_{min}) and at t_1=t_f=αT , where H is now open

$$I_{max} = E\left(\frac{1-\alpha}{L}\right)\alpha T + I_{min} \qquad (3.20)$$

H open: $L\frac{di_c}{dt} = -\alpha E \Rightarrow \frac{di_c}{dt} = -E\frac{\alpha}{L}$

$$ic(tf) = I_{min} \quad ic(t) = \alpha E\left(\frac{t-\alpha T}{L}\right)t + I_{min}$$

at t_2 =T , where H is now closed

$$I_{max} = E\left(\frac{1-\alpha}{L}\right)\alpha T + I_{min}$$

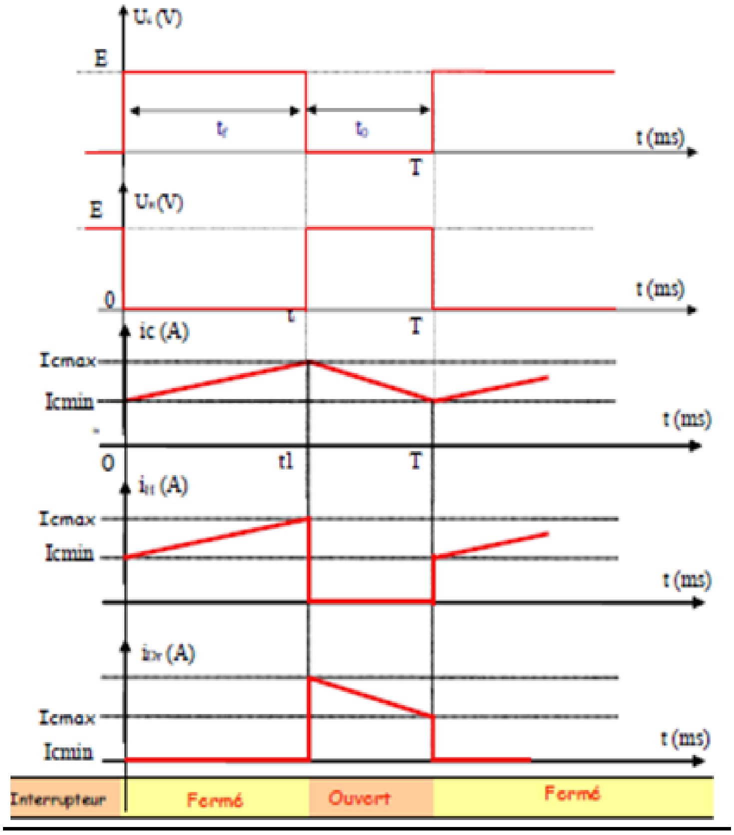


Fig. 3.21: Current and Voltage Chronogram for RL Load

To calculate the average value of the current in the load, we will use the fact that it is carried by segments of straight lines, so the average value is calculated by taking the 2 extremes, and directly averaging them.

$$\bar{I}_c = \frac{I_{max}+I_{min}}{2} \qquad (3.21)$$

To calculate the average value of the current in the diode and the electronic switch, we will use the same area method as the one used to calculate the voltage average value at the load.

$$\bar{I}_D = (1-\alpha)\bar{I}_c \quad (3.22)$$

$$\bar{I}_H = \alpha\bar{I}_c \quad (3.23)$$

3.1.6.1.4.Current ripple

The current in the load ic varies between I_{min} and I_{max}, we call ripple Δic the half difference $\frac{I_{min}-I_{max}}{2}$. It can be calculated as in (3.24) :

$$\Delta I_c = E\left(\frac{1-\alpha}{2L}\right)\alpha T \quad (3.24)$$

3.1.6.1.5.Analogous to the transformer

- Power supplied by the source: $P1 = E.\bar{I} = \alpha E\bar{I}_c$
- Power received by the load: $P2 = \bar{U}_c.\bar{I}_c = \alpha E\bar{I}_c$

Table 3.4: Transformation Table

	transformation ratio	Inverter duty cycle α
Voltage	$\frac{U_2}{U_1} = m$	$\frac{U_c}{E} = \alpha$
Current	$\frac{I_2}{I_1} = \frac{1}{m}$	$\frac{I_c}{I} = \frac{1}{\alpha}$
Power	P1=P2	P1=P2

The Inverter can be considered as a direct current transformer.

3.1.6.1.6. Adjustment procedure: Influence of the adjustment parameters

In order to vary the average inverter voltage, the duty cycle has to be varied. They are 2 adjustment procedures: - at constant Tf and variable T; - at variable Tf and constant T.

3.1.6.2.Parallel inverter (boost) [4]

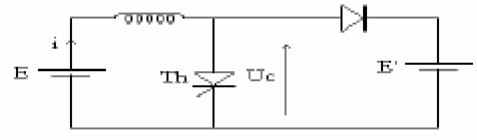


Fig. 3.22: Booster Inverter Structure

Initially, Th closed, the electromagnetic energy is stored directly in the inductance L (Uc=0).

In a second step, Th (forced switching) is opened, the inductance L discharges through D, so E'>E Uc=E'.

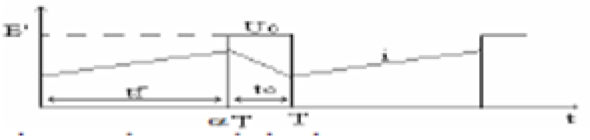


Fig. 3.23: Boost Inverter chronogram

The average value of the voltage at the load terminals:

$$\overline{U_c} = \frac{1}{T}\int_{\alpha T}^{T} E\,dt = E(1-\alpha) \;\; or \; E = V_{Lmoy} + U_{cmoy} = U_{cmoy} = \overline{U_c}$$

Because the mean value V_{Lmoy} is zero, all the energy stored during tf is restored during t_o, so:

$$\overline{U_c} = E = E'(1-\alpha) \Rightarrow E' = \frac{E}{1-\alpha} \qquad (3.25)$$

This Inverter is voltage booster where I_{out}=(1-α)I_{in}.

3.1.6.3.Buck-Boost Inverter [4]

At first the source E is closed on an inductance which stores energy.

In a second step to, the source is disconnected and the inductor restores the energy accumulated in the load (represented by a fictitious fcem E').

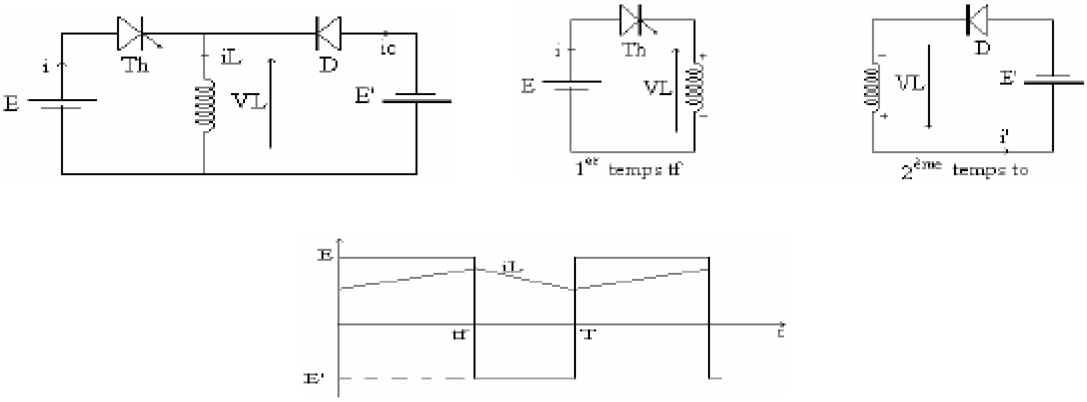


Fig. 3.24: Structure and Chronogram of Buck-Boost Inverter

$$V_{lmoy} = \frac{1}{T}\int_0^{tf} E\,dt = +\frac{1}{T}\int_{tf}^{T} E'\,dt = \frac{E.tf}{T} - E^{\prime\frac{E'.Tf}{T}} = E\alpha - E'\alpha - E' \Rightarrow E' = \frac{\alpha}{1-\alpha}E \qquad (3.26)$$

We have a Inverter buck (α<50) and a Inverter boost (α>50)

$$i_{moy} = \frac{\alpha}{1-\alpha} i_{cmoy} \qquad (3.27)$$

Transited Power:

$$P = E.\,i_{moy} = E.\frac{\alpha}{1-\alpha} i_{cmoy} \qquad (3.28)$$

3.1.6.4.Reversibility of Inverters [4]

In order to transfer the energy from a source E to a load presenting itself as a fcem E' such that E'< E the use of a devolve type assembly is required.

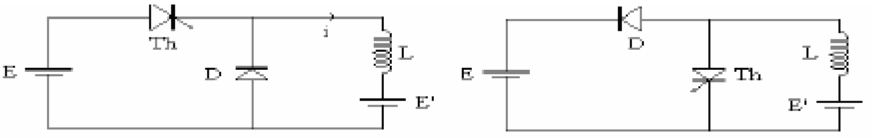


Fig. 3.25: Reversible Inverter Structure

To reverse the direction of energy transfer, the source E must of course be capable of receiving energy and the load must be capable of supplying energy, hence the use of the booster assembly. The load can be a DC motor for example.

3.1.6.4.1. Reversible voltage Inverter (two quadrants) [4]

The required structure must allow voltage reversibility of the current source which remains unidirectional in current. As the reversibility is not the same in the two sources, the active operating phases in both cases require a crossing of the interconnection of the sources. The combination of the two structures allows us to design an assembly with the following scheme principle is this one. This assembly requires the inversion of the polarity of the fcem E'.

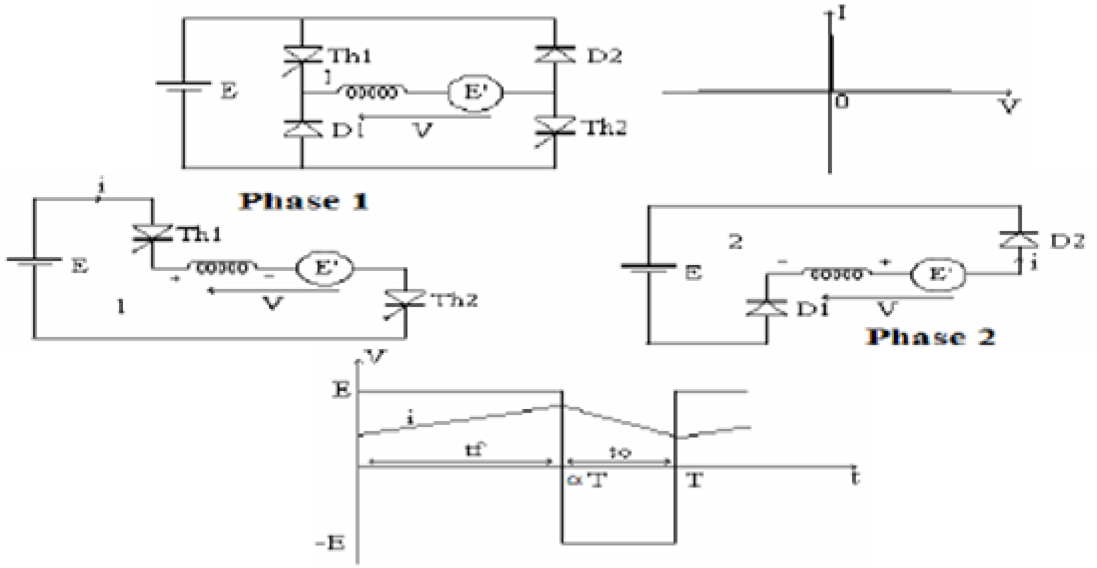


Fig. 3.26: Structure and Chronogram of a Reversible Voltage Inverter

The direction of the current in the load remains the same, but the voltage E' can vary between E and -E.

3.1.6.4.2.Reversible current Inverter (2 quadrants) [4]

The input and output sources are always of different natures, but the desired structure must allow reversibility in average power of the device. To fix the ideas, this structure must be able to be applied to the supply of a MCC by an inverter and allow traction and braking phases without speed reversibility (unidirectional voltage), but with torque reversibility (current reversibility). Since there is no voltage reversibility, the interconnection modes of the two sources are shown in the figure , which behaves :

- Like a de-voltage inverter when the current source imposes a positive current (I > 0);
- As a booster Inverter when the current source imposes a negative current (I < 0).

The combination of the structures (parallel Inverter-serial inverter) allows us to make the following assembly:

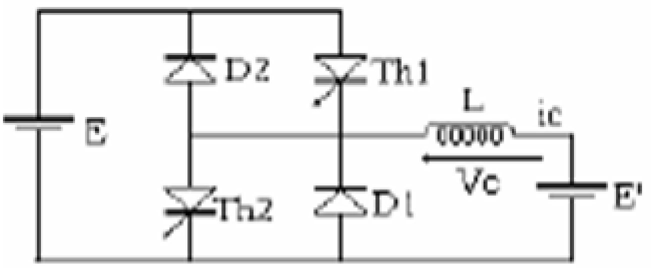


Fig. 3.27: Structure of a Reversible Current Inverter

We alternately command Th1 and Th2 to obtain a change of sign of the average value of the current ic, while the sign of Ec remains the same.

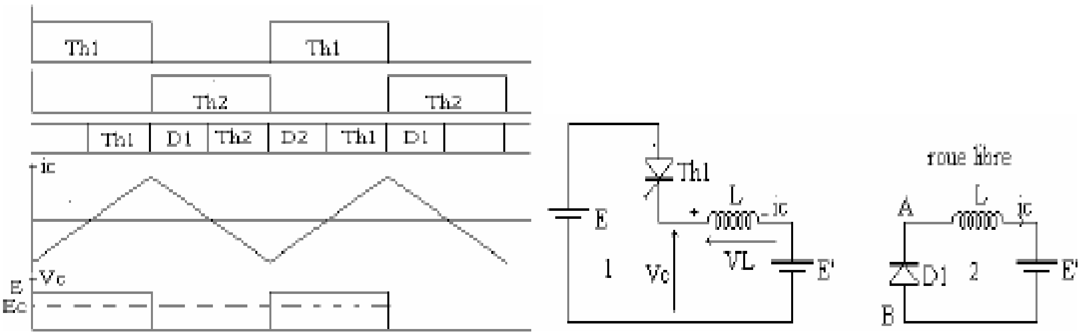
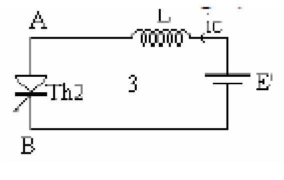


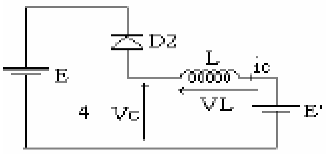
Fig. 3.28: Chronogram of a Reversible Current Inverter

Th2 is likely to conduct, it conducts at the moment when the charging current ic cancels. The coil is charged (energy storage).



$$V_A - V_B = U_C + V_L \quad \text{with } V_L = L.\frac{dic}{dt} < 0$$

dic<0; ic<0; Vc=0 Th2 is blocked and D2 conducts in the following sequence:



dic>0; ic<0; Vc=E when the current is cancelled, Th1 is initiated and the cycle starts again.

3.1.6.4.3.Reversible voltage and current Inverter (4 quadrants)

The required structure must allow full voltage and current reversibility of the source of power.

The voltage source imposes a constant voltage E, but must be reversible in current.

The general structure of the converter will necessarily be a bridge structure.

The structure is deduced by superimposing the two previous structures, hence the assembly below.(operating sequences : see the inverters).

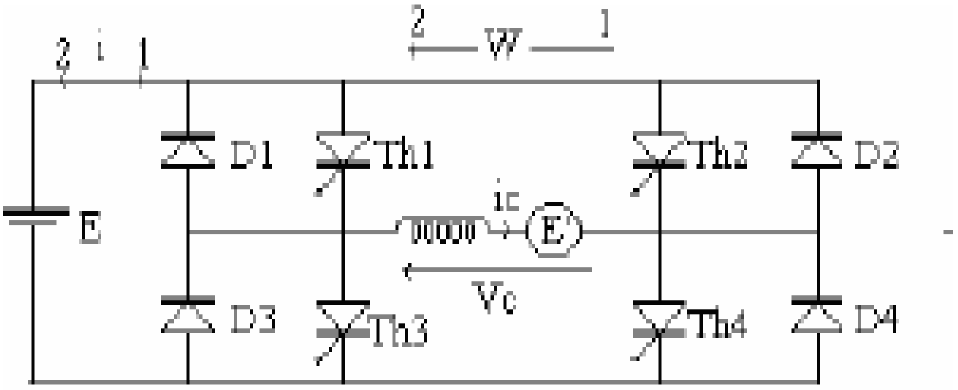


Fig. 3.29: Four quadrants Inverter Structure

- Th1 and Th4 ordered simultaneously; Th2 and Th3 blocked.

V_{cmoy} =E(2α-1)

if α >0.5 ; V_{cmoy}>0 E'>0 i and W are in sense1

if α<0.5 ; V_{cmoy}<0 0 E'<0 i and W are in sense2

i_c in sense 1

- Th2 and Th3 ordered simultaneously; Th1 and Th4 blocked.

V_{cmoy} =E(2α-1)

if α >0.5 ; V_{cmoy}>0 E'>0 i and W are in sense2

if α<0.5 ; V_{cmoy}<0 0 E'<0 i and W are in sense1

3.1.7.Batteries [5]

Solar batteries are a smart investment for energy storage. If you're tied to the grid, no battery means no backup power when the utility grid suffers an outage. If you live off-grid, your system simply won't work at all.

When installing a solar battery as part of your solar panel system, you can store excess solar energy instead of sending it back to the power grid. If your panels are producing more electricity than you need, this energy can go back into charging your battery.

When your solar panels aren't producing electricity, you can draw from the stored energy when you need it. The electricity is sent back to the grid only when your battery is full or draws from the grid only when the battery is low.

3.1.7.1.Characteristic of solar batteries

As you consider your solar battery options, you'll want to compare each type of battery based on the capacity, depth of discharge (DoD), round trip efficiency, and battery life to find the best batteries for solar depending on your system's requirements.

- Capacity: it is the total amount of electricity that a solar battery can store (kWh).
- Depth of discharge (DoD): indicates the amount of battery capacity that's used. The higher the DoD, the more usage you'll get from the battery's capacity. DoD should generally be at least 70% or higher.
- Battery life and warranty: since battery performance declines over time, a warranty guarantees good performance for years or cycles as well as ensuring the battery maintains a certain capacity.
- C-Rate: A C-rate of 1C is also known as a one-hour discharge; 0.5C or C/2 is a two-hour discharge and 0.2C or C/5 is a 5-hour discharge. Some high-performance batteries can be charged and discharged above 1C with moderate stress.

Table 3.4: Typical times at various C-rates.

C-rate	**Time**
1C	1h
2C	30min
0.5C or C/2	2h
0.2C or C/5	5h

3.1.7.2.Types of solar batteries

There are varieties of batteries that can be used to store the energy for solar panels.

3.1.7.2.1.Lead Acid Batteries

These batteries in fact are the first rechargeable batteries that were invented and even until now this is the most popular of options that has been proven to work out the best for different situations. These batteries have the highest capacity, extended life cycle, they can be charged comparatively fast and they waste relatively little energy.

3.1.7.2.2.Absorbed Glass Mat *(AGM)* Batteries.

AGM batteries contain a thin ultra-fine fiberglass mat which has been placed between the plates that are saturated with battery acid to about 95% of what they can hold. This mat which is packed between the plates, is compressed and after that welded in place.

Some of the main advantages of AGM are the fact that AGMs are capable to deliver high currents on demand, they have very low internal resistance, and they can provide rather long life expectancy, even when deep cycled.

3.1.7.2.3.Gel Cell Batteries

Celled lead acid batteries were introduced a lot sooner than AGM type but they are actually losing the market share. They have similar advantages over flooded lead acid batteries for example ease of transportation but you have to keep in mind that the gelled electrolyte in these batteries is very viscous.

3.2. Solar Based Water Pumping

Solar water pumps can replace the current pump systems and result in both socio-economic benefits as well as climate related benefits.

A solar water pump system is essentially an electrical pump system in which the electricity is provided by one or several PV panels. A typical solar powered pumping system consists of a solar panel array that powers an electric motor, which in turn powers a bore or surface pump. The water is often pumped from the ground or stream into a storage tank that provides a gravity feed, so energy storage is not needed for these systems.

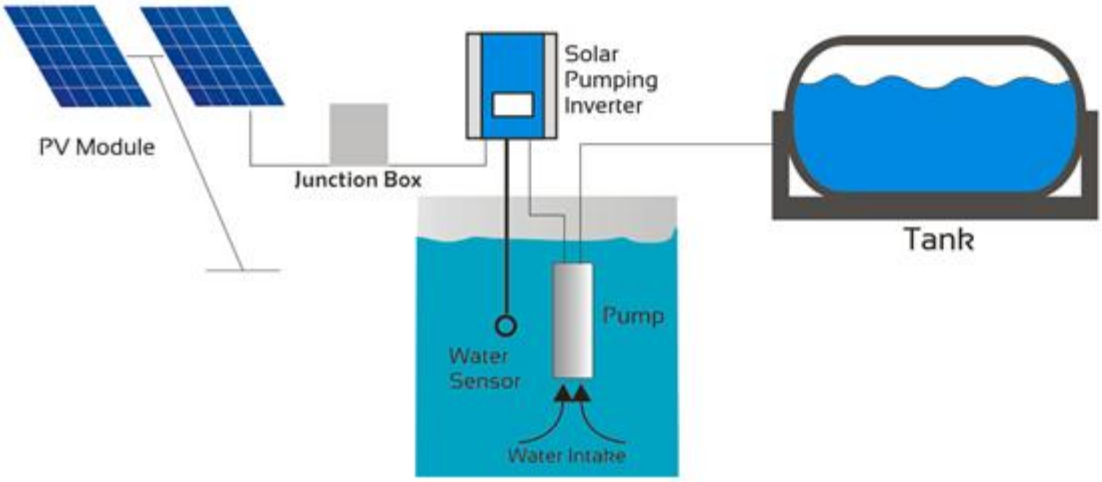


Fig. 3.30: Solar Based Water Pumping System

3.2.1.Types of Solar Powered Water Pumps

3.2.1.1.Surface water pumps

A surface pump sucks up water at point A and pumps it out at point B. Point A may be a well, river, pool or garden pond and Point B a garden, hose, wastewater network, ditch, etc. A surface pump can also supply domestic appliances such as washing machines, dishwashers and toilets.

For this pumping to take place, the surface pump creates suction via one or more turbines or **i**mpellers rotating at high speed.

A surface pump, as the name suggests, remains on the surface of the water (unlike a submersible pump). Surface pumps can also be used as part of a hydrophore group **-** alongside a booster. Surface pumps are designed for **w**ater sources less than 8m deep, beyond which the submersible pump takes over.

The key characteristics of a surface pump are flow rate**,** pressure**,** discharge height and materials - principally of the pump body.

These pumps are suitable for lifting and pumping water from a maximum depth of 20 meters.

3.2.1.2.Submersible water pumps

A submersible pump, also called an electric submersible pump, is a pump that can be fully submerged in water. The motor is hermetically sealed and close-coupled to the body of the pump.

A submersible pump pushes water to the surface by converting rotary energy into kinetic energy into pressure energy. This is done by the water being pulled into the pump: first in the intake, where the rotation of the impeller pushes the water through the diffuser. From there, it goes to the surface.

The major advantage to a submersible pump is that it never has to be primed, because it is already submerged in the fluid. Submersible pumps are also very efficient because they don’t really have to spend a lot of energy moving water into the pump. Water pressure pushes the water into a submersible pump, thus “saving” a lot of the pump’s energy.

Also, while the pumps themselves aren’t versatile, the selection certainly is. Some submersible pumps can easily handle solids, while some are better for liquids only. Submersible pumps are quiet, because they are under water, and cavitation is never an issue, because there is no “spike” in pressure as the water flows through the pump.

There are a few disadvantages with submersible pumps, and two have to do with the seal. The seals can become corroded with time. When that happens, water seeps into the motor, rendering it useless until it is repaired. Also, that seal makes the submersible pump a bit difficult to get into for repairs.

The other main disadvantage is that one pump does not fit all uses. Single stage pumps are used for most home and light industrial pumping. This includes aquarium filters, sewage pumping, or sump pumps for drainage. Multiple stage pumps are used for anything underground, such as water wells or oil wells. Also, pumps are made to work with thin liquids like water, or thick ones like sewage.

Caution must be used with submersible pumps; they must be fully submerged. The water around a submersible pump actually helps to cool the motor. If it is used out of water, it can overheat.

These pumps can be used in areas where water is available at a greater depth and where open wells are not available. The maximum recommended depth these systems can pump is 50 meters.

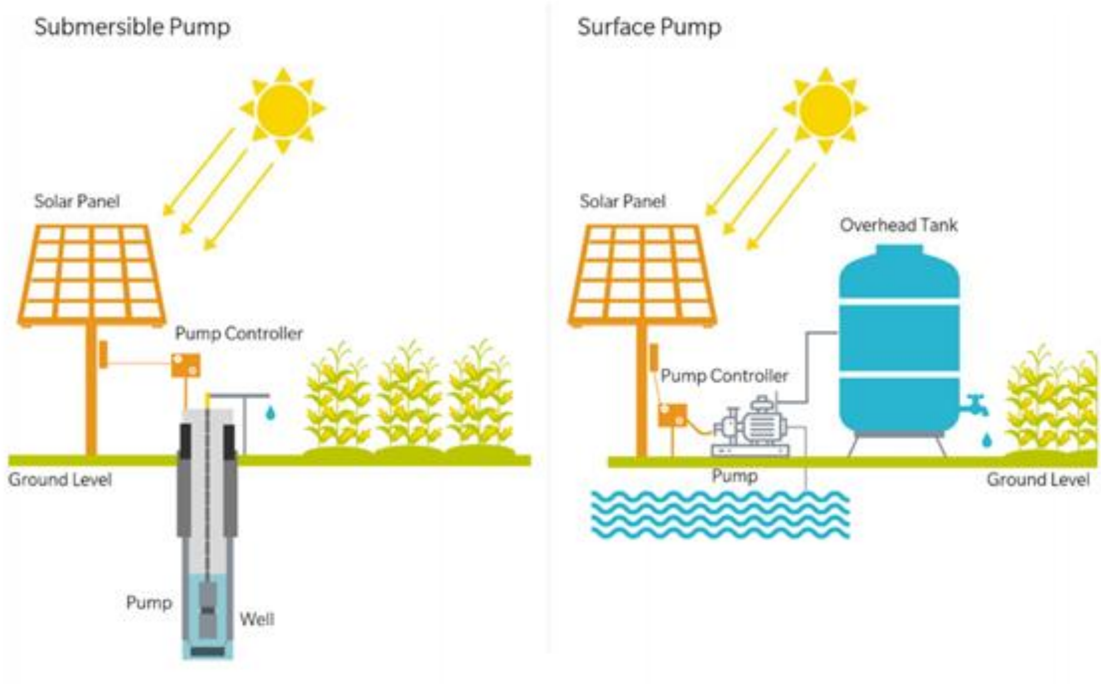


Fig. 3.31: Water Pumps Types

3.2.2.Solar Pump Advantages

The solar pump advantages include the following.

- The installations of solar pumps are flexible & applicable to different applications.
- It allows people to handle their water supply for drinking, farm animals watering, irrigation, and other housing applications.
- Generally, the usage of water in summer is utmost. During this season, the PV panels can generate the most power so that more water can be pumped into the water tank.
- Because of the ease of PV power-driven water pumps, solar technology is consistent, as well as needs small protection.

3.2.3.Solar Pump Disadvantages

The solar pump disadvantages include the following.

- It is expensive.
- The output of the panel will depend on the weather.
- It requires a water storage tank as well as a battery.

3.2.4.Solar Pump Applications

The applications of solar pumps mainly used where pumping water is required.

- Water supply for animals
- Water supply for harvest irrigation
- Water supply for Cooking and Drinking water supply

3.2.5.Solar Pump Speed Inverter [8]

Solar pump inverter, also called solar variable frequency drive, converts the direct current of solar panel into alternating current, thereby driving various AC motor water pumps (centrifugal pump, irrigation pump, deep well water pump, swimming pool pump, etc.), the input can be the solar DC power supply, also can be single phase or three phase AC power supply, built-in MPPT control system to maximize the output power of the PV array, is very suitable for use in remote and dry areas.

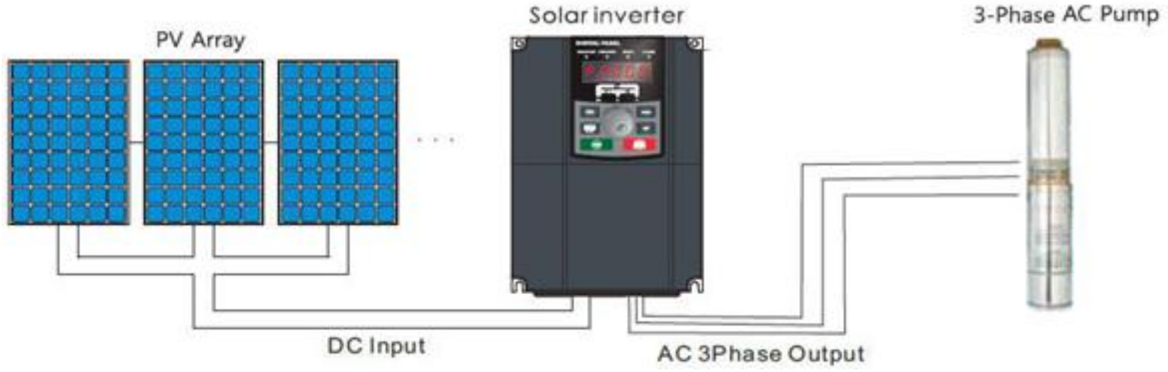


Fig. 3.32: Solar Water Pumping With a Solar Inverter

Solar pump inverter adopts advanced MPPT control technology, real-time detection of solar panels power voltage, tracking the highest voltage and current, efficiency is as high as 98%. It can enter automatically to sleep mode when the intensity of sunlight is weak, as well as can exit the sleep mode when the intensity of sunlight is becoming strong. Automatic sleep when on high-water level and automatic restart when on low-water level to realize automatic control through water level. Multiple power supply design, power input can be solar energy PV power supply (DC 260 ~ 350V, DC 450~750V), can also be single phase or 3-phase AC power.

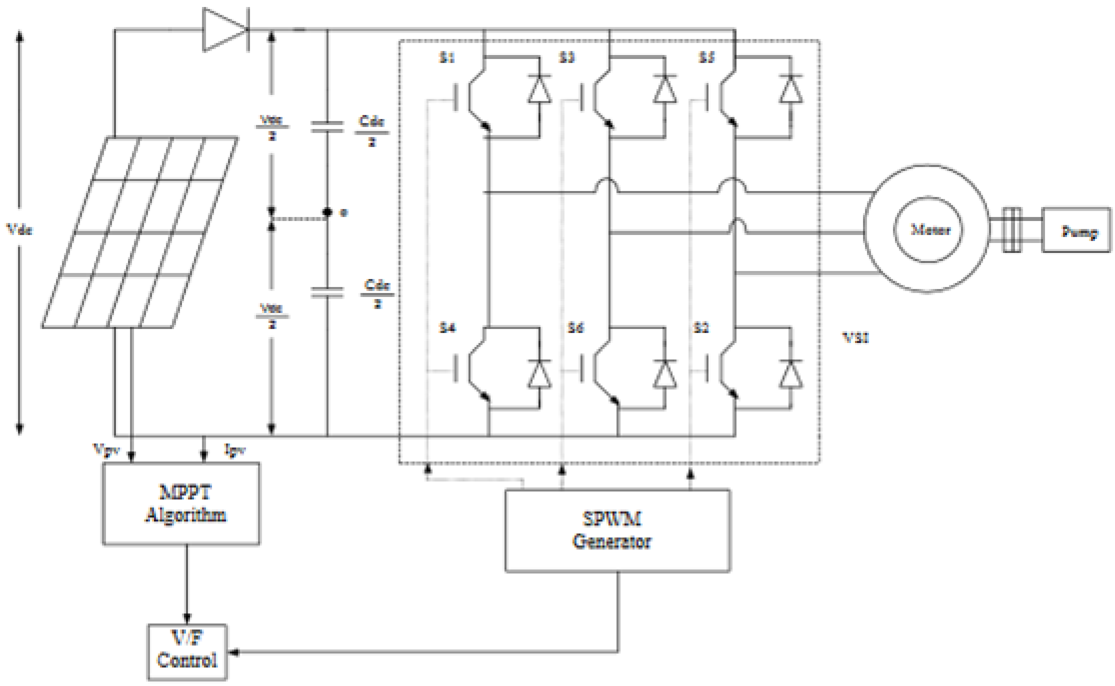


Fig. 3.33: Speed Variation Diagram

Smart operation, water level detection and operation panel to prevent overflow, dry pumping. Protect itself in trouble and improve the reliability of whole system.

When ever possible, the controller attempts to regulate the pump load in a manner that optimizes for maximum power transfer from the solar array.

1. Maximize your pump delivery without wasting a watt
2. Automatic start and stop with Solar irradiation
3. Self diagnostic and protection
4. Dry run protection
5. Dual supply mode - Solar and Grid compatible with all pumps with easy operation
6. Dc current, voltage, power input can be monitor, easy to know power input.
7. No need for parameters setting after pumps correct selecting.
8. Built in RS485 ports, laptop software control is available,
9. Remote control management with GPRS/GPS is option.
10. Good quality with Infineon IGBT module and other top brand components using long term guarantee with 24 months

3.3.Solar lighting [9]

Solar street lighting is the modern solution for night security, especially in areas poorly covered by electricity distribution. If your plot remains lit at night even if there is a power cut, you can be sure that bandits will choose another place to operate. These lights are intended for both municipal and private areas, although they have many other applications such as construction sites, car parks and school complexes where night lighting is required for vision or security purposes.

3.3.1.Types of lighting panels

There are 2 types of lighting panels:

3.3.1.1.All in one

This is the model where all the components are integrated in the system.
(led lighting, monocrystalline solar panel with high efficiency ,
MPPT regulator, battery, mast mounting bracket)

Fig. 3.34: all in One Solar Lighting Panels

- Advantages: Quick installation; This type is recommended for fencing of establishments that do not exceed 3m.

- Disadvantages: A low power generator; The battery will never reach 100% of its charge; The luminator does not supply energy; Not recommended for installation on roads.

3.3.1.2.The Classic Type

In this type the panel is separated from the light, the battery and the regulator are in a box attached to the mast.

Fig. 3.35: The Classic Solar Lighting Panel

- Advantage: The perfect choice for road lighting; Production of high power; Battery charges 100% regardless of weather conditions; High battery capacity; The luminser provides the necessary power.

Choosing the type of the lightning panels alone is not enough, another factor must be token under consideration which is the road type.

3.3.2.Roads Type [10]

For the light on the streets, it is required to make the driver more comfortable, do not make a dazzling and so He can highlight the details of the road and not be busy with nothing but the road so that he can take important decisions and fast reactions in a tight time.

Only limited vehicle lighting can enable the driver to see the entire road and therefore road lighting must be designed to be close to daylight.

Streets are usually divided into: Expressways; Arterial Street; Sub-Arterial street; Collectors; Local Street.

Chapter4

Design of Household Electrification, Water Pumping and Public Lighting System

4.1. Design of a household electrification system

This study took a place to fulfill a costumer request to electrify his house with solar energy. The house is a part of 2.5 hectares land situated in Bousedra, El-Bouni, Annaba, it consumes around 10kW per day. The whole process is explained in the following steps:

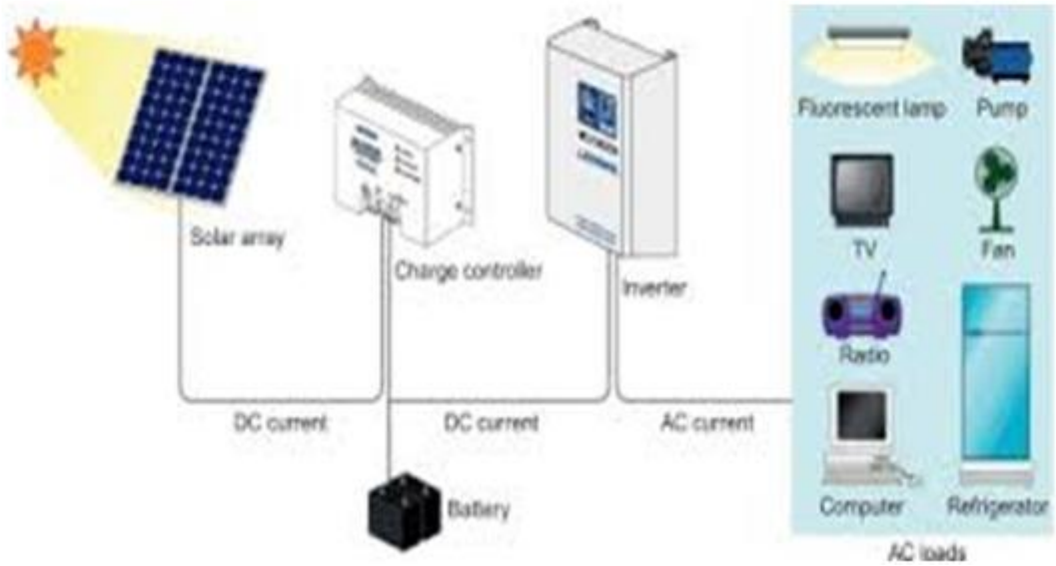


Fig. 4.1: Household Solar Electrification System.

4.1.1.Daily Consumption of Electricity

Table 4.1.1: Daily Electricity Consumption

Devise	**Quantity**	**Power (W)**	**Period (h)**	**Energy (Wh/day)**
Lamps	12	40	1	480
Fridge	1	/	/	1000
TV	2	190	4h	1520
Fan	3	60	12	2160
Washing Machine	1	480/cycle	2	960
Microwave	1	1150	1	1150
Others	/	/	/	1500
			Total Energy	9070
			Total Power	3140 (W/day)

4.1.2.Geographical Localization Data

The land took a place in Boussedra, El-bouni, Annaba, at 36°50’57’’ N and 7°43’48’’ E,

Required surface: 9 m^2.

Orientation: to the South.

Tilt angle: 36.5°.

I_r max: 7.6 kWh/m^2/day.

I_r min: 2.2 kWh/m^2/day.

Minimum solar hours: 5h.

4.1.3.PV Modules Selection

The chosen PV module is a 280W module. 25 year transferrable power output warranty: 10 years/90%, 25 years/80%; Linear performance warranty manufacture; 12 year material and workmanship warranty.

ELECTRICAL PARAMETERS AT STC			
Rated Maximum Power	Pmax	W	280
Open Circuit Voltage	Voc	V	36.71
Maximum Power Voltage	Vmp	V	30.09
Short Circuit Current	Isc	A	9.96
Maximum Power Current	Imp	A	9.31
Power Tolerance	Dp	W	0/+5
Module Efficiency	η	%	17.5

Required energy: 10kWh/day.; System efficiency: 60-80%.

Connection system: 48W

Necessary peak energy: 2kW_p.

Necessary energy (Losses included): 3.34 K$W_{p.}$

Which means:

$$\mathrm{NPVm} = \frac{\text{Necessary energy (Losses included)}}{\text{Module peak power}} = \frac{3340}{280} = 12\ modules \tag{4.1}$$

12 module of 280 W_P are needed to carry out the system.

4.1.4.Solar Inverter/Charger/Mppt Controller Selection

The inverter chosen for the system has an MPPT controller integrated inside thus we don’t need to use a separate Mppt Controller devise.

Connection System :48; Necessary power :P=3.34 KW/day; Inverter efficiency: 80-90%

Necessary inverter power: Pi= P/0.93 =3376W=4KW ➔(5KW-48VDC-240VAC).

For a 5kw solar inverter, 3 conditions must be checked to consider this inverter is appropriate for the system ,which are :

- **Compatibility in Voltage**

PV voltage range : 120V—500V ; Voc=36.71V

Maximum number of modules in series is:13

Mnimum number of modules in series is:3

The inverter support 13 modules in series.

- **Compatibility in Current**

Max current: 80Amps ; I_{sc}=9.96 Amps

The inverter supports 8 string of 13 modules in series

- **Compatibility in Power**

Since we only needs 12 modules , the nominal power is :

$$12 * 280 = 3360\mathrm{Wp} < 4000Wp \tag{4.2}$$

4.1.5.Battery Selection

The chosen battery is an AGM 120Ah battery. This type is well known for its low self discharge and the long service life and most importantly its top quality materials and advanced technology.

Capacity	120Ah
Voltage	12V
Discharge percentage	70%
Connection System	48V
Inverter Efficiency	93%
Backup days	2
Required Energy	9070kWh
Temperature factor	1

The necessary energy transformed to the batteries is:

$$\frac{9070}{0.93} = 9752.7 \text{ kWh} \qquad (4.3)$$

$$\frac{9752.7*1*2*0.7}{48} = 284.45Ah \qquad (4.4)$$

Number of batteries in series:

$$\frac{48}{12} = 4 \qquad (4.5)$$

Number of batteries strings:

$$\frac{284.45}{100} = 2.37 = 3 \text{ strings} \qquad (4.6)$$

The total number of batteries is:

$$4 * 3 = 12 \text{ batteries.} \qquad (4.7)$$

4.1.6.Security and protection

This procedure is the most important and indispensible act in order to protect the system from any failure and damage.

The combiner box is the ideal tool to fulfill this task. It contains:

- 1 Combiner Box; - 12 Holes in one side for placing the MC4s (6 positive inputs and 6 negative inputs); - 3 holes in the side for the Phase-Neutral –Ground outputs; - A rail to place all the components on it; - 6 terminal blocks with 2 covers for the sides; 1 Ground/Earth block; - 3 separators/stabbers; 6 fuses 10A; - 1 bridge with screws; - 12 MC4s; - 3 outputs (red- black-yellow/green); - 1 Surge protector; - PV Cables (4 and 6 mm); - AC Cables.

4.1.7 Mounting System

The supporting lift of the modules must be rigid, strong with wind resistance to avoid any problems and disorientation or misplace.

As for the solar modules, all the 12 modules are identical with the same dimensions (1960*990*40mm).

To form the mounting system for 12 modules, we combine 4 modules per line placed in a horizontal way, and 3 modules per column as the following:

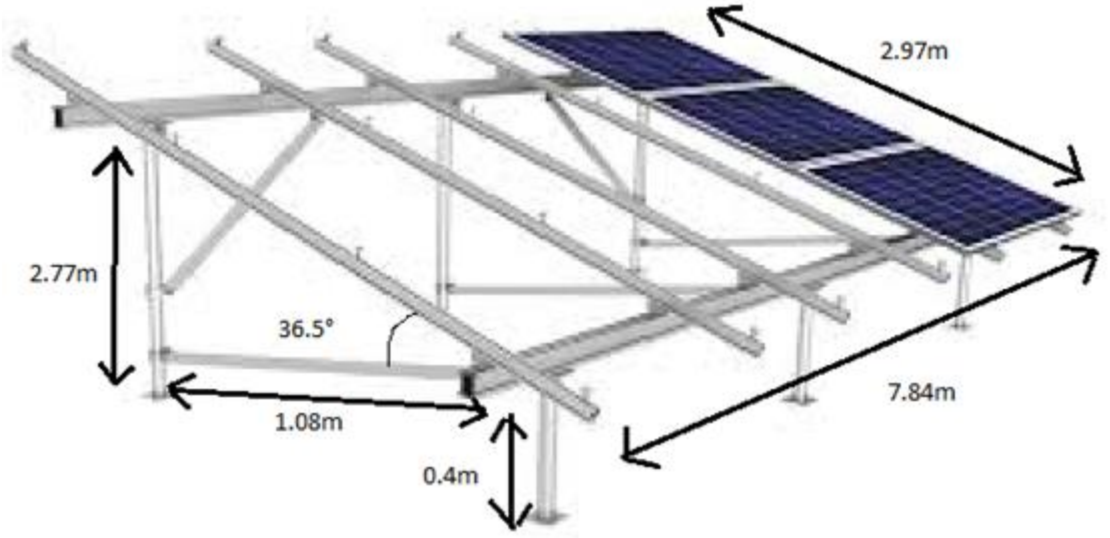


Fig. 4.2: Mounting System.

4.2. Solar Based Water Pumping System Design

The same costumer wanted to water his 50*65 m² farm of lemon trees from the well located also in his land, by solar energy.

He has a 130 full grown 8 years old lemon trees, which requires each around 200l, watered twice a week.

The well is at 110m depth and 36m far from the planted land.

Daily water volume is:

$$V = 130 * 200 = 26000l = 26\text{m}^3/\text{day} \tag{4.8}$$

To realize this system the following steps are passed through:

4.2.1.Determine the water flow rate and TDH

Since we need 26m^3 of water every day twice a week and the minimum daily sun hours is 5h then we have:

$$\text{Q} = \frac{V}{NbH} = \frac{26}{5} = 5.2\ \text{m}^3/\text{h} \tag{4.9}$$

$$\text{Q} = \frac{5200}{60} = 87\ \text{l/mn} \tag{4.10}$$

As for the TDH, it represents the pressure difference in meters of water column between the suction and discharge openings. Since the selected pump is an AC Submersible Pump the equation is represented below:

$$\text{TDH} = \text{Hg} + \text{Pc} + \text{Pu} \tag{4.11}$$

While:

$$Hg = Hs + Nd \tag{4.12}$$

And:

$$Pc = \text{Ja} + \text{Js} \tag{4.13}$$

Also:

$$Nd = Ns + Dd \tag{4.14}$$

TDH: Total Dynamic head; Hg: Geometric height; Hs: Static height; Nd: Dynamic Lift; Pc: Pressure losses; Ja: Linear losses; Js: Singular losses; Dd: The Drawdown of the well; Pu: Pressure at the end of the pipe.

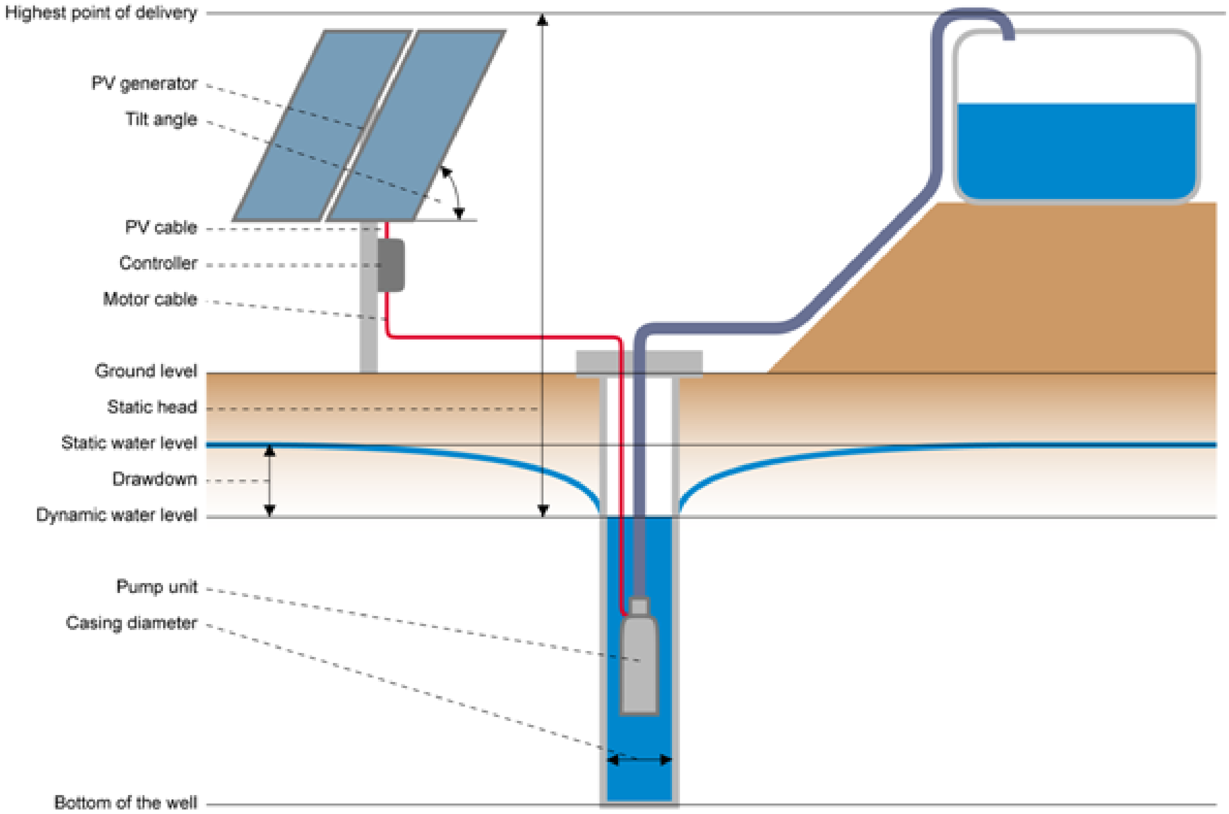


Fig. 4.3: Schematic Diagram of Water Pumping System.

The distance between the well and the tank is: 36m. To calculate the pressure losses (Pc), we need to calculate the linear and singular losses.

$$Ja(mCe) = -Ks * \frac{V^2}{2} \tag{4.15}$$

$$Js\ (mCe) = -\lambda * \frac{L*V^2}{2D} \tag{4.16}$$

With :

$$V = \frac{Q}{S}\ \ and\ S = \frac{\pi D^2}{4} \tag{4.17}$$

Ks: Flamant viscosity coefficient ($s^{1.75}.m^{-0.5}$); V: Water speed (m/s); λ : depend on Reynolds number; L: pipe length; D: Diameter of the pipe; Q: water flow rate; S: Pipe section surface.

Or, more easy way is to determine the pressure losses from next the pressure losses table:

CALCUL DE PERTES DE CHARGE DANS LES TUYAUX - (en m de CE pour 100 mètres de tuyauterie)

DEBIT : (m3/h)	DEBIT : (l/min)	DEBIT : (l/s)	Tuyau 15	Tuyau 20	Tuyau 25	Tuyau 32	Tuyau 40	Tuyau 50	Tuyau 65	Tuyau 80	Tuyau 100	Tuyau 125	Tuyau 150
			1/2" Ø15/21	3/4" Ø20/27	1" Ø26/34	1"1/4 Ø33/42	1"1/2 Ø40/49	2" Ø50/60	2"1/2 Ø66/76	3" Ø80/90	4" Ø102/114	5" Ø127/140	6" Ø152/165
			PE 20	PE 25	PE 32	PE 40	PE 50	PE 63	PE 75	PE 90	PE 110	-	-
0.5	8.33	0.14	9	2	0.7	0.2							
0.7	11.66	0.19	16	3	1.5	0.4							
1	16.66	0.28	33	8	2.8	1.0	0.25						
1.5	25	0.42		12	6.2	2.0	0.50	0.16					
2	33.33	0.55		20	10	3.3	0.9	0.3					
3	50	0.83			23	7.5	1.9	0.7	0.2	0.1			
4	66.66	1.10			40	12	3	1	0.3	0.2			
5	83.33	1.40				20	4.6	1.6	0.4	0.2			
6	100	1.70				28	6.5	2.5	0.7	0.3			
7	116.66	1.90					8	3	1	0.4			
8	133.33	2.20					11	4.5	1.2	0.5	0.1		
9	150	2.50					14	5	1.5	0.6	0.2		
10	166.66	2.80					17	6	1.8	0.7	0.2		
12	200	3.30						7.6	2.5	0.9	0.3		
15	250	4.20						12	3.2	1.2	0.4		
20	333.33	5.50							5.2	2.2	0.6	0.2	0.1
30	500	8.30							12	4.7	1.3	0.45	0.18
40	666.66	11.10								8	2.3	0.7	0.3
50	833.33	13.90								12	3.5	1.1	0.45
60	1000	16.70									5.0	1.6	0.6
75	1250	21.00									9.0	2.5	1.0
90	1500	25.00										3.4	1.4
105	1750	29.00										4.6	1.8
150	2500	41.70											3.8

Fig. 4.4:Friction Lose Table.

We have:

Q=5.2 m^3/h ; DN40 ; Hr=8m. ; Nd=20m. ; Distance well-tank: 36m ; 3 bends ; Pu=1bar.

$$\mathrm{Pc} = \frac{64.5*6.5}{100} + (3*2) = 10.2\mathrm{m} \tag{4.18}$$

Which leads to calculate the TDH:

Hg=28m

$$\mathrm{TDH} = 28 + 10.2 + 10 = 48.2\mathrm{m} \tag{4.19}$$

The allowed range for the flow velocity is: [1.1-2 m/s]

$$\mathrm{V} = \frac{Q}{S} = \frac{5.2/3600}{\pi*(\frac{0.04}{2})^2} = 1.15m/s \tag{4.20}$$

4.2.2.Determination of the hydraulic energy

$$\mathrm{HE\ (kWh)} = \mathrm{m.g.}TDH \tag{4.21}$$

$$\mathrm{HE\ (kWh)} = \mathrm{\rho.V.g.}TDH \tag{4.22}$$

While:

$$\mathrm{C_h} = \frac{\mathrm{g*\rho}}{3600} = \frac{9.81*1000}{3600} = 2.725\ (Kg.s.h/m^3) \tag{4.23}$$

Finally we have:

$$\mathrm{HE\ (kWh)} = \mathrm{C}_h * V(\frac{m^3}{day}) * TDH \tag{4.24}$$

$$HE = 2.725 * 26 * 48.2 = 3414.5(Kwh) \tag{4.25}$$

m: water masse (kg); V: water volume (m^3/day); ρ : water density (1000kg/m^3); g=9.81m/s^2.

4.2.3.Pump selection

To determine the appropriate pump for the system, first we determine the Necessary Electrical Energy:

He < Ee

2.725*V*TDH < I_r*P_p*η_t

$$P_p = \frac{\mathrm{2.725*V*TDH}}{\mathrm{Ir*\eta t}} \tag{4.26}$$

$$P_p = \frac{2.725*26*48.2}{2.2*0.42} = 1626.2Wp \tag{4.27}$$

System Efficiency: 42%

Ee: Electrical Power (kWh); P_p: Peak Power (Wp); η_t:: Total System Efficiency.

Water pumps are generally chosen by their Horsepower not their Watt, therefore:

1hp=746 Watt.

$$P_p = \frac{1626.2}{746} = 2.18\ hp \tag{4.28}$$

So, the selected pump must be a 3hp, 6 boreholes Panelli pump.

The characteristics of this submersible pumps for 6" boreholes correspond to the most common needs of domestic and industrial pumping installations, pressure boosting systems, fire-fighting and irrigation groups and public water networks.

Panelli's continuous innovation and the mastery of the most modern microfusion technology make it possible to obtain the following strong points:

- A long service life; - Easy to assemble and disassemble; - Reduced handling; - Low maintenance costs.

Fig. 4.5: Panelli pump.

4.2.4.Solar Pump Speed Inverter

Since the used pump is an AC Solar Pump, the speed inverter is a must to control the pump and to assure its normal functioning through the day.

- **Motor Data**

AC Motor Name Plate Data : Panelli 140 Pr8 N/5;

Power: 2.2 Kw; 3 Hp;

Nominal Voltage: 400 VAC;

Nominal Current: 5.5 Amps ;

Efficiency: 77%.

- **Selecting Drive**

Required Drive Output Current

Motor Nominal Current: 12.5 Amps

$$\mathrm{I}_{\mathrm{n\ max}} = \frac{5.5}{0.77} == 7.86\mathrm{Amps} \tag{4.29}$$

Drive output current should be >= 7.86 Amps to run a 12.5 Amps AC motor on DC input supply.

The ideal drive will be ACS355-03E-08A8-4 R1 with output current 8.8 Amp (4 Hp).

- **Calculating Drive DC values**

DC Voltage Calculation:

Drive Nominal AC Voltage: 400 VAC

$$VDC_{MPP} = 400VAC * 1.35 = 540VDC \tag{4.30}$$

Selected PV array should produce 540 VDC at maximum power point.

DC Current Calculation:

Drive Input AC Current: 8.8 Amps

$$IDC_{MPP} = 8.8 * 0.817 = 7.1\ Amps\ DC \tag{4.31}$$

Selected PV array should produce 7.1 Amps at maximum power point.

4.2.5.Selected PV Module Data

P_p=280 Wp; Vmp=30.09 V; Imp=9.31A.

- **Calculating required PV Array Size:**

Number of panels in series:

$$\mathrm{Ns} = \frac{\mathrm{VDC}}{\mathrm{Vmp}} = \frac{540}{30.09} = \text{ 18 module in series} \tag{4.32}$$

Number of panels in parallel:

$$\mathrm{Np} = \frac{\mathrm{IDC}}{\mathrm{Imp}} = \frac{7.1}{9.31} = \text{ 1 Series in parallel} \tag{4.33}$$

- **Total PV Array Values:**

$$Pmax:\ 280\ X\ 36\ =\ 10080\ Watts \tag{4.34}$$

$$VOC:\ 36.71x18\ =\ 660.78\ VDC \tag{4.35}$$

$$Vmp: 30.09\ X\ 18\ =\ 541.62\ VDC \tag{4.36}$$

$$\mathrm{Isc: 9.96x1 = 9.96\ Amps} \tag{4.37}$$

$$\mathrm{Impp: 9.31x1 = 9.31\ Amps} \tag{4.38}$$

Note 1: VoC or Vmpp of the PV array should not exceed 800 VDC at any point.

Note 2: Drive will consume required power and current as per limit of the drive so PV Impp and Pmax can be slightly above the drive limits.

4.2.6.Security box for solar pumping

The power of the Solar Pump Drive must be adapted to the pump. The number and power of the PV modules must be adapted to that power too.

- The box is sealed and equipped with MC4 connectors for quick and secure connection of photovoltaic panels. It contains :
- A DC switch allows cutting the arrival of solar panels to the inverter.
- An ABB ASC355 solar Pump Drives that has been specifically developed for solar pumping applications. These drives are equipped with software adapted to solar pumping, a soft start function and a dry running detection function. They perfectly protect pump motors.
- An AC circuit breaker that protects the pump output.
- In option, it is possible to add a switch that allows using the pumps with a PV source or with the network or a generator.

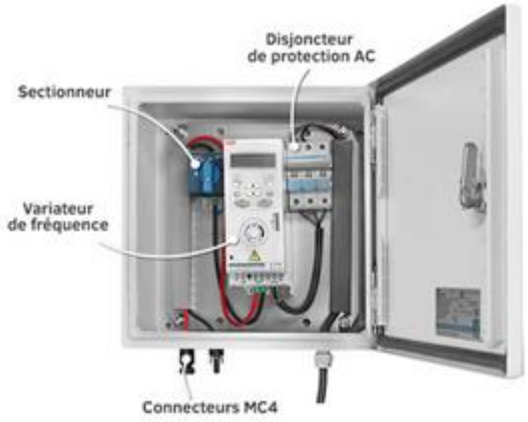


Fig. 4.6 : Security box

It will be placed right at the output of the generator and will be used, among other things, to electrically isolate the PV field in order to allow safe maintenance operations. It must be dimensioned according to the following rule:

- **Fuse choice:**

Rated fuse voltage ≥759.9V.

Nominal current ≥ 29.88 A.

Type: FDS-32.

- **The selected DC surge arrester:**

Type: FSP-D40 .

Maximum current: 40 kA.

Maximum voltage 800 Vdc .

- **Ac circuit breaker choice:**

Is based on the motor's output power 5.5 kW:

$$\mathrm{I}_{\text{breaker}} = \frac{\mathrm{P}}{(\cos\varphi.\sqrt{3})} \tag{4.39}$$

Circuit breaker for motor 2.2kW - 3~420Vac is of the following types: FSP-A.

- **Cable sections:**

The cable cross-section of the continuous part is calculated as follows:

The relation of Ohm's law:

$$\Delta\mathrm{V(V)} = \mathrm{RI} \tag{4.40}$$

Where:

$$R = 2\rho L/S \tag{4.41}$$

Or

$$\Delta V(V) \leq \Delta V(\%) \times U(V) \tag{4.42}$$

So

$$2\rho\frac{L}{S}I \ \leq \Delta V(\%) \times U(V) \tag{4.43}$$

$$2\rho LI\ /\Delta V(\%) \times U(V)\ \leq S \tag{4.44}$$

L (m): Assumed cable length (10m) to reduce voltage drops between the PV generator and the controller; S: cross section (mm²) of the conductor; ρ: Copper resistivity (0.017 Ω.mm²/m); ΔV(%): Limit voltage drop (<3% of the nominal voltage in the DC part); U(V): Voltage at maximum power of the PV generator obtained under the conditions (STC); I (A): Current at maximum power PV generator obtained under the conditions (STC).

$$I = Imaxmodule\ PV\ x\ number\ of\ parallel\ strings = 18.6A \tag{4.45}$$

$$2x0.017x9.31/(0.03x30.09) \leq S$$

$$3.5mm^2 \leq S \tag{4.46}$$

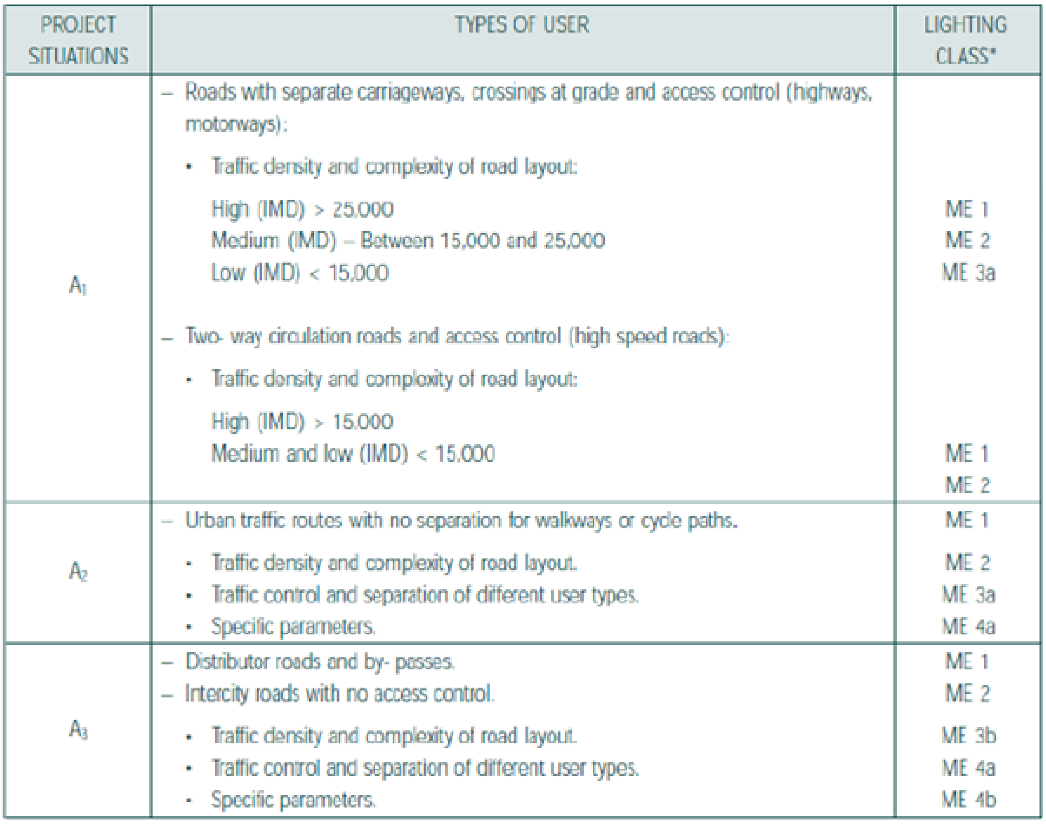
S=4mm²

4.3. Solar Street Light System

Solar Street Light System represent another form of Photovoltaic applications , this domain flourished through the years , the same client as before , wanted to light up the surrounding roads since it goes all dark by nightfall which to carry out a Solar Street Light system the following steps are run through.

4.3.1.Road Classification

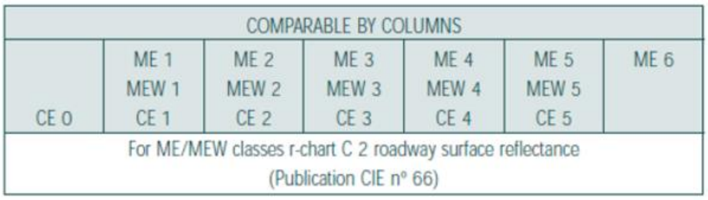
Choosing the road according to its parameters:



PROJECT SITUATIONS	TYPES OF USER	LIGHTING CLASS*
A_1	– Roads with separate carriageways, crossings at grade and access control (highways, motorways):	
	• Traffic density and complexity of road layout:	
	High (IMD) > 25.000	ME 1
	Medium (IMD) – Between 15.000 and 25.000	ME 2
	Low (IMD) < 15.000	ME 3a
	– Two- way circulation roads and access control (high speed roads):	
	• Traffic density and complexity of road layout:	
	High (IMD) > 15.000	ME 1
	Medium and low (IMD) < 15.000	ME 2
A_2	– Urban traffic routes with no separation for walkways or cycle paths.	ME 1
	• Traffic density and complexity of road layout.	ME 2
	• Traffic control and separation of different user types.	ME 3a
	• Specific parameters.	ME 4a
A_3	– Distributor roads and by- passes.	ME 1
	– Intercity roads with no access control.	ME 2
	• Traffic density and complexity of road layout.	ME 3b
	• Traffic control and separation of different user types.	ME 4a
	• Specific parameters.	ME 4b

As for the land surrounding roads its classed under the A_3 project situations and ME1 class (a By-pass road).

After selecting the street's class (ME1) now is turn for the CE parameter selection.

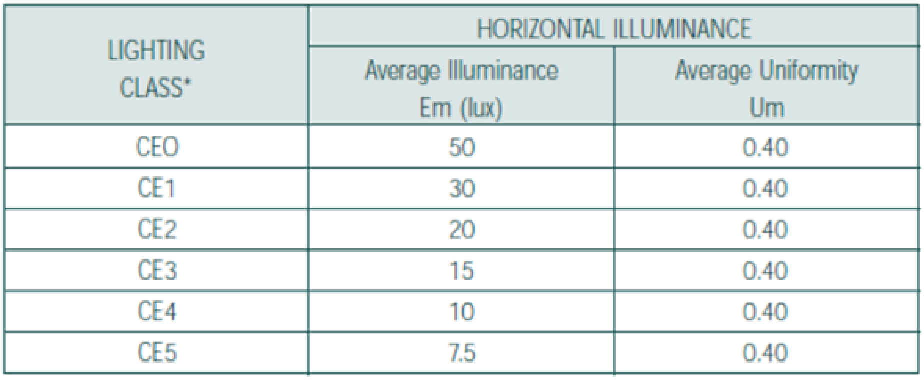


COMPARABLE BY COLUMNS						
CE 0	ME 1 MEW 1 CE 1	ME 2 MEW 2 CE 2	ME 3 MEW 3 CE 3	ME 4 MEW 4 CE 4	ME 5 MEW 5 CE 5	ME 6
For ME/MEW classes r-chart C 2 roadway surface reflectance (Publication CIE nº 66)						

According to Fig 4.16, the corresponding CE parameter to an ME1 road class is: CE1.

4.3.2.Determining the light luminance

Basically is to determine the surface the light take under a certain distance.



LIGHTING CLASS*	HORIZONTAL ILLUMINANCE	
	Average Illuminance Em (lux)	Average Uniformity Um
CEO	50	0.40
CE1	30	0.40
CE2	20	0.40
CE3	15	0.40
CE4	10	0.40
CE5	7.5	0.40

A 30 lux light is enough to light this by-pass road.

4.3.3.Solar Street Light Kit Selection

Generally, solar street light comes with watt identification not with lux identification. The conversion from lux (Ix) to Watt (W) is:

1 W = 680 lumen (for classic lamp).

1 lux = 1 lumen/m² (illuminated surface). You have to know the illuminated surface.

A 50W Led power is perfect for the system.

Fig. 4.7: All Top Street light System.

4.3.4.Implementation Choice

There are so many different implementation figures where each correspond to the road type, its width, as well as to the street light pole height.

For a 3m bypass road and an 8m pole height, the adequate implementation structure all along the road is the following:

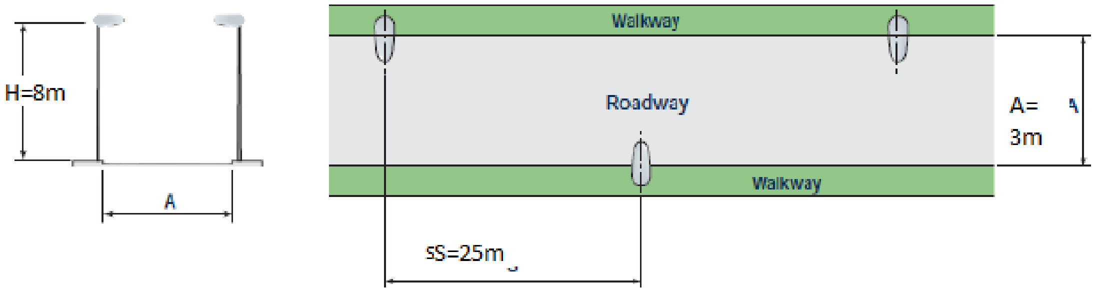


Fig. 4.8: Street Light Implementation Structure.

CONCLUSION

Solar power is an immense source of directly useable energy and ultimately creates other energy resources: biomass, wind, hydropower and wave energy.

Most of the earth surface receives sufficient solar energy to permit low-grade heating of water and buildings, although there are large variations with latitude and season. At low latitudes, simple mirror devices can concentrate solar energy sufficiently for cooking and even for driving steam turbines.

The energy of light shifts electrons in some semiconducting materials. This photovoltaic effect is capable of large-scale electricity generation. However, the present low efficiency of solar PV cells demands very large areas to supply electricity demands.

Direct use of solar energy is the only renewable means capable of ultimately supplanting current global energy supply from non-renewable sources, but at the expense of a land area of at least half a million km^2.

The design and analysis of results of the implemented system and technological configuration of off-grid solar electrification of a house in El Bouni, Annaba preformed very well. Replacing the conventional energy supplier by a renewable energy showed a smooth energy flow and no power cuts that used to damages the devices before, now it’s all green sustainable with no electric bills.

Beside solar home systems, Solar pumping systems can provide real opportunities to improve water availability in areas where grid power cannot be relied upon, or where power costs are an impediment to effective water use. There is massive future potential for the application of these technologies worldwide.

Solar water pumping is an ideal solution for developing countries having sufficient solar irradiance and technology. It is a good time for research in this area as the fossil fuels are depleting and becoming scarcer. All governments in the world are motivating local population, designer, industrial, … for adopting renewable energy technologies and energy efficiency measures and has initiated various development schemes for all types of renewable energy based projects like solar, wind, biomass, small hydro, waste to energy etc.

Solar street lighting is a low cost project, effective, practical and mostly is eco friendly and the safest way to save energy, it clearly tackles the two problems that the world is facing today, saving energy and also disposal of incandescent lamps, very efficiently.

Overall, Solar PV systems are the next step the world should make to replace all the conventional energy sources by a green, sustainable and low cost source of energy.

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