# Solar & Wind Electrical Systems

(R20A0231)

# Lecture Notes


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## CONTENTS

# Syllabus:

**B.Tech (EEE) R-18**

**MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY**

**B.Tech. EEE I SEM** **L T/P/D C**

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**(PROFESSIONAL ELECTIVE - IV)**

**(R18A0221) SOLAR & WIND ELECTRICAL SYSTEMS**

**COURSE OBJECTIVES:**

To study and understand:

- Basics of Solar Energy & Radiation, Solar look angles and Solar cells.
- I-V Characteristics of Solar cells, MPPT, Solar Power plants and their Classification.
- Power contained in wind and efficiency limit. Basics of Wind turbines & their subsystems. Power-Speed and Torque-Speed characterizes. Control strategy.
- Generation schemes with Constant & variable speed Wind turbines in conjunction with Induction & Synchronous Generators-Their integration with Grid

**UNIT-I: BASIC CONCEPTS OF SOLAR ENERGY & SOLAR CELLS:** Introduction to solar energy. Terrestrial and Extraterrestrial Solar Radiation. Characteristics of Solar Radiation & Radiation Spectrum. Solar Constant. Air mass ratio. Geometry of Earth and Sun. Atmospheric effects on solar radiation. Solar radiation measurement & Instrumentation. Types of Solar Cells - Mono crystalline & Poly crystalline. Solar cells-Energy requirement, Basic operation, construction & concepts.

**UNIT-II: SOLAR CELL CHARACTERISTICS, BOS AND CLASSIFICATION OF PV SYSTEMS:** Solar cell VI-characteristics. Maximum Power Point. Cell efficiency & Fill factor. Effect of Irradiation and Temperature. Principles of Maximum Power Point Trackers. PV Arrays and Modules. Balance of Systems (BOS)- Inverters, Batteries, Charge controllers. Classification of PV Systems - Stand- alone PV system - Grid Interactive PV System- Hybrid Solar PV system.

**UNIT-III: FUNDAMENTALS OF WIND TURBINES:** Power contained in wind - Efficiency limit for wind energy conversion. Design of wind turbine rotor: Diameter of the rotor - Choice of numberof blades - The tower- Transmission system and Gear box - Power speed characteristics - Torque speed characteristics. Wind turbine control systems - Pitch angle control, Stall control, Yaw control, Control strategy.

**UNIT-IV: CLASSIFICATION OF WIND POWER GENERATION SCHEMES & SELF EXCITED INDUCTION GENERATORS:** Criteria for classification-Fixed and Variable speed wind turbines- Electrical Power Generators-Self excited vs. Grid connected Induction Generators. Classification of Wind Power Generation Schemes. Advantages of variable speed systems. Induction Generators-Basic Principle of operation-Operation in self excited mode-Initial Voltage build up - Limitations. Methods to overcome limitations - Controlled firing angle scheme with AC side capacitor-Inverter/converter system with DC side capacitor.

**UNIT-V: GRID INTEGRATION OF WIND TURBINE SYSTEMS:**

Grid Connected Induction Generators Operation - Single output system with Fixed speed - Double output system with variable speed - Grid connected Synchronous generators Operation - Wound field Synchronous generator- Permanent magnet Synchronous generator. Grid connected Wind Turbine systems – Features and configuration - Interface Requirements - Synchronizing with Grid - Power Flow between Two Synchronous Sources - Effect of a Wind Generator on the network

**TEXT BOOKS:**

1. Wind Electrical Systems, S.N. Bhardra, D.Kastha and S.Banerjee, Oxford University Press.
2. G. M. Masters, "Renewable and Efficient Electric Power Systems", John Wiley and Sons, 2004.
3. Wind and Solar Power Systems- Mukund R. Patel. CRC Press Boca Raton-London-New York,Washington, D.C. 1999
4. Solar PV and Wind Energy Conversion Systems. An Introduction to Theory, Modeling withMATLAB/SIMULINK, and the Role of Soft Computing Techniques' S. Sumathi , L. Ashok Kumar & P. Suresh. Springer

**REFERENCE BOOKS:**

1. Grid integration of wind energy conversion systems. H. Siegfried and R. Waddington. John Wiley and Sons Ltd., 2006.
2. T. Ackermann, "Wind Power in Power Systems", John Wiley and Sons Ltd., 2005.
3. Solar Cells from Basics to Advanced Systems, Chenming Hu and Richard M. White, TataMcGraw Hill Education Private Limited.

**COURSE OUTCOMES:**

After going through this course, the student gets a working knowledge on:

- The basic concepts of solar energy, solar radiation and fundamentals of wind turbines.
- Different types of Solar cells, Solar power systems and their integration.
- Generation schemes with both constant & variable speed turbines and different types of Generators.
- Various other subsystems of Solar and Wind based power plants and their Integration with Grid.

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# SOLAR & WIND ELECTRICAL SYSTEMS

## UNIT-1: BASIC CONCEPTS OF SOLAR ENERGY AND SOALR CELLSCONTENTS:

1. **Introduction to solar energy**
2. **Terrestrial & Extra Terrestrial solar radiation**
3. **Characteristics of solar radiation & Radiation Spectrum. Solarconstant & Air Mass Ratio**
4. **Geometry of Earth and Sun**
5. **Atmospheric effects on Solar Radiation**
6. **Solar radiation measurement and Instrumentation**
7. **Types of solar cells: Mono crystalline & Poly crystalline**
8. **Solar cells - Energy requirement, Basic operation, construction & concepts**
9. **Important Formulae**
10. **Important Questions**

**Appendix: Brief Review of the background Semiconductor Physics**

# 1. Introduction to solar energy:

Solar energy is the radiant light and heat from the sun that has been harnessed by humans since ancient times using a range of ever-evolving technologies. Solar radiation along with secondary solar resources account for most of the available renewable energy on earth. All other renewable energies other than geothermal derive their energy from energy received from the sun.
Solar technologies are broadly characterized as either passive solar or active solar depending on the way they capture, convert and distribute sunlight. Active solar techniques include the use of Photovoltaic Modules (Solar cells) (Solar to Electrical) and Solar Thermal Collectors (Solar to Thermal) with suitable equipment to convert sunlight into useful outputs.
Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties, and designing spaces that naturally circulate air.

**We will study only Active Solar techniques with Solar Cells in this course.**

**Important features of Solar Energy:**

- **SUN** the source of '**Solar energy'** is a huge, glowing sphere of hot gas with **1.4 million kilometer** diameter. Most of this gas is hydrogen (about 70%) and helium (about 28%).
- Due to Nuclear fusion reaction of Hydrogen with Helium internal temperatures reach over **20 million Kelvin**.
- The resulting loss of mass due to fusion is converted into about **$3.8 \times 10^{20}$ MW** of electromagnetic energy (power) that radiates outward from the surface into space.
- The spectrum of solar radiation is close to that of a blackbody @ **5800 K**.
- The amount of energy reaching the surface of the Earth every hour is greater than the amount of energy used by the Earth's population over an entire year.

**Terms used in Solar Energy: Irradiance, Irradiation & Insolation :**

**Irradiance:** is the rate at which radiant energy is incident on a surface per unit area ( **W/m$^2$** ) and is represented by the symbol **G.**

**Irradiation:** is the incident energy per unit area (**J/m$^2$**) on a surface -determined by integration of irradiance over a specified time, usually an hour or a day.

**Insolation**: is a term used to indicate '**Solar Energy Irradiation'**. (An abbreviation for '**In**cident **Sol**ar Radi**ation'**)

- While solar irradiance is most commonly measured, a more common form of radiation data, solar Insolation is the total amount of solar energy received at a particular location during a specified time period, often in units of kWh/(m$^2$ -day).

- While the units of solar Insolation and solar irradiance are both a power density (for solar Insolation the "hours" in the numerator are a time measurement as is the "day" in the denominator), solar Insolation is quite different than the solar irradiance as the solar Insolation is the instantaneous solar irradiance averaged over a given time period.

- Solar Insolation data is commonly used for simple PV system design while solar radiance is used in more complicated PV system performance evaluation which calculates the system performance at each point in the day.

## 2. Extra Terrestrial &Terrestrial Solar Radiation:

While the solar radiation incident on the Earth's atmosphere which is known as **Extraterrestrial Solar Radiation** is relatively constant, the radiation at the Earth's surface which is known as **Terrestrial Solar Radiation** varies widely due to:

- Atmospheric effects, including absorption and scattering.
- Local variations in the atmosphere, such as water vapour, clouds, and pollution.
- Latitude of the location and

- Season of the year and the time of day.

The above effects have several impacts on the solar radiation received at the Earth's surface. These changes include:

- Variations in the overall power received, the spectral content of the energy and the angle from which light is incident on a surface.
- In addition, a key change is that the variability of the solar radiation at a particular location increases dramatically. The variability is due to both local effects such as clouds and seasonal variations, as well as other effects such as the length of the day at particular latitude.
- Desert regions tend to have lower variations due to local atmospheric phenomena such as clouds. Equatorial regions have low variability between seasons.
- As solar radiation makes its way toward the earth's surface, some of it is absorbed by various constituents in the atmosphere, giving the terrestrial spectrum an irregular, bumpy shape.
- The terrestrial spectrum also depends on how much atmosphere the radiation has to pass through to reach the surface. This is explained by a term called Air Mass Ratio.

## 3. Characteristics of Solar Radiation & Radiation Spectrum

The characteristics of Solar Radiation are best explained with the help of the Solar spectrum plots which give data on intensity as spectral content. These characteristics are normally shown at **Extra Terrestrial** (above the atmosphere) level and at **Terrestrial level** (sea level) in comparison with a standard, a Black body at 5800 k. The solar spectrum typically extends from the **IR** to the **UV** region, wave - length range from 3 μm to 0.2 μm. But the intensity is not uniform. A typical solar spectrum, as a plot of spectral irradiance vs. wavelength, is shown in the figure below. The area under the curve gives the total areal intensity and this is approximately **1.35 kW/m$^2$**. In this context let us define a commonly used term **'Solar Constant'**.

**Solar constant:** The Sun-Earth distance varies about the mean distance by around 1.7 percent. At the mean distance of **149.5 million km** which is known as one **Astronomical Unit (AU),** the solar flux outside the earth's atmosphere is 1.353 kW/m$^2$, which is a quantity known as the **Solar Constant.**

The solar spectrum can be approximated by a black body radiation curve at temperature of approximately 5800$^0$C. There is also a difference in the spectra measured at the top of the atmosphere and at the surface, due to atmospheric scattering and absorption. It can also be seen that as solar radiation makes its way towards the earth's surface, some of it is absorbed by various constituents in the atmosphere, giving the terrestrial spectrum an irregular, bumpy shape.

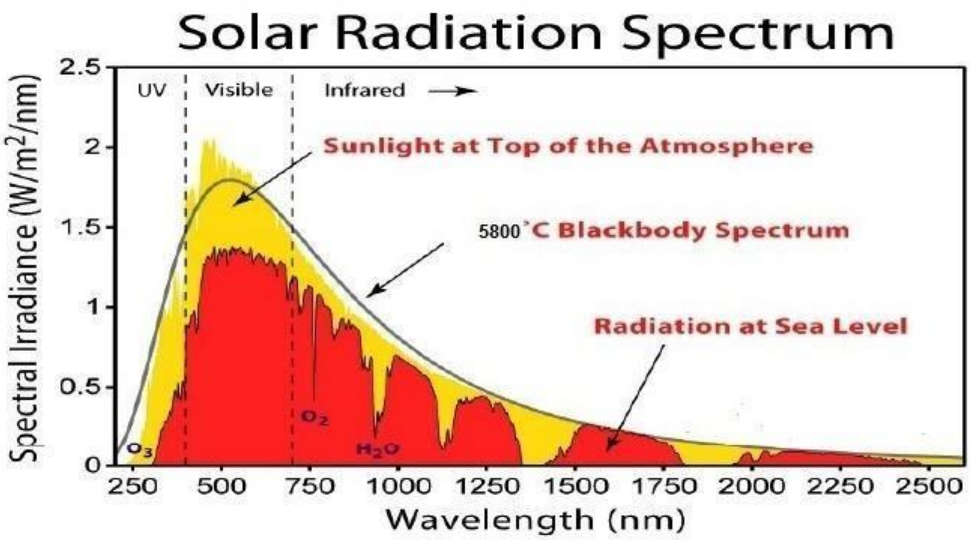


**Figure-1: Typical solar spectrum at the top of the atmosphere and at sea level. The difference is the radiation absorbed/scattered by the atmosphere. The spectrum of a black body at 5800$^0$C is also superimposed.**

Also shown are the areas under the actual solar spectrum that corresponds to wavelengths within the ultraviolet UV (7%), visible (47%), and infrared IR (46%) portions of the spectrum. The visible spectrum, which lies between the UV and IR, ranges from 0.38 μm (violet) to 0.78 μm (red).

**Air Mass Ratio:** The terrestrial spectrum also depends on how much atmosphere the radiation has to pass through to reach the surface. As shown in the figure below, under the simple assumption of a flat earth the air mass ratio can be expressed as:

**Air mass Ratio 'm' =** $\dfrac{h2 \text{ (path length through the atmosphere with sun directly overhead )}}{h1 = \text{(path length through the atmosphere to reach a spot on the surface )}}$

**= 1/ Sin β (β** = the altitude angle of the sun as shown below)

Thus an air mass ratio of 1 (designated "AM1") means, the sun is directly overhead. By convention, AM0 means no atmosphere i.e. it is the extraterrestrial solar spectrum. Often, an air mass ratio of 1.5 is assumed for an average solar spectrum at the earth's surface.

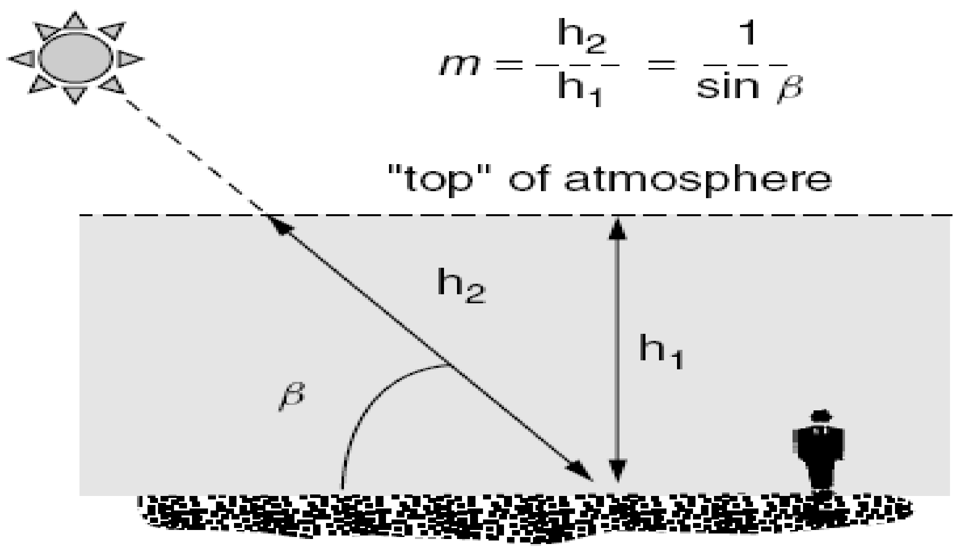


**Figure-2: The air mass ratio m is a measure of the amount of atmosphere the sun's rays must pass through to reach the earth's surface. For the sun directlyoverhead, m = 1.**

As sunlight passes through more and more atmosphere i.e. as the **'air mass'** ratio increases , less energy arrives at the earth's surface and the spectrum shifts somewhat towards longer wavelengths.

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This impact of the atmosphere on incoming solar radiation for various air massratios is shown in the figure below.

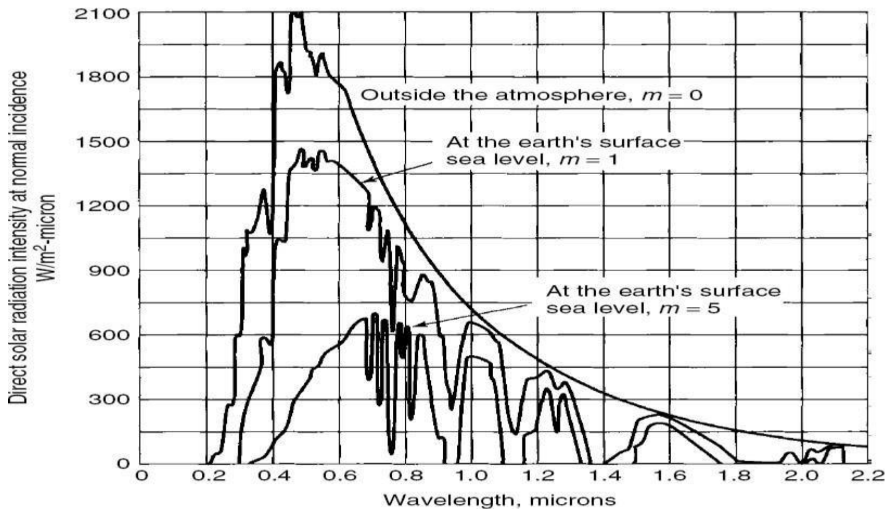


**Figure-3: Solar spectrum for extraterrestrial (m = 0), for sun directly overhead (m = 1), and at the surface with the sun low in the sky, m = 5.**

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## 4. Geometry of the Earth and Sun:

**Earth's orbit around the Sun:** The earth revolves around the sun in an elliptical orbit, every 365.25 days making one rotation a day around its own NS axis. The eccentricity of the ellipse is small and the orbit is, in fact, quite nearly circular. The point at which the earth is nearest the sun, the **perihelion**, occurs on **January 2**, at which point it is a little over **147 million kilometers** away. At the other extreme, the **aphelion**, which occurs on **July 3**, the earth is about **152 million kilometers** from the sun. This variation in distance is given by the following relationship:

$$d = 1.5 \times 10^8 \, [1 + 0.017 \sin \{360(n - 93)/365\}] \text{ km}$$

Where n is the day number, with January 1 as day 1 and December 31 being day number 365. Table below provides a convenient list of day numbers for the first day of each month.

It should be noted that the above equation and all other equations developed in this chapter involving trigonometric functions use angles measured in degrees, not radians.

**Table: Day Numbers for the First Day of Each Month**

| | | | |
|---|---|---|---|
| January | n =1 | July | n = 182 |
| February | n = 32 | August | n = 213 |
| March | n = 60 | September | n = 244 |
| April | n = 91 | October | n = 274 |
| May | n = 121 | November | n = 305 |
| June | n = 152 | December | n = 335 |

Each day, as the earth rotates about its own axis, it also moves along the ellipse. If the earth were to spin only $360^0$ in a day, then after 6 months, our clocks would be off by 12 hours. That is, at noon on day 1 it would be the middle of the day, but 6 months later noon would occur in the middle of the night. To keep synchronized, the earth needs to rotate one extra turn each year, which means that in a 24-hour day the earth actually rotates by $360.99^0$.

As shown in the figure below (Figure - 4) the plane swept out by the earth in its orbit is called the **ecliptic plane**. The earth's spin axis is currently tilted 23.45◦ withrespect to the ecliptic plane and that tilt is, of course, what causes our seasons. On March 21 and September 21, a line from the center of the sun to the center of the earth passes through the equator and everywhere on earth we have 12 hours of daytime and 12 hours of night, hence the term **equinox** (equal day and night). On December 21, the **winter solstice** in the Northern Hemisphere, the inclination of the North Pole reaches its highest angle away from the sun (23.45◦), while on June 21 the opposite occurs (**summer solstice**).

**Important terms in Earth's orbit around the sun :**

**Solstice:** Either of the two times in the year, the **summer solstice** ( June 21st) and the **winter solstice** ( December 21st), when the sun reaches its highest or lowest point in the sky at noon, marked by the **longest** and **shortest** days.

**Equinox**: The time or date (twice each year) at which the **sun crosses the equator**, **when day and night are of equal length** (21st September and 21st March).

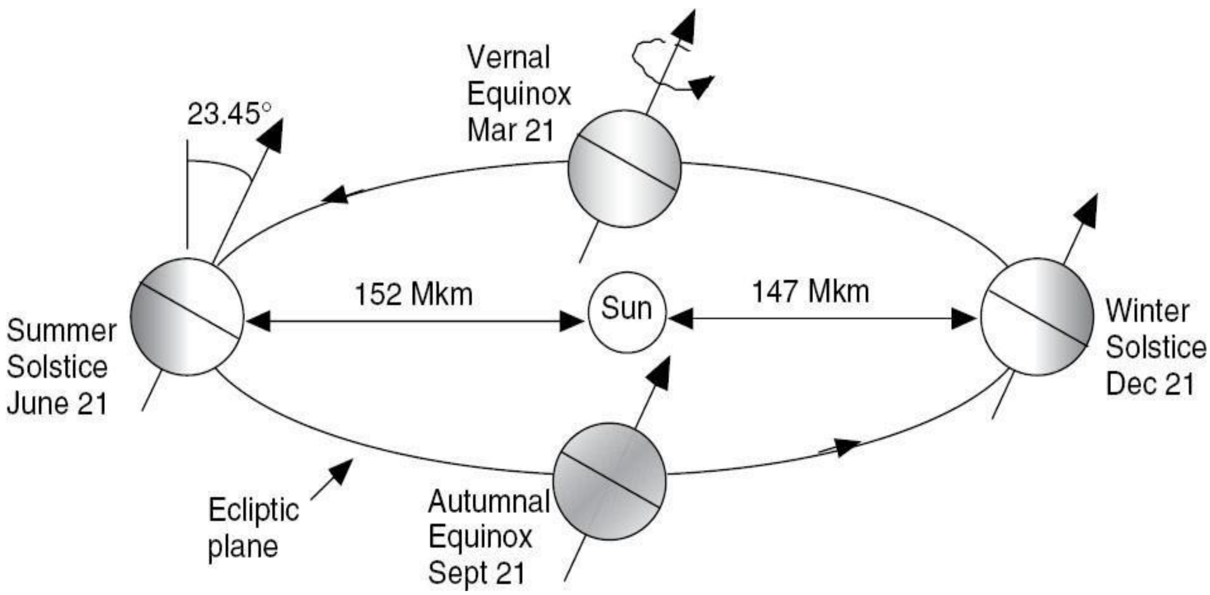


**Figure-4: The tilt of the earth's spin axis with respect to the ecliptic plane is what Causes our seasons. "Winter" and "Summer" are designations for the Solstices in the Northern Hemisphere.**

**Solar Look Angles:**

We all know that the sun rises in the east and sets in the west and reaches its highest point sometime in the middle of the day. For our solar photovoltaic power requirements, it is quite useful to predict exactly where in the sky the sun will be at any location, at any time, on any day of the year. We can use this informationof **Solar Look Angles** to fix up the best **tilt angle** (orientation) for solar modules soas to expose them to the highest **insolation.**

The following material (italicized) and a few Earth centered Sun-Earth orbital figures are shown here to get a better understanding of the sun-earth relationship taking earth as centre. After that, simplified Earth centric figures are used to derive and explain the important **Solar Look Angles** like **solar declination $\delta$, altitude angle $\beta_N$, Azimuth angle etc** .

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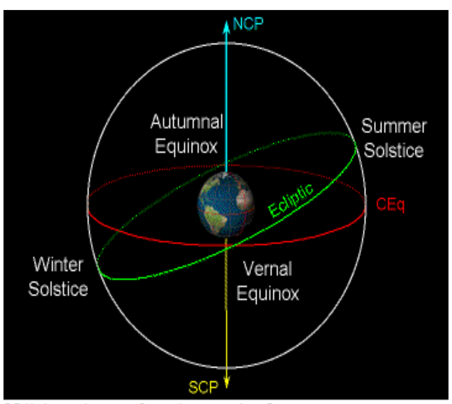
The sun-earth relationship can be visualized more easily in an earth centered(earth centric) view, two views of which are shown in the figure-5 below. The two figures (4 and 5) of course, are equivalent through coordinate transformations. In figure 5(two views are shown both of which are same), the earth is shown to be stationary with its polar axis pointing upward. The sun moves around the earth exactly **once every day** at a constant angular speed ($15^0$ per hour) tracing an almost perfectly centered and circular path. The solar path is highest over the North Pole with the sun rays making a $23.5^0$ angle with the plane of the equator around June 21. Around September 23 and March 22, the sun's path is parallel to the earth's equatorial plane and the sunrays arrive parallel to the equatorial plane. Around December 22, the solar path is lowest below the South Pole, makinga - $23.5^0$angle with the equatorial plane.



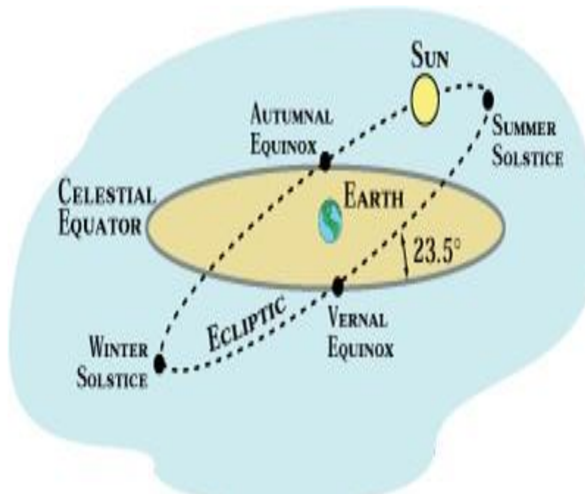




**Figure: 5**

In the figure-6 below both the (a) actual Sun centered view and (b) Earth centered view are shown in the same figure with some additional data but still depicting the daily rotation. These figures do not reflect the annual movement of the Sun which is the basis for the seasons.

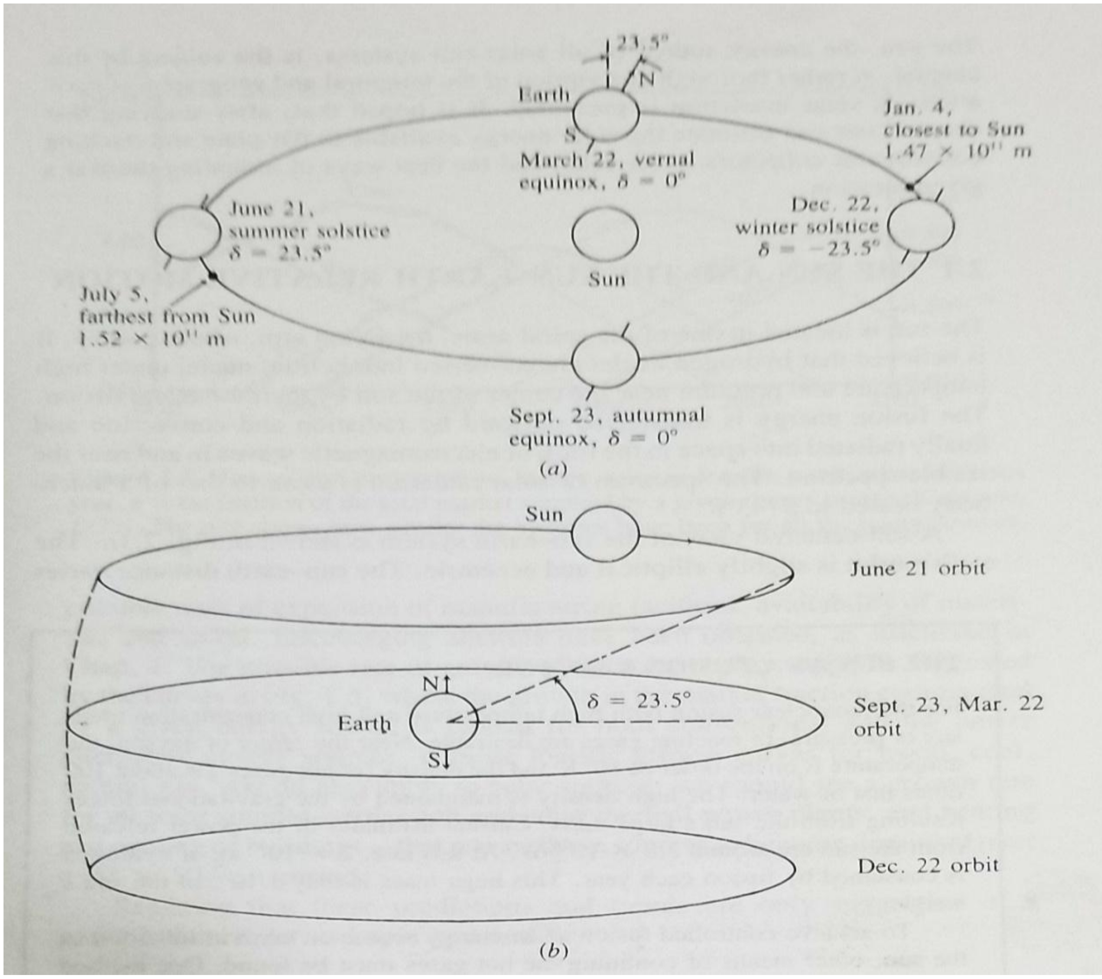



**Figure-6: (a) The conventional sun-centered view of the sun-earth system (b) An earth-centered view, which is easier to visualize. For example, the declination angle 'δ' between the sun ray and the plane of the equator is easily illustrated in figure (b). The dates given may vary by one day or so.**

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An alternative earth centered perspective which is easier to visualize the annual movement of the sun with respect to the earth is shown in the figure below (figure -7). In this figure the earth is fixed, spinning around its north–south axis and the sun lies somewhere outside in space, slowly moving up and down as the seasons progress. In this figure the daily rotation of the sun around the earth is not depicted. Hence forth this figure will be adopted with changes where ever required to explain the various **Solar Look Angles**.

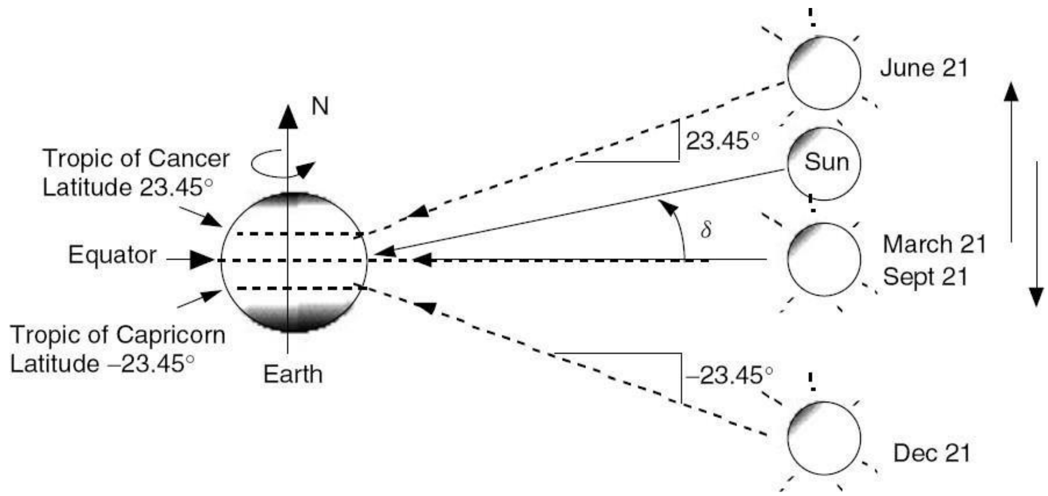



**Figure-7: An alternative view with a fixed earth and Sun that moves up and down. The angle between the sun and the equator is called Solar Declination δ.**

On June 21 (the summer solstice) the sun reaches its highest point, and a ray drawn at that time from the center of the sun to the center of the earth makes an angle of 23.45◦ with the earth's equator. On that day, the sun is directly over the Tropic of Cancer at latitude 23.45◦. At the two equinoxes, the sun is directly over the equator. On December 21 the sun is 23.45◦ below the equator, which defines the latitude known as the Tropic of Capricorn. As shown in the figure above **(Fig. 6 &7)**, the angle formed between the plane of the equator and a line drawn from the center of the sun to the center of the earth is called the **solar declination, δ**. It varies between the extremes of ± 23.45◦, as a simple sinusoid with a period of 365-days. This puts the spring equinox on day n = 81 and provides a very good approximation for evaluation of **δ** by the expression:

$$\delta = 23.45 \sin [360 / 365] (n - 81)]$$

Computed values of solar declination on the twenty-first day of each month aregiven in the table below.

**Table: Solar Declination δ for the 21st Day of Each Month (degrees)**

| **Month:** | Jan | Feb | Mar | Apr | May | Jun | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **δ:** | −20.1 | −11.2 | 0.0 | 11.6 | 20.1 | 23.4 | 20.4 | 11.8 | 0.0 | −11.8 | −20.4 | −23.4 |

While the above figure doesn't capture the subtleties associated with the earth's orbit, it is entirely adequate for visualizing various latitudes and solar angles. It is also easy to use the above figure to gain some intuition into what might be a good **tilt angle** for a solar collector.

**Effect of Collector tilt:**

Except for locations near the equator, laying a PV cell panel **flat** on a horizontal surface is not the best option. **Tilting** the panel towards the equator, i.e. towards the south for northern hemisphere location, increases the total amount of annual solar energy collection and smooth out the difference between summer and winter collections. This can be best explained with the help of the following figure.

Figure below shows a south-facing collector on the earth's surface that is tipped up at an angle equal to the local latitude, L.

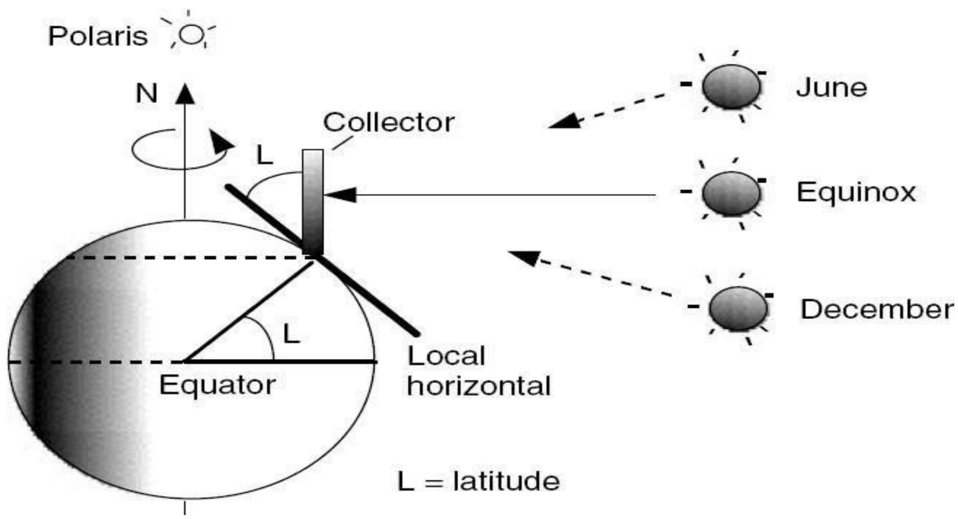



**Figure-8: A south-facing collector tipped up to an angle equal to its latitude is perpendicular to the sun's rays at solar noon during the equinoxes.**

As can be seen, with this tilt angle the collector is parallel to the axis of the earth. During an equinox, at solar noon, when the sun is directly over the local meridian (line of longitude), the sun's rays will strike the collector at the best possible angle; that is, they are perpendicular to the collector face. At other times of the

year the sun is a little high or a little low for normal incidence, but on the average it would seem to be a good tilt angle.
On the average, facing a collector toward the equator (for most of us in the Northern Hemisphere, this means facing it south) and tilting it up at an angle equal to the local latitude is a good rule-of-thumb for annual energy collection.

**Altitude angle $\beta_N$ :**

Having drawn the earth-sun system in a simpler way as shown earlier, now it is easy to determine a key solar angle, namely the **altitude angle $\beta_N$** of the sun at **solar noon**.
The **altitude angle $\beta_N$** is the angle between the sun and the local horizon directly beneath the sun. From the figure shown below, we can write down the expression for the **altitude angle $\beta_N$** as: $\beta_N = 90^\circ - L + \delta$
where **L** is the latitude of the site. Notice in the figure the term **zenith** is introduced, which refers to an axis drawn directly overhead at a site.

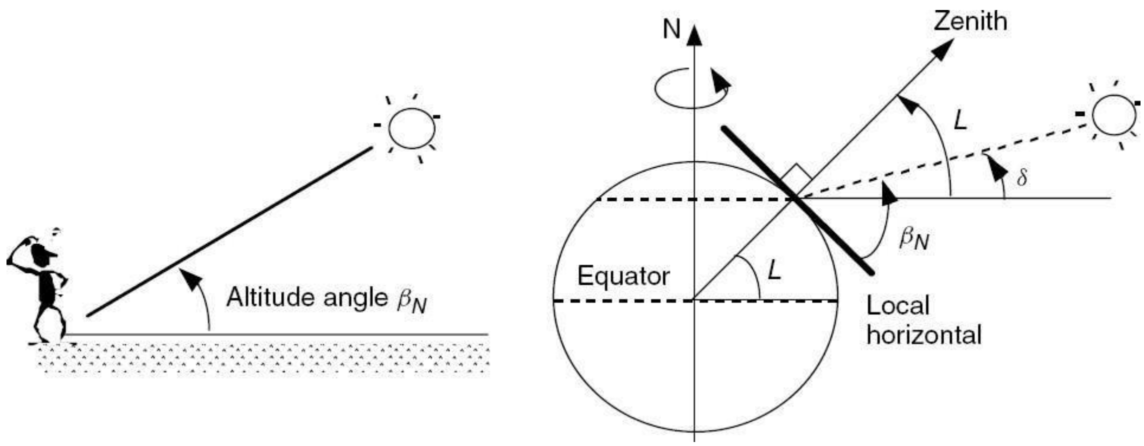



**Figure-9: The altitude angle of the sun at solar noon.**

**Example-1: Tilt Angle of a PV Module.** Find the optimum tilt angle for a south-facing photovoltaic module in Tucson (latitude 32.1◦) at solar noon on March 1.

**Solution:** From Table given above ( 7.1) March 1 is the sixtieth day of the year so the solar declination (7.6) **δ** is given by :

$$\delta = 23.45 \sin [360/365\ (n - 81)]$$

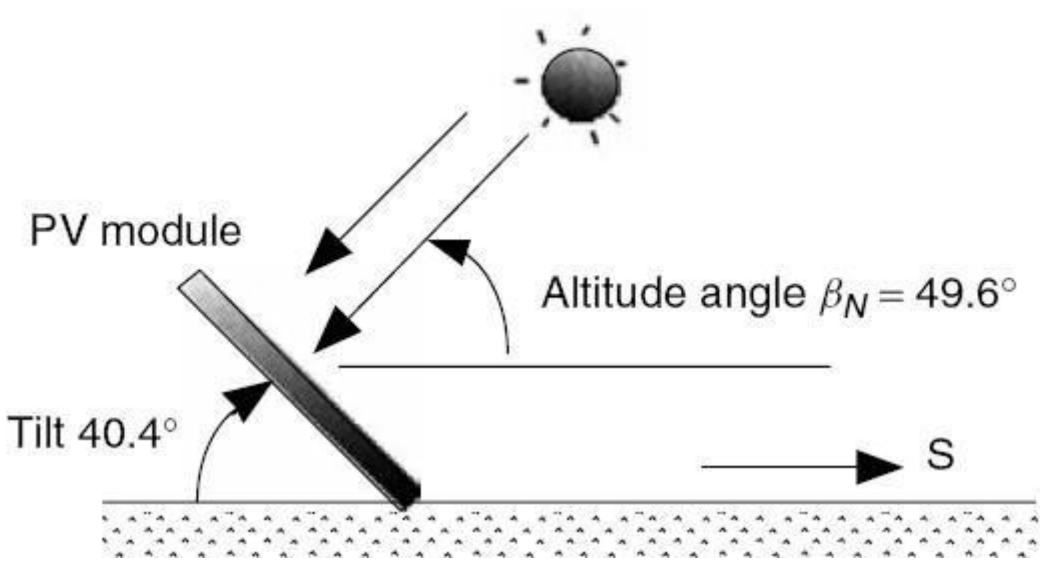
$$= 23.45^0 \sin [360/365\ (60 - 81)^0] = -8.3^\circ$$

which, from the earlier equation for the altitude angle at solar noon (7.7), makes the altitude angle of the sun equal to

$$\beta_N = 90^0 - L + \delta = 90 - 32.1 - 8.3 = 49.6^0$$

The tilt angle that would make the sun's rays perpendicular to the module at noon would therefore be

$$\text{Tilt angle} = 90 - \beta_N = 90 - 49.6 = 40.4^0$$




**Solar position at any time of day:**

The location of the sun at any time of day can be described in terms of its altitude angle **β** and its azimuth angle $\varphi_s$ as shown in the figure below. The subscript **'s'** in the azimuth angle helps us remember that this is the azimuth angle of the sun.

**By convention, the azimuth angle is positive in the morning with the sun in the east and negative in the afternoon with the sun in the west.**

Notice that the azimuth angle shown in this figure uses true south as its reference, and this will be the assumption in this text unless otherwise stated.

For solar work in the Southern Hemisphere, azimuth angles are measured relative to north.

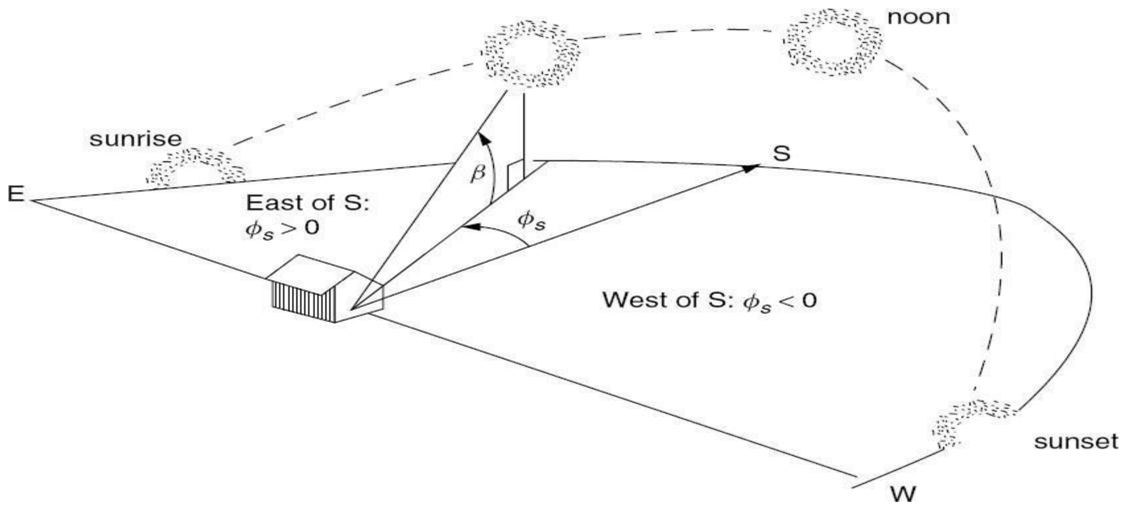



**Figure-10: The sun's position can be described by its altitude angle β and itsazimuth angle φS.**

By convention, the azimuth angle is considered to be positive before solar noon. The azimuth and altitude angles of the sun depend on the latitude, day number, and, most importantly, the time of day. For now, we will express time as the number of hours before or after solar noon. Thus, for example, 11 A.M. solar time is one hour before the sun crosses your local meridian (due south for most of us). Later we will learn how to make the adjustment between solar time and local clock time. The following two equations allow us to compute the altitude and azimuth angles of the sun.

$$\sin \beta = \cos L \cos \delta \cos H + \sin L$$

$$\sin \delta \sin \varphi_S = \cos \delta \sin H / \cos$$

$$\beta$$

Notice that **time** in these equations is expressed by a quantity called the **hour angle, H.**

**The 'Hour angle' is the number of degrees that the earth must rotate before the sun will be directly over your local meridian (line of longitude).**

As shown in the figure below, at any instant, the sun is directly over a particular line of longitude, called the sun's meridian. **The difference between the local meridian and the sun's meridian is the 'Hour angle', with positive values occurring in the morning before the sun crosses the local meridian.**

Considering the earth to rotate $360^0$ in 24 h, or $15^0$/h, the hour angle can be described as follows:

$$\textbf{Hour angle H} = (\mathbf{15^0 / hour}) \textbf{ x (hours before solar noon)}$$

Thus, the hour angle H at 11:00 A.M. solar time would be +$\mathbf{15^0}$ (the earth needs to rotate another $\mathbf{15^0}$, or 1 hour, before it is solar noon). In the afternoon, the Hour angle is negative, so, for example, at 2:00 P.M. solar time H would be $\mathbf{-30^0}$.

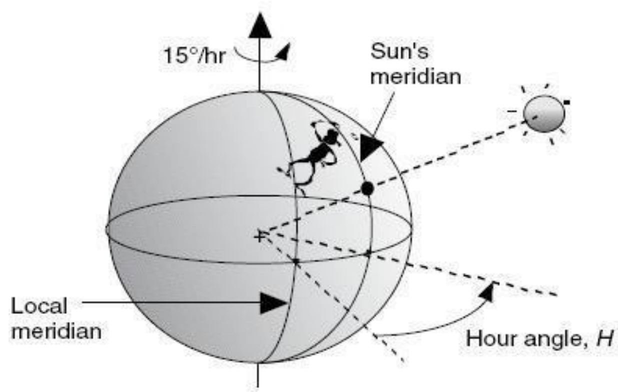



**Figure-11: The hour angle is the number of degrees the earth must turn before the sun is directly over the local meridian. It is the difference between the sun'smeridian and the local meridian.**

There is a slight complication associated with finding the azimuth angle of the sun from the above equation. During spring and summer in the early morning and late afternoon, the magnitude of the sun's azimuth is liable to be more than $90^0$ away from south (that never happens in the fall and winter). Since the inverse of a sine is ambiguous, sin x = sin (180 − x), we need a test to determine whether the azimuth is greater than or less than $90^0$ away from south. Such a test is:

$$\textbf{if } \cos H \geq \tan\delta / \tan L \textbf{, then } |\varphi_S| \leq 90^0\textbf{; otherwise } |\varphi_S| > 90^0$$

**Example-2: Where Is the Sun?** Find the altitude angle and azimuth angle for the sun at 3:00 P.M. solar time in Boulder, Colorado (latitude $40^0$) on the summer solstice.

**Solution:** Since it is the solstice we know, without computing, that the solar declination δ is 23.45◦. Since 3:00 P.M. is three hours after solar noon, we obtain $H = (15^0/ h) \cdot (\text{hours before solar noon}) = 15^0/ h \cdot (-3\ h) = -45^0$

Using (7.8), the altitude angle is given by

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta$$
$$= \cos 40^0 \cos 23.45^0 \cos(-45^0) + \sin 40^0 \sin 23.45^0 = 0.7527 \quad \beta = \sin^{-1}(0.7527) = 48.8^0$$

From (7.9) the sine of the azimuth angle is

$$\sin\varphi_S = \cos\delta \sin H / \cos\beta$$
$$= \cos 23.45^0 \cdot \sin(-45^0) / \cos 48.8^0 = -0.9848$$

But the arcsine is ambiguous and two possibilities exist:

$\varphi_S = \sin^{-1}(-0.9848) = -80^0$ ($80^0$ west of south)

or $\varphi_S = 180 - (-80) = 260^0$ ($100^0$ west of south)

To decide which of these two options is correct, we apply the condition:

**if $\cos H \geq \tan\delta / \tan L$, then $|\varphi_S| \leq 90^0$; otherwise $|\varphi_S| > 90^0$**

$\cos H = \cos(-45^0) = 0.707$ and

$\tan\delta / \tan L = \tan 23.45^0 / \tan 40^0 = 0.517$

Since $\cos H \geq \tan\delta / \tan L$

we conclude that the azimuth angle is

$\varphi_S = -80^0$ ($80^0$ west of south)

---

Additional study material for better clarity on the length of the day:

Solar altitude and azimuth angles for a given latitude can be conveniently portrayed in graphical form, called '**Sun Path Diagrams'** an example of which is shown in the figure below. A careful study of these plots gives us a clear understanding of the formation of seasons and their dependence on the latitudeof the location.

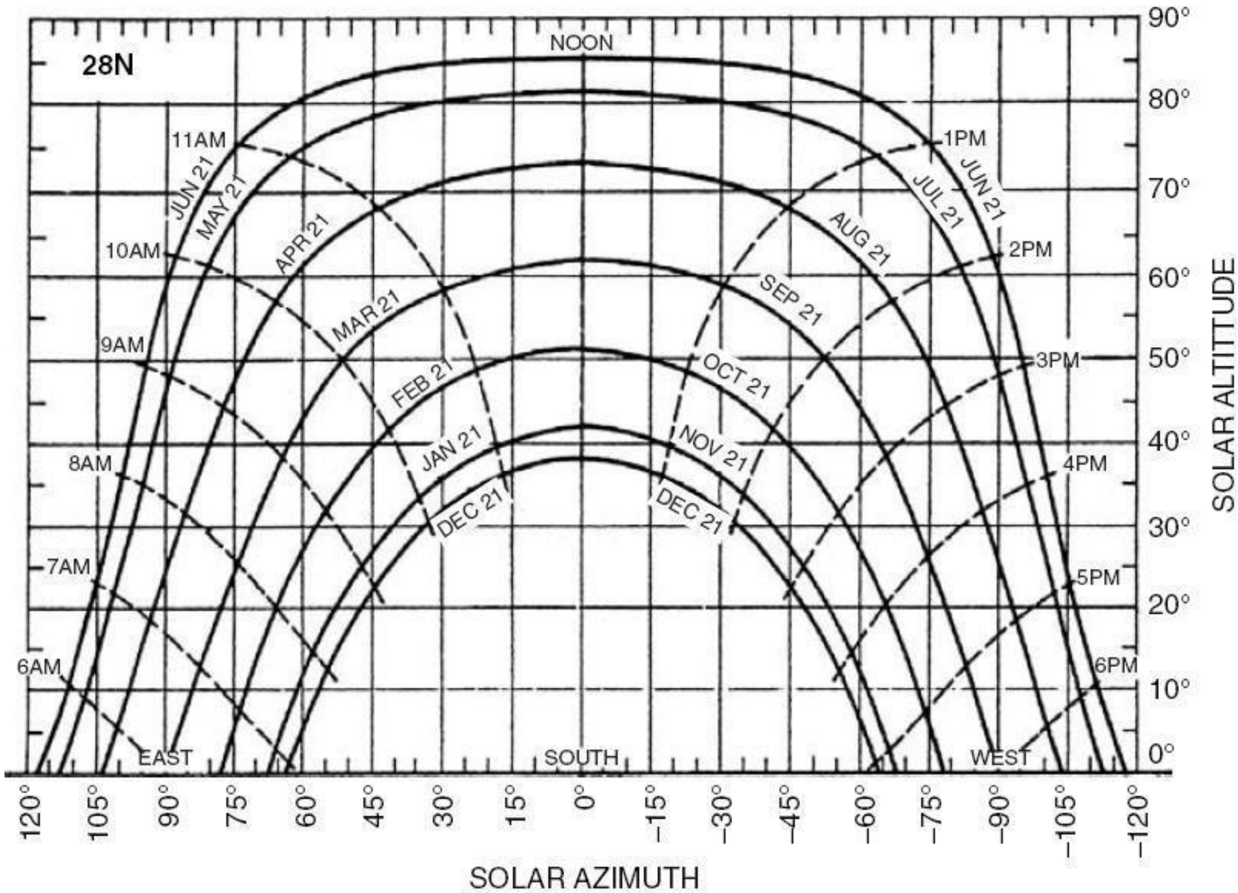



**Figure-12: A sun path diagram showing solar altitude and azimuth angles for28$^0$ latitude ( Close to Latitude of Delhi 28.7$^0$ )**

Similar sun path diagrams for other latitudes are given in Appendix B. As can be seen, in the spring and summer the sun rises and sets slightly to the north i.e azimuth angle is greater than 90$^0$ and our need for the azimuth test given earlier is apparent. At the equinoxes, it rises and sets precisely due east and due west i.e. azimuth angles are equal to 90$^0$ (Day and night hours are equal and that too everywhere on the planet) During the fall and winter the azimuth angle of the sun is never greater than 90$^0$.

----------------------------------------------------------------------------------------------------------

**5. Atmospheric effects on Solar Radiation:** Atmosphere has several effects on solar radiation on Earth's surface. The major effects for our Solar Cell applications are:

- 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 radiant energy at some wavelengths.
- Introduction of a diffused or indirect component into the solar radiation.

Local variations in the atmosphere (such as water vapor, clouds and pollution) have additional effects on the incident power, spectrum and directionality.

**In summary:**

On a clear day and when the sun is directly overhead, 70 percent of the solar radiation incident on the earth's atmosphere reaches the earth's surface undisturbed. Another 7 percent or so reaches the ground in an approximately isotropic manner after scattering from atmospheric molecules and particulates. The rest is absorbed or scattered back into space. These effects are effectively summarized and shown in the figure below.

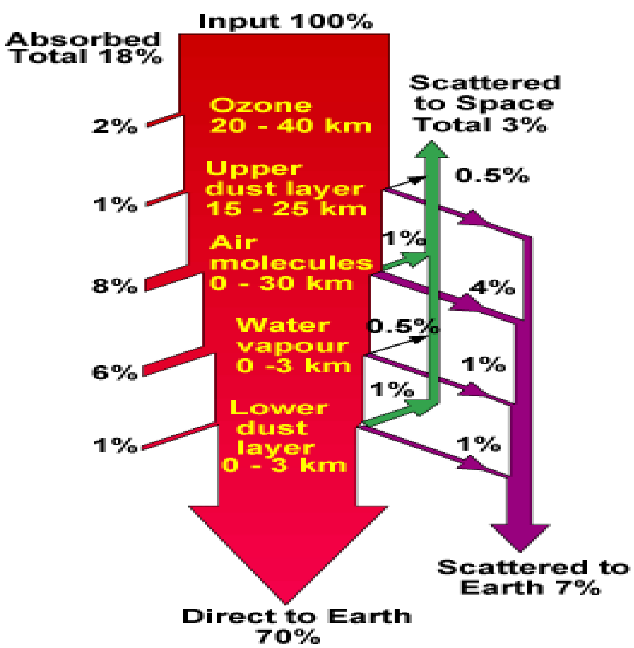



**Figure-13: Typical clear sky absorption and scattering of incidentsunlight**

## 6. Solar Radiation Measurement and Instrumentation:

Creation of solar energy data base at different locations is very important to select suitable locations for setting up of Solar power plants. We will study three such important instruments which measure solar radiation for setting up of Solar Radiation Data bases (i) Pyranometer: Total (direct and diffuse) radiation
(ii) Pyrheliometer: Direct radiation at normal incidence (iii) Shading-ring pyranometer: Diffuse radiation

**Pyranometer**: This instrument measures the total radiation arriving from all directions, including both **direct and diffuse** components i.e. it measures all of the radiation that is of potential use to a Solar Energy collecting system.
This instrument also known as solarimeter is generally mounted in a horizontal position away from tall objects so that the 2π field of view of the instrument covers the entire sky. It responds equally to the energy in all wavelengths.
The most important part of a pyranometer (or pyrheliometer) is the detector that responds to incoming radiation. The most accurate detectors use a stack of thermocouples, called a thermopile, to measure how much hotter a black surface becomes when exposed to sunlight relative to a White surface . They incorporatea sensor surface that consists of alternating black and white segments as shown inthe figure below.

**Figure-14: (a) A thermopile-type, black-and-white pyranometer (also known as'Eppley' Pyranometer in USA )**

**Pyrheliometer:** The pyrheliometer has a small field of view, around 6°, and tracks the sun continuously and thus measures the **direct normal beam radiation**. Since the field of view is larger than the 0.53° subtended by the solar disk, the reading is higher than the true direct flux by a few percent. Data collected by pyrheliometers are especially important for focusing collectors since their solar resource is pretty much restricted to just the beam portion of incident radiation. Hence Pyrheliometer measurements are also needed to predict the performance of tracking concentrator photovoltaic systems. Pyrheliometer stations are relatively rare. For example, among the approximately 100 stations that record solar radiation in the United States, only about 18 record direct normal **insolation.** Figure below shows a pyrheliometer with filters.

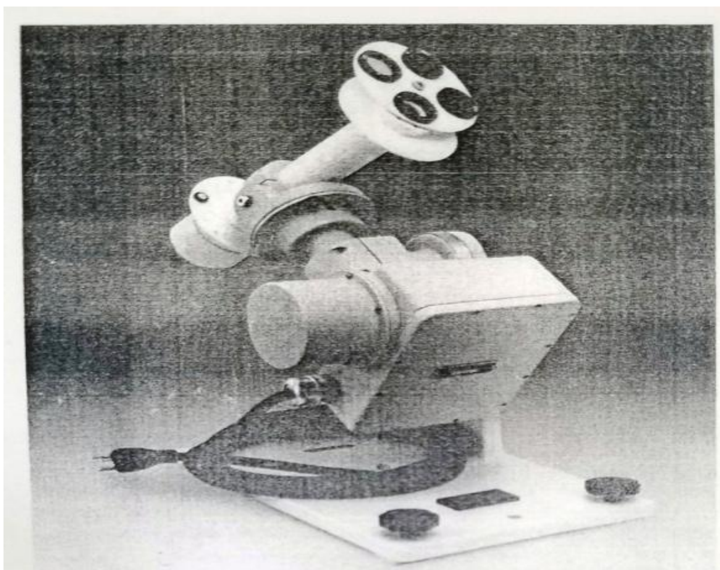


**Figure-15: Pyrheliometer**

**Shading-ring pyranometer**: A ring-shaped hoop sunshield is added to a pyranometer to exclude direct sunlight and thereby permits measurement of the diffuse components. When this reading is subtracted from that of a standard pyranometer, the result is the direct solar radiation. To keep the obstruction of the sky small, the ring is made narrow, shading only about 5°, and the position of the ring is changed every few days.

**Figure-16: Pyranometer with a shade ring to measure diffuse radiation**

**Solar Radiation Data base:**

Creation of solar energy data base at different locations is very important to select suitable locations for setting up of Solar power plants. Apart from the global network of ground monitoring stations deploying the Radiation measurement Instruments we have studied earlier, cloud mapping data taken by satellites is also now a very important complement to the Solar energy database. Solar irradiation data is needed at all levels of solar power development, from initial planning to large-scale project development or the calculations needed to size smaller systems. Solar energy data base , including **Global Horizontal Irradiation (GHI)** , **Direct Normal Irradiation (DNI)** and **PVOUT** is now available globally, for free, via the **Global Solar Atlas** **(link available)** which is provided by the **World Bank Group** **(link available).** The same website has downloadable global, regional and country maps available in high resolution.

## 7. Types of Solar Cells:

Solar cells are mostly Silicon based. It is the second most abundant element on earth, comprising approximately 20% of the earth's crust. Pure silicon almost immediately forms a layer of SiO2 on its surface when exposed to air, so it exists in nature mostly in $SiO_2$-based minerals such as quartzite or in silicates such as mica, feldspars, and zeolites. The raw material for solar cells and other semiconductors is naturally purified, high-quality silica or quartz ($SiO_2$) from mines. Such high quality Silica is converted into pure silicon in several energy-intensive chemical processing steps. We will study briefly about two most common types of Solar cells.

**Single crystalline (Mono Crystalline) silicon cells:**

They are manufactured by drawing small seed crystals slowly in molten silicon with required ‘p’ type of dopants added thus forming small P type Silicon Semiconductors. Usually the dopant is boron and the ingot is therefore a p-type semiconductor. This results in a solid single-crystal p type silicon ingot as shown inthe figure (a) below.

The manufacturing process is slow and energy intensive, resulting in high raw material cost. The ingot is sliced using a diamond saw into 200 to 400 μm (0.005 to 0.010 inch) thick wafers. During the above wafer fabrication, to form the p-n junction, a thin 0.1- to 0.5-μm n-type layer is created by diffusing enough donor (phosphorous) atoms into the top of the wafer to overwhelm the already existing acceptors.

The wafers are further cut into rectangular cells to maximize the number of cells that can be effectively mounted together on a rectangular panel. Unfortunately, almost half of the expensive silicon ingot is wasted in slicing ingot and forming square cells.

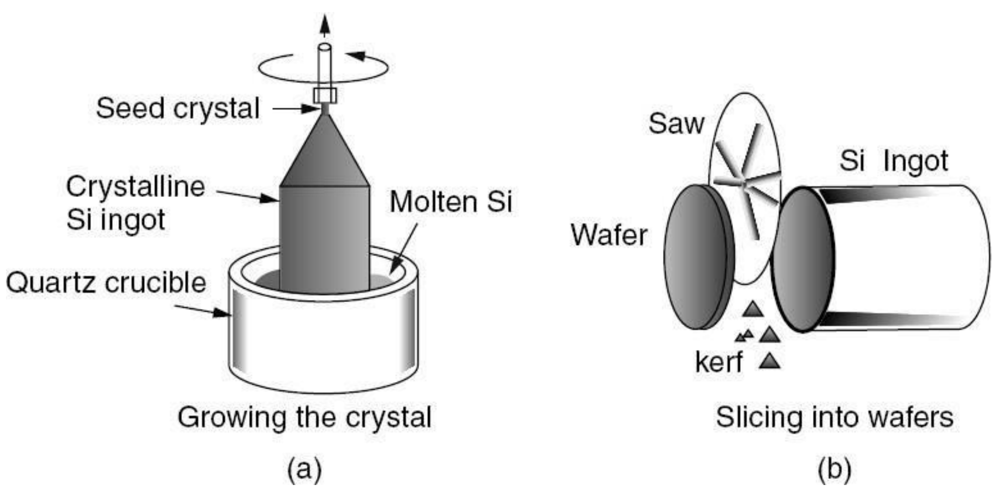



**Figure-17: The Czochralski method for growing single-crystal silicon.**

Since silicon is naturally quite reflective to solar wavelengths, some sort of surface treatment is required to reduce those losses. An antireflection (AR) coating of some transparent material such as tin oxide ($SnO_2$) is applied. These coatings tend to readily transmit the green, yellow, and red light into the cell, but some of the shorter-wavelength blue light is reflected, which gives the cells their characteristic dark blue color.

**Figure-18: Mono crystalline Silicon**

**PanelMerits and demerits of Mono crystalline Solar**

**Panels:**

**Merits:**

- Efficiency is high in the range of 15-24% as they are fabricated from the highest grade silicon, making them cost effective in the long term

**Demerits:**

- High initial cost and Fragility.
- Mono crystalline silicon is produced using the Czochralski process, whichinvolves significant silicon wastage.

**Multi (Poly) crystalline silicon cells:**

One way to avoid the above costly Single-Crystal Czochralski (CZ) Silicon is based on carefully cooling and solidifying a crucible of molten silicon, yielding a large, solid rectangular ingot. They are cut into smaller, more manageable blocks, which are then sliced into silicon wafers using either the saw or wire-cutting techniques as shown in the figure below.

This is relatively a fast and low cost process to manufacture thick crystalline cells. Instead of drawing single crystals using seeds, the molten silicon is cast into ingots. In the process, it forms multiple crystals and hence the name Multi crystalline or Poly Crystalline. The conversion efficiency is lower, but the cost is much lower, giving a net reduction in cost per watt of power.

Defective atomic bonds in the crystal formation increase recombination and diminish current flow, resulting in lesser cell efficiencies than monocrystalline cells. Figure below illustrates the casting, cutting, slicing, and grain boundary structure of these multicrystalline silicon (mc-Si) cells.

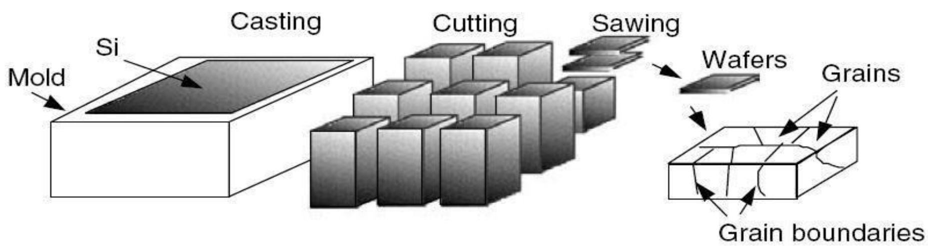



**Figure-19: Casting, cutting and sawing of silicon results in wafers with individualgrains of crystalline silicon separated by grain boundaries.**

The appearance of polycrystalline cells is not as uniform as the monocrystalline solar cells. They have a surface with a random pattern of crystal borders rather than the solid blue color of single-crystal cells. Due to increased recombination rate and reduced current flow, their efficiency is typically in the range of 12%- 14%, a value slightly lesser than the monocrystalline cells, but much higher than other solar technologies such as thin film.

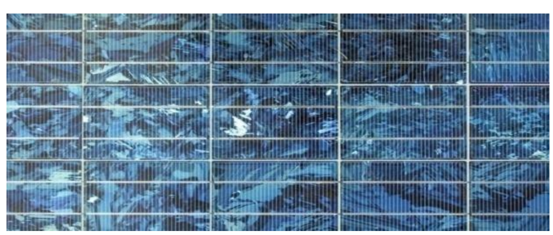


**Figure-20: Polycrystalline Silicon Panel**

**The major advantage** is the production process is simple, cost-effective, and reduces silicon waste compared to single crystal panels
**The major disadvantage** is lower conversion efficiency compared to mono crystalline panels due to the use of low purity silicon and faster fabrication technology

**Applications of Polycrystalline Solar Panels:**

Polycrystalline solar panels are the most commonly used PV panels on the Earth. They are offered in a wide range of power ratings, from 5 W to 250 W or more, for use in both residential and commercial installations.

## 8. Solar Cells

**Energy requirement:**

Photons with enough energy only can create hole-electron pairs in a semiconductor which contribute to the current flow. Photons can be characterized by their wavelengths or their frequency and their energy by the following relations: **(i)** $c = \lambda\nu$

Where ‘c’ is the speed of light ($3 \times 10^8$ m/s), ‘v’ is the frequency (hertz), ‘λ’ is thewavelength (m), and

**(ii)** $E = h\nu = Hc/\lambda$ ( Energy ‘E’ is inversely proportional to wavelength ‘λ’)

Where E is the energy of a photon (J) and h is Planck’s constant ($6.626 \times 10^{-34}$ J-s)

The energy required by a Photon to liberate Hole-Electron pairs depends on the Band gap energy of the particular semiconductor material used in the Solar cell. In the case of Silicon the band gap energy is 1.12 eV. The following example illustrates the energy required from a Photon to liberate Hole Electrons pairs in a Silicon Solar Cell.

**Example -3**: Required energy of Photons to Create Hole-Electron Pairs in Silicon: What maximum wavelength can a photon have to create hole–electron pairs in silicon? What minimum frequency is that? Silicon has a band gap of 1.12 eV (1 eV
= $1.6 \times 10^{-19}$ J)
Solution: From equation: $E = h\nu = Hc/\lambda$

the wavelength must be less than

$$\lambda \le hc/E = [6.626 \times 10^{-34}\ \text{Js} \times 3 \times 10^{8}\ \text{m/s}] / [1.12\ \text{eV} \times 1.6 \times 10^{-19}\text{J/eV}]$$
$$= 1.11 \times 10^{-6}\ \text{m} = 1.11\ \mu\text{m}$$

and from (8.1) the frequency must be at least

$$\nu \ge c/\lambda = 3 \times 10^{8}\ \text{m/s} / 1.11 \times 10^{-6}\ \text{m} = 2.7 \times 10^{14}\ \text{Hz}$$

For a silicon photovoltaic cell, photons with wavelength greater than 1.11 μm have energy **hν** less than the 1.12-eV band-gap energy needed to excite an electron. None of those photons can create hole-electron pairs capable of carrying current, so all of their energy is wasted. It just heats the cell. On the other hand, photons with wavelengths shorter than 1.11 μm have more than the energy needed to excite an electron. Since one photon can excite only one electron, any extra energy above the 1.12 eV needed is also dissipated as waste heat in the cell. Figure ( Figure -21) below shows a plot of the above equation (**E = hν = Hc/λ)** to illustrate this important concept.

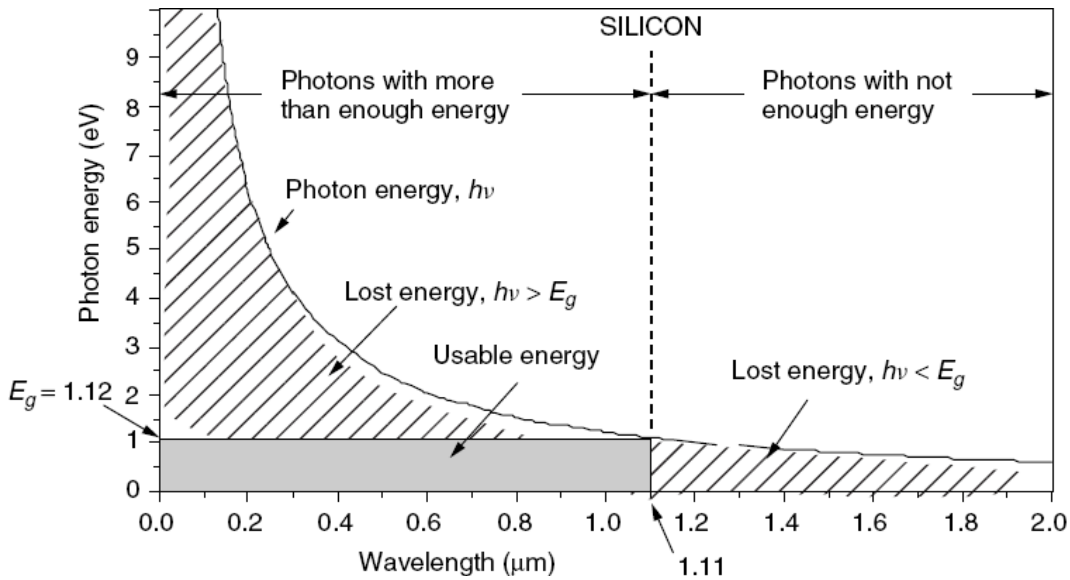



**Figure-21: Photons with wavelengths above 1.11 µm don't have the 1.12 eV needed to excite an electron, and this energy is lost. Photons with shorter wavelengths have more than enough energy, but any energy above 1.12 eV iswasted as well.**

These two phenomena relating to photons with energies above and below the actual band gap establish a maximum theoretical efficiency for a solar cell. To explain this aspect, the solar spectrum for an AM 1.5 is shown in the figure below. As can be seen Photons with wavelengths longer than 1.11 µm don't have enough energy to excite electrons (20.2% of the incoming solar energy).Those with shorter wavelengths can't use all of their energy, which accounts for another 30.2% unavailable to a silicon photovoltaic cell. And finally effective available energy is 49.6%.

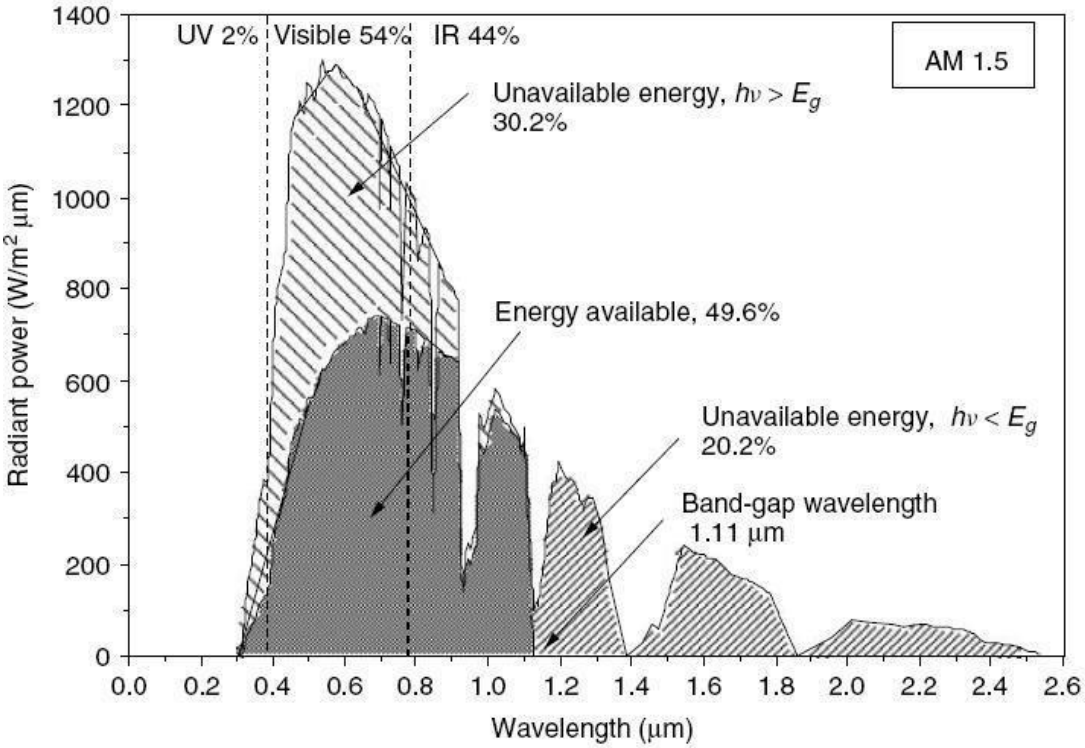



**Figure-22: Solar spectrum at AM 1.5. Photons with wavelengths longer than µm don't have enough energy to excite electrons (20.2% of the incomingsolar energy); those with shorter wavelengths can't use all of their energy, which accounts for another 30.2% unavailable to a silicon photovoltaic cell**.

**Effective available energy is**

**49.6%Band-Gap Impact on Photovoltaic Efficiency:**

Based on the above data and plots we can summarize and say **"the constraints imposed by silicon's band gap energy limit the efficiency of silicon to just under 50%".**

This summary gives us some insight into the trade-off between choosing a photovoltaic material that has a small band gap versus one with a large band gap.

- With a smaller band gap, cutoff wave length is larger, more solar photons have the energy needed to excite electrons, which is good since it creates more charges that will enable higher current to flow. However, a small band gap means that more photons have surplus energy above the threshold needed to create hole–electron pairs, which wastes their energy.

- High band-gap materials have the opposite combination. A high band gap means that fewer photons have enough energy to create the current carrying electrons and holes, which limit the current that can be generated. On the other hand, a high band gap gives those charges a higher voltage with less leftover surplus energy.

In other words, **low band gap** gives **more current** with **less voltage** while **high band gap** results in **less current** and **higher voltage**.

Typical efficiencies of most commonly used photovoltaic materials are : Silicon < 20% , GaAs < 25% , CdTe < 24% . It can be seen that the efficiencies are lesser than 20–25% range which is well below the 49.6% we found when we considered only the losses caused (a) photons with insufficient energy to push electrons into the conduction band and (b) photons with energy in excess of what is needed to do so. Other factors that contribute to the drop in theoretical efficiency include:

1. Only about half to two-thirds of the full band-gap voltage will be available across the terminals of the solar cell.
2. Recombination of holes and electrons before they can contribute to current flow.
3. Photons that are not absorbed in the cell either because they are reflected offthe face of the cell, or because they pass right through the cell, or because they are blocked by the metal conductors that collect current from the top of the cell.
4. Internal resistance within the cell, which dissipates power.

**Basic operation & working principle of solar cells:**

Solar cell is basically a PN Junction diode with special construction features so that the impinging Photons from Solar energy liberate adequate Electron hole pairs for generation of electric current form the Solar cell. Let us now see what happens in the vicinity of a p–n junction when it is exposed to sunlight. As photons are absorbed, hole-electron pairs are formed. If these mobile charge carriers reach the vicinity of the junction, the electric field in the depletion region will push the holes into the p-side and push the electrons into the n-side, as shown in the figure below. Thus p-side accumulates holes and the n-side accumulates electrons, which creates a voltage that can be used to deliver currentto a load. When an external load is connected the electrons that are getting collected flow from n-side through the load to p-side and recombine with the holes in the p-side.

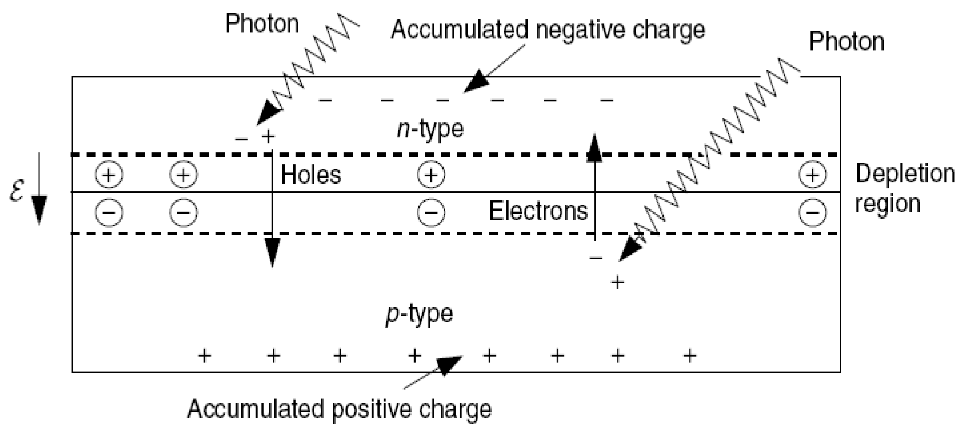



**Figure-23: when photons create hole–electron pairs near the junction, the electric field in the depletion region sweeps holes into the p-side and sweepselectrons into the n-side of the cell.**

If electrical contacts are attached to the top and bottom of the cell, electrons will flow out of the n-side into the connecting wire, through the load and back to thep-side as shown in the figure below . Since wire cannot conduct holes, it is only the electrons that actually move around the circuit. When they reach the p-side, they recombine with holes completing the circuit. By convention, positive current flows in the direction opposite to electron flow, so the current arrow in the figure shows current going from the p-side to the load and back into the n-side.

(Compare this with a conventional P-N junction when used as a forward biased Diode in which current flows in the opposite direction.)

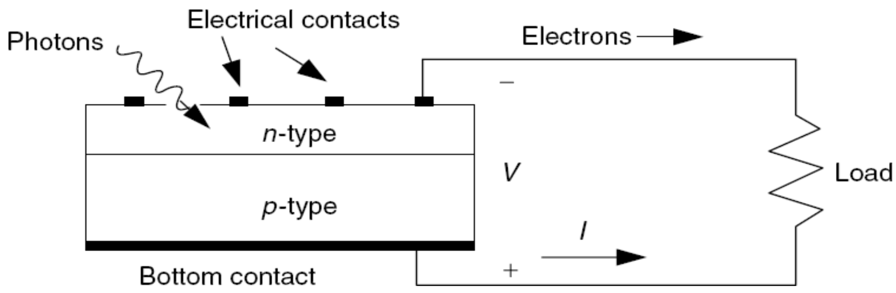



**Figure-24: Electrons flow from the n-side contact, through the load, and back tothe p-side where they recombine with holes. Conventional current I is in the opposite direction.**

## Construction of Solar Cell:

A solar cell is basically a junction diode, although its construction is little bit different from conventional p-n junction diodes. A very thin layer of n-type is grown on a relatively thicker p-type semiconductor. Then a few finer (very small) electrodes are fixed on the top of the **n-**type semiconductor layer.

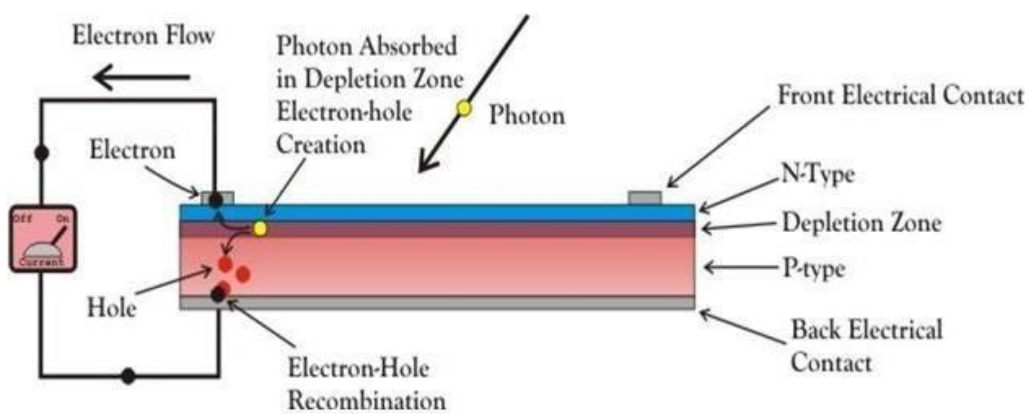



**Figure-25: Construction of a Solar Cell**

These electrodes are made small so that they do not obstruct light to reach the thin **n -** type layer. Just below the **n -** type layer lies the p-n junction. A very large current collecting electrode is provided at the bottom of the **p-**type layer. The entire assembly is encapsulated by a thin glass to protect the **solar cell** from any external damage.

## Important and Basic concepts of Solar cells:

- A solar cell or photovoltaic (PV) cell is a device that converts solar energy into electricity by the photovoltaic effect. A material or device that is capable of converting the energy contained in the photons of solar energy into an electrical current is said to be **photovoltaic.** Photovoltaics normally denoted by abbreviation PV is the field of technology and research related to the application of solar cells to harness solar energy.
- Generally, the term **Solar Cell** is reserved for devices intended specifically to capture Solar energy from sunlight, while the term **Photovoltaic Cell** is used when the source is unspecified.
- Basically, Photovoltaic generation of power is caused by radiation that separates positive and negative charge carriers in an extrinsic semiconductor material. When this happens in the presence of an electric field, these charges can be pulled/pushed to the nearby metal electrodes to produce a current in an external circuit. Such fields exist permanently at p-n junctions as 'built-in' electric fields and provide the required e.m.f. for useful power production.

- **In the case of Solar cells, the impinging radiation is the solar radiation and the required electric field is provided by a suitably designed p-n junction.**

- The term **cell** in **photovoltaic cells** or **solar cells** is a misnomer in the sense that it is the 'current' that is produced by the radiation photons and not a 'voltage'. The cell itself provides the source of electromagnetic force (voltage). It is to be noted that photoelectric devices are electrical current sources driven by a flux of radiation. A majority of photovoltaic cells are **silicon semi-conductor p-n junction devices.**

- It is very important to know that all **impinging photons also can not release the electrons from the atoms to become charge carriers**. A photon with short enough wavelength and high enough energy only can cause an electron in photovoltaic material to break free of the atom that holds it.

- A **solar cell** (also known as a photovoltaic cell or PV cell) is defined as an electrical device that converts light energy into electrical energy through the photovoltaic effect. A solar cell is basically a p-n junction diode. Solar cells are a form of photo electric cell, defined as a device whose electrical characteristics – such as current , voltage or resistance vary when exposed to light.

- Individual solar cells can be combined to form modules commonly known as solar panels. The common single junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 to 0.6 volts. By itself this isn't much – but we should remember that these solar cells are tiny. When combined into a large solar panel, considerable amount of renewable energy can be generated.

## 9. Important Formulae

**1. Air mass ratio $m = h2/h1 = 1/\sin\beta$**

Where h1 = path length through the atmosphere with the sun directly overhead, h2 = path length through the atmosphere to reach a spot on the surface, and $\beta$ = the altitude angle of the sun (see Figure) below .

**2. Solar declination, $\delta$**: The angle formed between the plane of the equator and a line drawn from the center of the sun to the center of the earth is called the **solar declination, $\delta$**. It varies between the extremes of ± 23.45°, as a simple sinusoid with a period of 365-days.

$$\delta = 23.45 \sin [360 / 365] (n - 81)]$$

Where n is the day number, with January 1 as day 1 and December 31 being day number 365.

**3.** The **altitude angle $\beta_N$** is the angle between the sun at **solar noon** and the local horizon directly beneath the sun. **Altitude angle $\beta_N$** is given by**:**

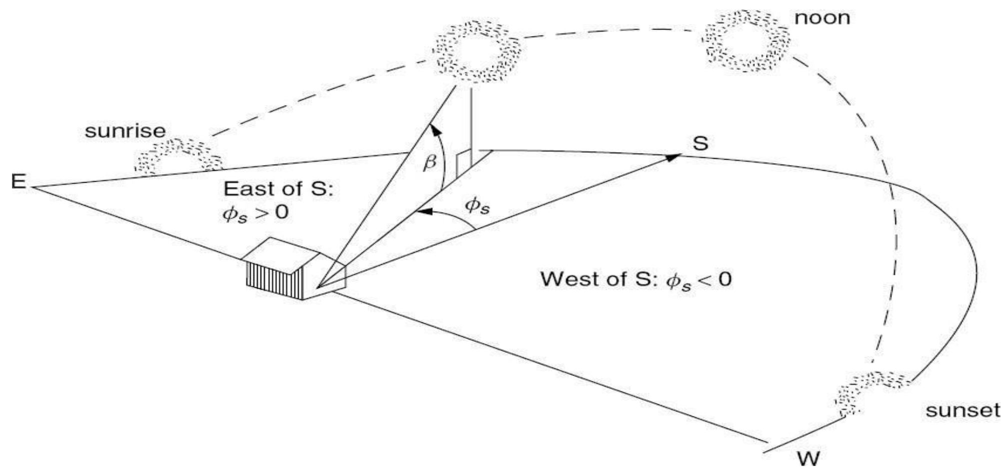
$$\beta_N = 90^\circ - L + \delta$$

where **L** is the **Latitude** of the site and **$\delta$** is the **Solar declination angle**

**4. Tilt angle :** Is that would make the sun's rays perpendicular to the module at noon and given by :

$$\textbf{Tilt angle} = 90 - \beta_N$$

**5. Altitude angle β** is the angle between the sun at **any given time** and the local horizon directly beneath the sun. The azimuth angle $\varphi_S$ is the angle between the true South and the sub point of the sun on the local horizontal. These aredepicted clearly in the figure below.




The following two equations allow us to compute the altitude and azimuth angles of the sun.

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta$$

$$\sin\varphi_S = \cos\delta \sin H / \cos\beta$$

Since the inverse of a sine is ambiguous, sin x = sin (180 − x), we need a test to determine whether the azimuth is greater than or less than $90^0$ away from south. Such a test is:

$$\text{if } \cos H \geq \tan\delta / \tan L \text{, then } |\varphi_S| \leq 90^0\text{; otherwise } |\varphi_S| > 90^0$$

Notice that **time** in these equations is expressed by a quantity called the **hour angle, H.**

**6. The 'Hour angle' : is the number of degrees that the earth must rotate beforethe sun will be directly over the local meridian (line of longitude).**

**7. Energy of** a Photon is given by: **E = hν**

Where **'E'** is the energy of a photon (J) **'h'** is Planck's constant ($6.626 \times 10^{-34}$ J-s)and **'v'** is the frequency (hertz) of light.

Further the speed, frequency and wavelength of light are related by the equation:

$$\mathbf{c = \lambda v}$$

Where **'c'** is the speed of light ($3 \times 10^8$ m/s), **'v'** is the frequency (hertz), **'λ'** is thewavelength (m).

## 10. Important Questions

1. Define and explain the terms: (a) Irradiance (b) Irradiation (c) Insolation.
2. Define and explain the terms: (a) Extraterrestrial Radiation (b) Terrestrial Radiation (c) Solar constant (d) Air mass Ratio (with a relevant sketch)
3. Sketch the spectrum of radiation from sun available at the top of the atmosphere, at the sea level and compare it with that of a black body @5800 K. Identify the regions of UV, Visible and Infrared bands in the sketch.
4. Draw neatly the orbit of the earth around the sun depicting the two solstices, two equinoxes, and their dates of occurrence.
5. Assuming an Earth centric Solar system draw, define and explain the terms with the help of appropriate sketches: (a) Latitude **'L'** (b) Solar Declination angle **δ** (c) Altitude angle at Solar noon '$\boldsymbol{\beta_N}$' (d) Tilt angle (e)Hour angle.
6. Find the optimum tilt angle for a south-facing photovoltaic module in Delhi (Latitude of Delhi is $28.7^0$N) at solar noon on 30th June.
7. Explain the effects of Atmosphere on the Terrestrial Solar Radiation.
8. (a)Draw a sketch and explain the terms Altitude angle **'β'** and Azimuth angle '$\boldsymbol{\varphi_S}$' of the sun and their importance.

   (b) Find the altitude angle **'β'** and azimuth angle '$\boldsymbol{\varphi_S}$' for the sun at 3:00 P.M. solar time in Hyderabad (Latitude of Hyderabad is $17.38^0$), on summer solstice.
9. Explain the working of the following radiation measurement instruments (a) Pyranometer (b) Pyrheliometer.
10. Write short notes on (i) Mono crystalline and (ii) Poly crystalline Solar cells.

11.(a)Draw neatly a plot of the Photon energy as a function of its wavelength and show clearly the Energy wasted below & above the cutoff wavelengths and the usable energy for a Silicon Solar cell.

(b) Explain clearly why the energy is wasted both below and above the cutoff wavelengths highlighting the dependence on band gap energy of the particular material chosen for the solar cell.

12.(a) Explain the working principle of a solar cell

(b) Explain the construction of a solar cell with a neat figure

(c) Write down clearly all the important concepts of Solar cells

## Appendix: Brief Review of the background Semiconductor Physics:

**To fully understand the performance of solar cells, presented in this unit and the next unit, the basic concepts of semi-conductors are essential and hence a review of basic semiconductor physics covering the important concepts is presented here.**

**Basic Semiconductor Physics:**

**Photo Voltaics** use semiconductor materials to convert sunlight into electricity. The technology for doing so is very closely related to the solid-state technologies used to make transistors, diodes, and all of the other semiconductor devices. The starting point for most of the world's current generation of photovoltaic devices, as well as almost all semiconductors, is pure crystalline silicon (tetravalent). Germanium is another tetravalent element and that too is a semiconductor but not useful in **PV**. Elements that play important roles in **photo voltaics** are **Silicon, Boron, Phosphorus, Gallium, Arsenic, Cadmium, and Tellurium.** Gallium and arsenic are used in GaAs solar cells, while cadmium and tellurium are used in CdTecells.

Both Silicon and Germanium are intrinsic semiconductors. To increase the conductivity of intrinsic semi-conductors, controlled quantities of specific impurity atoms like boron (trivalent: three valence electrons in the outer orbit) and phosphorus (pentavalent: five valence electrons in the outer orbit) are added to silicon to make them extrinsic semiconductors. This process is known as doping.

Trivalent Impurity atoms (valency less than that of the semi-conductor) enter the semi-conductor lattice and become electron acceptor sites known as Holes. These holes have an energy level within the band gap, but near the valence band. These holes which are effectively positively charged also move through the material as free charge carriers. Such a material is called a p-type material, having holes as majority carriers and electrons as minority carriers. P-type of material is called **Acceptor** since it accepts electrons.

Similarly when Pentavalent impurity atoms (valency greater than that of the semi-conductor) are added then an n-type material results, which has electrons as majority carriers and holes as minority carriers. N-type of semiconductors are called **Donors** since they donate electrons.

Silicon has 14 protons in its nucleus, and so it has 14 orbital electrons as well. As shown in the figure below, its outer orbit contains four valence electrons i.e. it is tetravalent. Those valence electrons are the only ones that matter in electronics, so it is common to draw silicon as if it has a +4 charge on its nucleus and four tightly held valence electrons, as shown in figure below.

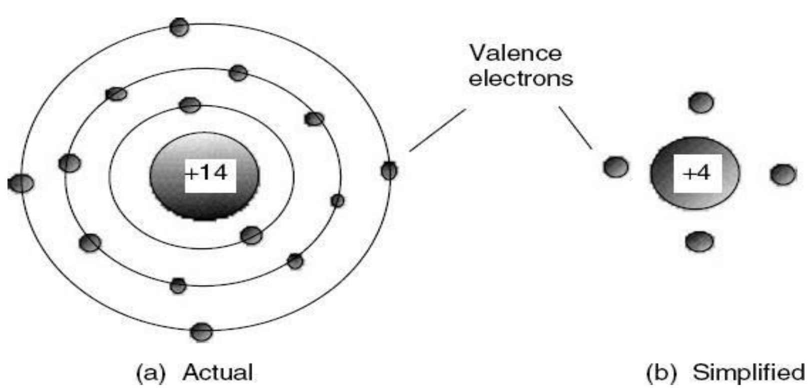



**Figure: Silicon has 14 protons and 14 electrons as in (a). Convenient shorthandis drawn in (b), in which only the four outer electrons are shown, spinning around a nucleus with a +4 charge.**

In pure crystalline silicon, each atom forms covalent bonds with four adjacent atoms in a three-dimensional tetrahedral pattern shown in the figure (a) below. For convenience, that pattern is drawn as if it were all in a plane, as in the figure *(b)* below.

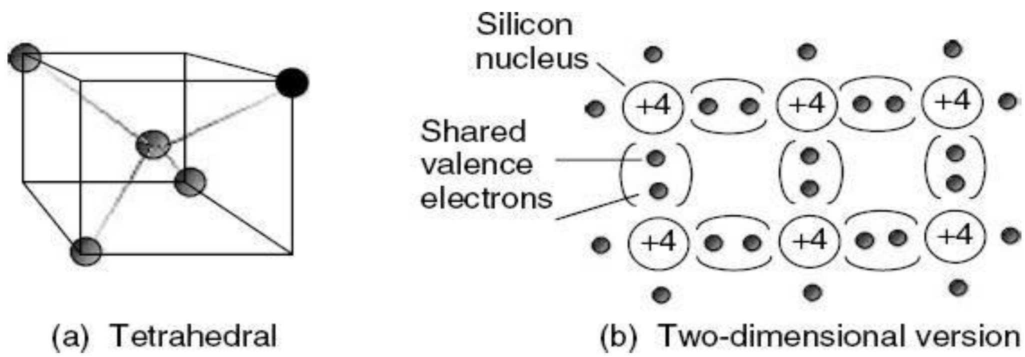



**Figure: (a) Crystalline silicon forms a three-dimensional tetrahedral structure (b) but it is easier to draw it as a two-dimensional flat array**

**The Band Gap Energy:** At absolute zero temperature, silicon is a perfect electrical insulator. There are no free electrons to roam around as there are in metals. As the temperature increases, some electrons will gain enough energy to free themselves from their nuclei, making themselves available to flow as electric current. The warmer it gets, the more electrons are there to carry current, so its conductivity increases with temperature (in contrast to metals, where conductivity decreases). That change in conductivity with temperature is used to advantage to make very accurate temperature sensors called thermistors. Silicon's conductivity even at normal temperatures is very low, and so it is referred to as a semiconductor. As we will see, by adding minute quantities of other materials, the conductivity of pure (intrinsic) semiconductors can be greatly increased.

Quantum theory describes the differences between conductors (metals) and Semiconductors (e.g., silicon) using energy-band diagrams such as those shown in the figure below. Electrons have energies that must fit within certain allowable (discrete) energy bands. The top energy band is called the conduction band, and it is those electrons within this region that contribute to current flow. As shown in the figure the conduction band for metals is partially filled, but for semiconductors at absolute zero temperature, the conduction band is empty. Even at room temperature, only about 1 out of $10^{10}$ electrons in silicon exists in the conduction band.

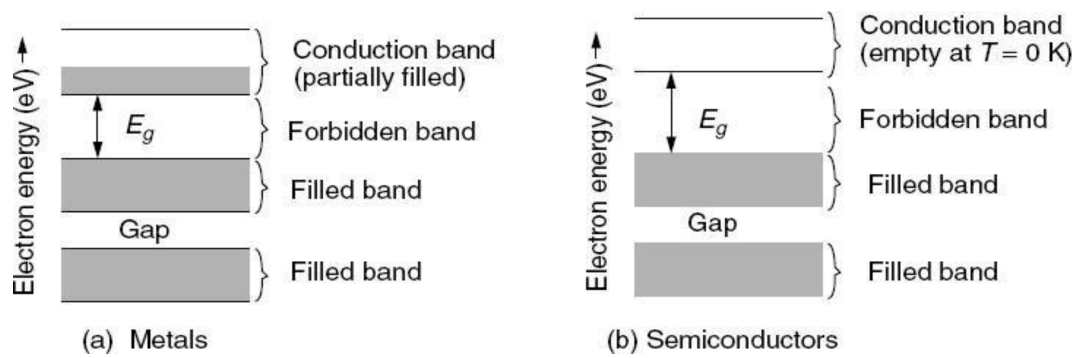



**Figure: Energy bands for (a) metals and (b) semiconductors. Metals have partially filled conduction bands, which allow them to carry electric current easily. Semiconductors at absolute zero temperature have no electrons in the conduction band, which makes them insulators.**

The gaps between allowable energy bands are called forbidden gaps, the most important of which is the gap separating the conduction band from the highest filled band below which is known as the valence band. The energy that an electron must acquire to jump across the forbidden band from valence band to the conduction band is called the **Band-gap energy**, designated $\mathbf{E_g}$. The units for band-gap energy are electron-volts (eV), where one electron-volt is the energy that an electron acquires when its voltage is increased by 1 V (1 eV = $1.6 \times 10^{-19}$ J).
The band-gap energy $\mathbf{E_g}$ for silicon is 1.12 eV, which means an electron needs to acquire that much energy to free itself from the electrostatic force that ties it to its own nucleus i.e. to jump into the conduction band from it's valence band .

**From where this energy can come?** We already know that a small number of electrons get that energy thermally. For photovoltaics, the energy source is photons of electromagnetic energy from light or the sun. When a photon with more than eV of energy is absorbed by a solar cell, a single electron jumps to the conduction band. When it does so, it leaves behind a nucleus with a +4 charge that now has only three electrons attached to it. That is, there is a net positive charge, called a **hole,** associated with that nucleus as shown in the figure below. Unless there is some way to sweep the electrons away from the holes, they will quickly recombine, removing both the hole and electron as shown in the figure (b) below. When recombination occurs, the energy that had been associated with the electron in the conduction band is released as a photon, which is the basis for Light-Emitting Diodes (LEDs).

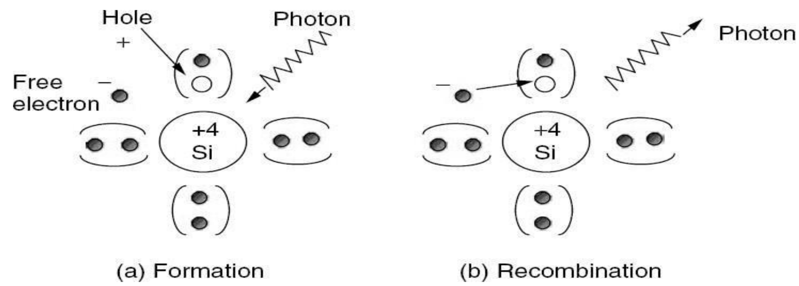



**Figure: A photon with sufficient energy can create a hole-electron pair as in (a).**
**The electron can recombine with the hole, releasing a photon of energy (b).**

It is important to note that not only the negatively charged electron in the conduction band is free to roam around in the crystal, but the positively charged hole left behind can also move. A valence electron in a filled energy band can easily move to fill a hole in a nearby atom, without having to change energy bands. Having done so, the hole, in essence, moves to the nucleus from which the electron originated, as shown in the figure below.

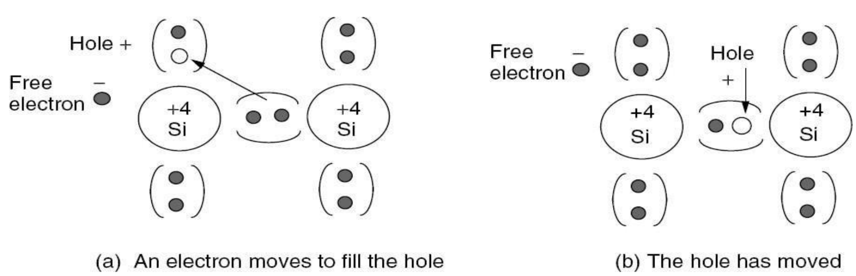



**Figure: When a hole is filled by a nearby valence electron, the hole appears to move.**

The important point here is that electric current in a semiconductor can be carried not only by negatively charged electrons moving around, but also by positively charged holes that move around.

**The p–n Junction:**

As already explained, when a solar cell is exposed to photons with energies above its band gap energy, hole - electron pairs are created. The problem is, these pairs can recombine and both charge carriers can disappear. To avoid such recombination and facilitate flow of current electrons in the conduction band must continuously be swept away from holes. In PVs, this is accomplished by creating a built-in electric field within the semiconductor itself by a suitably designed and formed p-n junction that pushes electrons in one direction and holes in the opposite direction. To understand how such a p-n junction works, let us first study in detail what are **'p'** and **'n'** type semiconductors and how they are joined to form an effective **p-n** junction which can serve as a Solar cell which can:

*a)* Efficiently enable Photons to generate hole – electron pairs from the semiconductor and also
*b)* Create an internal electric field which immediately pulls the electrons and holes in opposite directions before they recombine so as to create a useful current in an external circuit.

Since 'Silicon' is the most commonly used semiconductor in PV let us take it as the basic intrinsic semiconductor and study how it is converted into 'p' and 'n' type 'Extrinsic Semiconductor' for making a Solar cell.

**Structure of a p–n Junction:**

**'N' type semiconductor:** In this Silicon is doped with a pentavalent element such as phosphorus. These dopant atoms form covalent bonds with the adjacent silicon atoms in the crystal as shown in the figure (a) below.

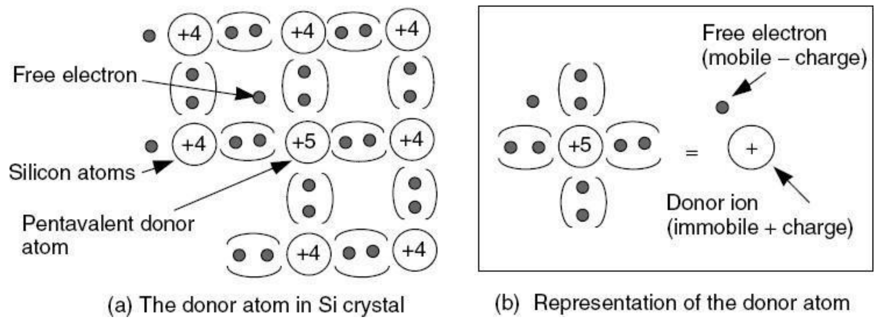



**Figure: A n-type material. (a) The pentavalent donor. (b) The representation ofthe donor as a mobile negative charge with a fixed, immobile positive charge.**

Four of its five electrons are now tightly bound, with the fifth electron left free on its own to roam around in the crystal. When that electron leaves the vicinity of its donor atom, there will remain a fixed +5 donor ion surrounded by only four negative valence electrons. i.e. each donor atom can be represented as a single, fixed, immobile positive charge plus a freely roaming negative charge as shown in figure (b). Since pentavalent elements donate electrons to the semiconductor into which they are doped, they are called donor atoms. Since there are now negative charges that can move around in the crystal, a semiconductor doped with donor atoms is referred to as an **"n-type material."**

**'P' type Semiconductor:** In this Silicon is doped with a trivalent element suchas boron. These dopant atoms form covalent bonds with the adjacent silicon atoms in the crystal as shown in the figure below.

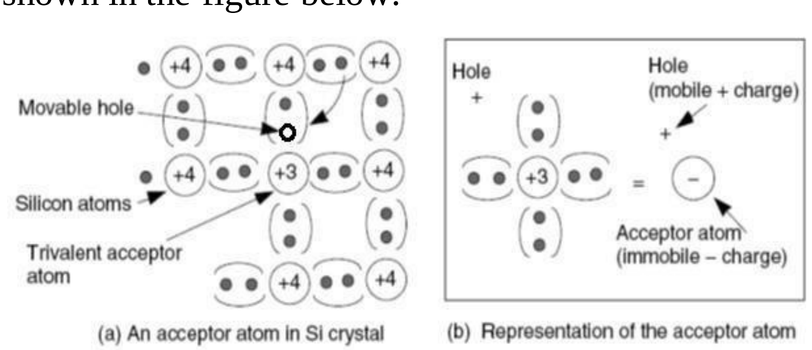



**Figure: In a p-type material, trivalent acceptors contribute movable, positively charged holes leaving rigid, immobile negative charges in the crystal lattice.**

Since each of these impurity atoms has only three electrons, only three of the covalent bonds are filled, which means that a positively charged hole appears next to its nucleus. An electron from a neighboring silicon atom can easily move into the hole, so these impurities are referred to as acceptors since they accept electrons. The filled hole now means there are four negative charges surrounding a +3 nucleus. All four covalent bonds are now filled creating a fixed, immobile net negative charge at each acceptor atom. Meanwhile, each acceptor has created a positively charged hole that is free to move around in the crystal as a charge carrier and , so this type of semiconductor is called a p-type material.

## Working principle of a p-n junction:

Now let us suppose that we join n-type material to a p-type material forming a junction between them. In the n-type material, mobile electrons move across the junction by diffusion. In the p-type material, similarly mobile holes move across the junction by diffusion in the opposite direction. As depicted in the figure below when an electron crosses the junction it fills a hole, leaving an immobile, positive charge behind in the n-region, while it creates an immobile, negative charge in the p-region. These immobile charged atoms in the p and n regions create an electric field that works against the continued movement of electrons and holes across the junction. As the diffusion process continues, the electric field that gets gradually built up counters the diffusion process until eventually (actually, almost instantaneously) all further movement of charged carriers across the junctionstops.

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**Diffusion current** is the movement of charge carriers caused by the gradient in the charge carrier concentration. Its direction depends on the slope of the carrier concentration gradient.

**Drift current** is the movement of charge carriers caused by the influence of an external electric field. Direction of the **drift current** is always **in the** direction of theelectric field.

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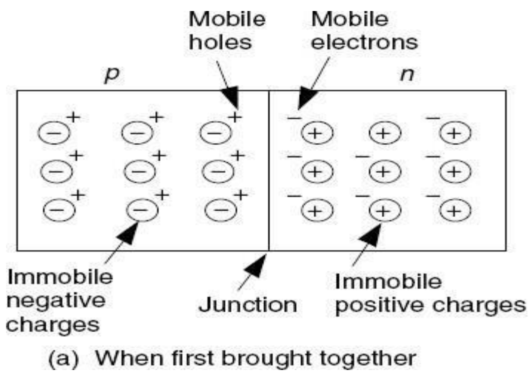


**Figure (a) When a p–n junction is first formed, there are mobile holes in the p-side and mobile electrons in the n-side. (b) As they migrate across the junction,an electric field builds up that opposes, and quickly stops, diffusion.**

The exposed immobile charges in the vicinity of the junction thus create an electric field, what is commonly known as a depletion region, meaning that the mobile charge carriers are depleted from this region. The width of the depletion region is only about 1 μm and the voltage across it is much less than 1 V. By convention, the arrows representing an electric field as shown in figure (b) below start on a positive charge and end on a negative charge The arrow, points in the direction that the field would push positive charges , which means that it holds the mobile positive holes in the p-region (while it repels the electrons back into the n-region)thus preventing further diffusion.

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# UNIT-II

# SOLAR & WIND ELECTRICAL SYSTEMS

## SOLAR CELL CHARACTERISTICS, BOS AND CLASSIFICATION OF PV SYSTEMS

## CONTENTS:

# 1. Solar Cell I-V Characteristics:

**The p–n Junction Diode:** Understanding the I-V characteristics of a Solar cell is very important and for that it is desirable to quickly recapitulate the I-V characteristics of a simple P-N junction diode given in the figure below.

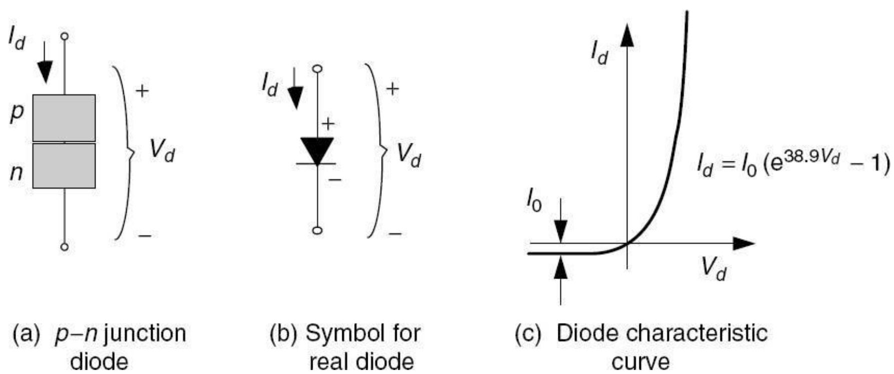



**Figure-1 : A p–n junction diode allows current to flow easily from the p-side to the n-side, but not in reverse. (a) p–n junction (b) its symbol (c) its characteristiccurve.**

If we apply a voltage $\mathbf{V_d}$ across the diode terminals with polarity as shown, a forward current would flow through the diode from the p-side to the n-side. But if we try to send current in the reverse direction, only a very small ($\approx 10^{-12}$ A/cm$^2$) reverse saturation current $\mathbf{I_0}$ will flow. This reverse saturation current is the result of thermally generated carriers with the holes being swept into the p-side and the electrons into the n-side. In the forward direction, the voltage drop across the diode is only a few tenths of a volt.

The voltage - current characteristic curve for the p–n junction diode is given by the following Shockley diode equation:

$$I_d = I_0(e^{qV_d/kT} - 1)$$

where $\mathbf{I_d}$ is the diode current in the direction of the arrow (A), $\mathbf{V_d}$ is the voltage across the diode terminals from the p-side to the n-side (V), $\mathbf{I_0}$ is the reverse saturation current (A), **q** is the electron charge ($1.602 \times 10^{-19}$C), **k** is Boltzmann's constant ($1.381 \times 10^{-23}$ J/K), and **T** is the junction temperature (K).

Substituting the above constants into the exponent of equation above for $\mathbf{I_d}$ gives

$$\frac{qV_d}{kT} = \frac{1.602 \times 10^{-19}}{1.381 \times 10^{-23}} \cdot \frac{V_d}{T(\mathrm{K})} = 11,600\frac{V_d}{T(\mathrm{K})}$$

A junction temperature of $25^0$C is often used as a standard, which when substituted in the Shockley diode equation gives the following diode current $I_d$.

$$I_d = I_0(e^{38.9V_d} - 1) \qquad (\text{at } 25^\circ\text{C})$$

**Example-1: A p –n Junction Diode.** Consider a p–n junction diode at 25◦C with a reverse saturation current of $10^{-9}$ A. Find the voltage drop across the diode when it is carrying the following currents:

a) No current (open-circuit voltage)  b) 1 A  c) 10 A

**Solution:**

a) In the open-circuit condition, $\mathbf{I_d}$ = 0, so from equation for $I_d$ we get $\mathbf{V_d}$ = 0.

b) With $\mathbf{I_d}$ = 1 A, we can find $\mathbf{V_d}$ by rearranging the above equation for '$\mathbf{I_d}$' :

$$e^{38.9V_d} = \left(\frac{I_d}{I_0} + 1\right)$$

Taking natural logarithms (to the base 'e') on both side and then dividing both sides by 38.9 we get

$$V_d = \frac{1}{38.9}\ln\left(\frac{I_d}{I_0} + 1\right) = \frac{1}{38.9}\ln\left(\frac{1}{10^{-9}} + 1\right) = 0.532 \text{ V}$$

c) with $\mathbf{I_d}$ = 10 A,

$$V_d = \frac{1}{38.9} \ln\left(\frac{10}{10^{-9}} + 1\right) = 0.592 \text{ V}$$

As can be seen, the voltage drop changes very little as the diode conducts more and more current, changing by only about 0.06 V as the current increased by a factor of 10. Often in normal electronic circuit analysis, the diode voltage drop when it is conducting rated current is about 0.6 V, which is quite in line with the above results.

**A Simple Equivalent Circuit of a Photovoltaic Cell:**

To derive the I-V characteristics of a Solar cell a simple equivalent circuit depictingall its characteristics is developed. It consists of a real PN Junction diode in parallel with an ideal current source as shown in the figure below. The ideal current source delivers current proportional to the solar **'Insolation'** to which it is exposed.

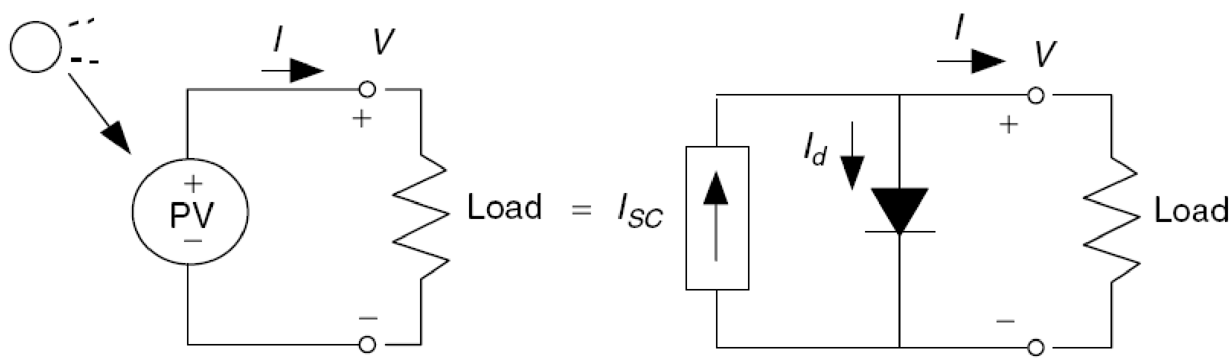



**Figure-2: A simple equivalent circuit of a photovoltaic (Solar) cell consists of a current source driven by sunlight in parallel with a real diode.**

There are two important conditions for the actual Solar cell in its equivalentcircuit as shown in the figure below (Figure -3). They are:

**(a)** The current that flows when the terminals are shorted together (the short- circuit current, $\mathbf{I_{SC}}$). When the leads of the equivalent circuit for the PV cell are shorted together, no current flows in the (real) diode since $\mathbf{V_d}$ = 0.That means $I_d$ =

0 and all the current from the ideal source $\mathbf{I_{SC}}$ flows through the shorted leads. Since that short-circuit current is $\mathbf{I_{SC}}$, the magnitude (maximum value) of the ideal current source itself is equal to $\mathbf{I_{SC}}$.

**(b)** The voltage across the terminals when the leads are left open (the open-circuit voltage, $\mathbf{V_{OC}}$). Since output terminals are open no current flows in the load i.e. **I =0**

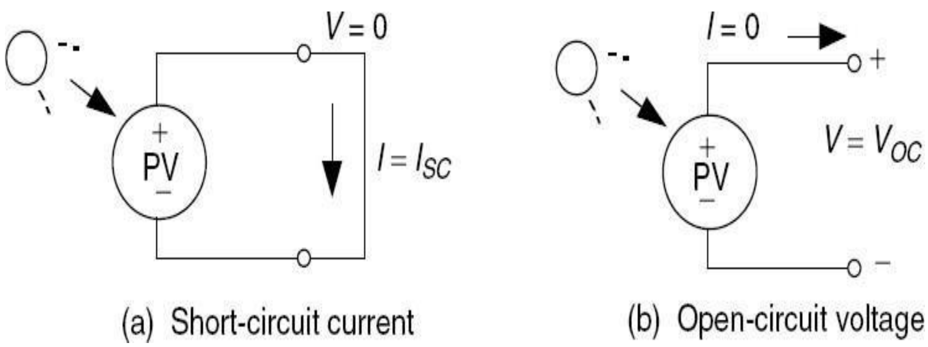



**Figure-3: Two important parameters for a Solar cell are the short-circuit current$\mathbf{I_{SC}}$ and the open-circuit voltage $\mathbf{V_{OC}}$.**

Now we can write a voltage and current equation for the equivalent circuit of the PV cell shown in figure (b) starting with

$$I = I_{SC} - I_d$$

and then substituting the value of $\mathbf{I_d}$ as per the Shockley equation into the above equation for **I** we get :

$$I = I_{SC} - I_0 \left(e^{qV/kT} - 1\right)$$

It is interesting to note that the second term in the above equation is just the diode equation with a negative sign. That means that a plot of the above equation is just $\mathbf{I_{SC}}$ added to the diode characteristic (in the first quadrant) turned upside- down. Figure below shows the current–voltage relationship for a PV cell when it is dark (no illumination) and light (with illumination) based on the above equation.

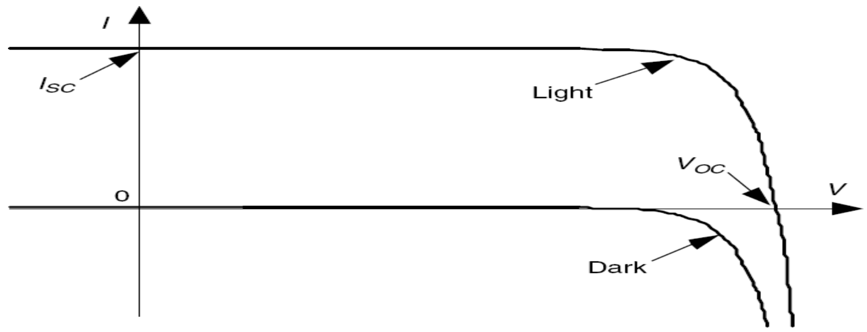



**Figure-4: Photovoltaic current–voltage relationship for "dark" (no sunlight) and"light" (an illuminated cell). The dark curve is just the diode curve turned upside-down. The light curve is the dark curve plus $I_{SC}$.**

When the leads from the PV cell are left open, **I** = 0 and we can solve the above equation (8.8) for the open-circuit voltage $\mathbf{V_{OC}}$ :

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

And at $25^0$C, both the above equations (8.8) and (8.9) become

$$I = I_{SC} - I_0(e^{38.9\ V} - 1)$$

And

$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

In both of the above equations (9&10) , short-circuit current, $\mathbf{I_{SC}}$, is directly proportional to solar **'Insolation'**, which means that we can now quite easily plot sets of PV current–voltage curves for varying sunlight for any given Solar Cell. Also, quite often laboratory specifications for the performance of photovoltaics are given per $cm^2$ of junction area, in which case the currents in the above equations are written as current densities. Both these points are illustrated in the following example.

**Example-2: I –V Curve of a Photovoltaic Cell.** Consider a 100-cm$^2$ photovoltaic cellwith reverse saturation current $\mathbf{I_0} = 10^{-12}$ A/cm$^2$. In full sun, it produces a short-circuit current of 40 mA/cm$^2$ at 25◦C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

**Solution:** The reverse saturation current of the cell $\mathbf{I_0} = 10^{-12}$ A/cm$^2$× 100 cm$^2$ = 1 × $10^{-10}$ A. At full sun $\mathbf{I_{SC}}$ is 0.040 A/cm$^2$ × 100 cm$^2$ = 4.0 A. From (8.11) the open-circuit voltage @ full sun light is:

$$V_{OC} = 0.0257 \ \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4.0}{10^{-10}} + 1\right) = 0.627 \text{ V}$$

Since short-circuit current is directly proportional to solar intensity, at half sun $\mathbf{I_{SC}}$ = 2A and the open-circuit voltage @ half sun light is:

$$V_{OC} = 0.0257 \ln\left(\frac{2}{10^{-10}} + 1\right) = 0.610 \text{ V}$$

Plot of the current using the equation $I = I_{SC} - I_0(e^{38.9 \text{ V}} - 1)$ @ full sun light @ half sun light along with the corresponding open circuit voltages is shown below.

It can be noticed that with reduced Sunlight intensity only $\mathbf{I_{SC}}$ gets reduced correspondingly but the reduction in $\mathbf{V_{OC}}$ is quite small ( 0.627 to 0.61 V )

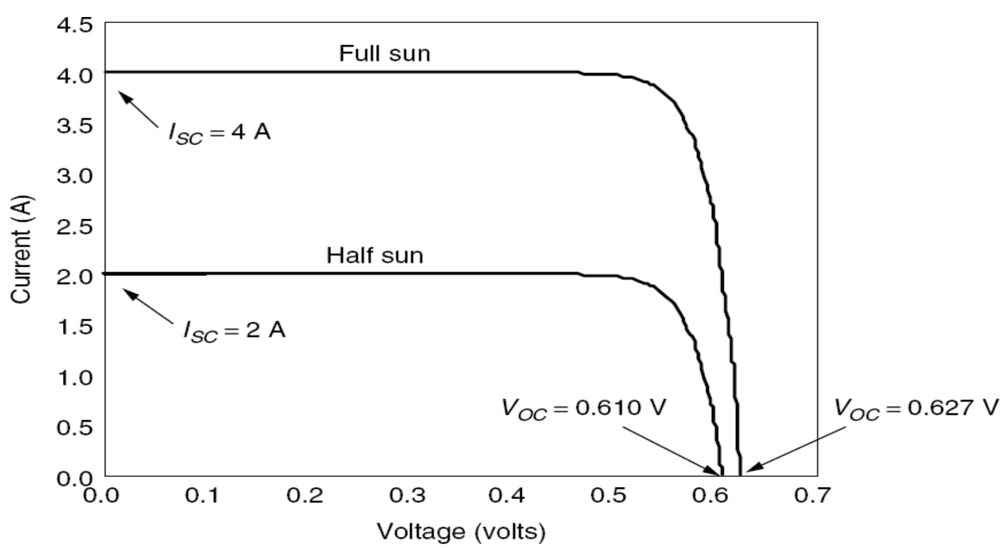
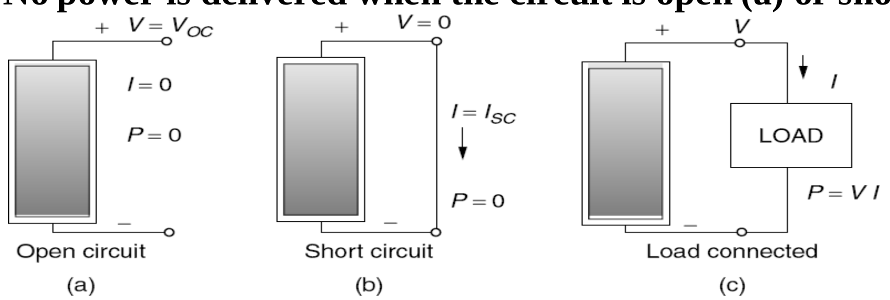



**Figure-5: I-V Plot corresponding to the above Problem**

## 2. Maximum Power Point

Let us consider, for the moment, a single PV module connected to a load as shown in the figure below. The load might be a dc motor driving a pump or it might be a battery, for example. Before the load is connected, the module sitting in the sun will produce an open-circuit voltage $\mathbf{V_{OC}}$, but no current will flow. If the terminals of the module are shorted together (which doesn't damage the module at all, by the way), the short-circuit current $\mathbf{I_{SC}}$ will flow, but the output voltage willbe zero. In both cases, since power is the product of current and voltage, no power is delivered by the module and no power is received by the load. When a load is connected, some combination of current and voltage will result and power will be delivered. To figure out how much power is delivered, we have to consider the **I-V** characteristic curve of the **module** as well as the **I-V** characteristic curve of the **load**.

**Figure-6: No power is delivered when the circuit is open (a) or shorted (b).**




**When the load is connected (c), the same current flows through the load andmodule and the same voltage appears across them.**

Figure-7 below shows a generic **I-V** curve for a PV module, identifying key parameters like open-circuit voltage $\mathbf{V_{OC}}$ and short-circuit current $\mathbf{I_{SC}}$ that we have explained**.** Also shown is the product of voltage and current, i.e., the power delivered by the module. At the two ends of the **I-V** curve, the output power is zero since either current or voltage is zero at those points. The **'Maximum Power Point'** (MPP) is that spot near the knee of the **I-V** curve at which the product of current and voltage reaches its maximum. The voltage and current at the MPP are designated as $\mathbf{V_m}$ and $\mathbf{I_m}$ in general and as $\mathbf{V_R}$ and $\mathbf{I_R}$ (rated voltage and rated current) under idealized test conditions.

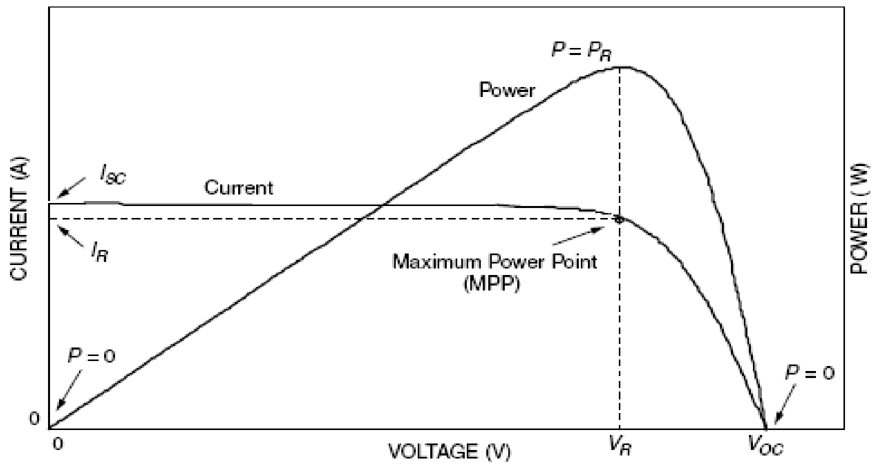



**Figure-7: The I –V curve and power output for a PV module. At the maximum power point (MPP) the module delivers the Maximum Power that it can underthe given conditions of sunlight and temperature .**

Another way to visualize the location of the Maximum Power Point is by trying to find the biggest possible rectangle that will fit beneath the **I-V** curve. As shown in the figure-**8** below the sides of the rectangle correspond to current and voltage, and so its area is power.

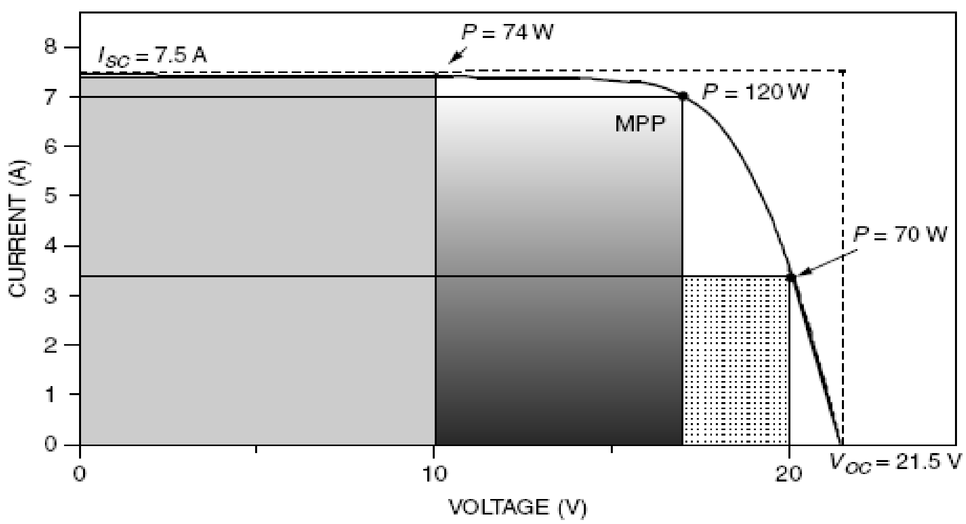



**Figure-8: The Maximum Power Point (MPP) corresponds to the biggest rectanglethat can fit beneath the I –V curve. The fill factor (FF) is the ratio of the area (power) at MPP to the area formed by a rectangle with sides $V_{OC}$ and $I_{SC}$.**

**The italicized material given below between the marked lines is not in syllabus. Furnished justfor information only.**

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*****Since PV I –V curves shift all around as the amount of insolation changes and asthe temperature of the cells varies, standard test conditions (STC) have been established to enable fair comparisons of one module to another. Those test conditions include a solar irradiance of 1 kW/m$^2$ (1 sun) with spectral distribution Shown in 'unit-1 Fig-22', corresponding to an air mass ratio of 1.5 (AM 1.5). Thestandard cell temperature for testing purposes is 25◦C (it is important to note that25◦ is cell temperature, not ambient temperature). Manufacturers always provideperformance data under these operating conditions, some examples of which areshown in table below. The key parameter for a module is its rated power; to helpus remember that it is dc power measured under standard test conditions, it hasbeen identified in the table below as PDC, STC. Later we'll learn how to adjustrated power to account for temperature effects as well as see how to adjust it togive us an estimate of the actual ac power that the module and invertercombination will deliver.

**Table: Examples of PV Module Performance Data Under Standard Test Conditions (1 kW/m2, AM 1.5, 25◦C Cell Temperature)**

| Manufacturer | Kyocera | Sharp | BP | Uni-Solar | Shell |
|---|---|---|---|---|---|
| Model | KC-120-1 | NE-Q5E2U | 2150S | US-64 | ST40 |
| Material | Multicrystal | Polycrystal | Monocrystal | Triple junction a-Si | CIS-thin film |
| Number of cells $n$ | 36 | 72 | 72 | | 42 |
| Rated Power $P_{DC,STC}$ (W) | 120 | 165 | 150 | 64 | 40 |
| Voltage at max power (V) | 16.9 | 34.6 | 34 | 16.5 | 16.6 |
| Current at rated power (A) | 7.1 | 4.77 | 4.45 | 3.88 | 2.41 |
| Open-circuit voltage $V_{OC}$ (V) | 21.5 | 43.1 | 42.8 | 23.8 | 23.3 |
| Short-circuit current $I_{SC}$ (A) | 7.45 | 5.46 | 4.75 | 4.80 | 2.68 |
| Length (mm/in.) | 1425/56.1 | 1575/62.05 | 1587/62.5 | 1366/53.78 | 1293/50.9 |
| Width (mm/in.) | 652/25.7 | 826/32.44 | 790/31.1 | 741/29.18 | 329/12.9 |
| Depth (mm/in.) | 52/2.0 | 46/1.81 | 50/1.97 | 31.8/1.25 | 54/2.1 |
| Weight (kg/lb) | 11.9/26.3 | 17/37.5 | 15.4/34 | 9.2/20.2 | 14.8/32.6 |
| Module efficiency | 12.9% | 12.7% | 12.0% | 6.3% | 9.4% |

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## 3. Cell efficiency & Fill Factor

Cell Efficiency: It is defined as the ratio of maximum electrical power output to the radiation power input to the cell and it is expressed in percentage. It is considered that the radiation power on the earth is about 1000 watt/square meter hence if the exposed surface area of the cell is A then total radiation power on the cell will be 1000 A watts. Hence the efficiency of a solar cell may be expressed as**:**

$$Efficiency(\eta) = \frac{P_m}{P_{in}} \approx \frac{P_m}{1000A}$$

Fill factor**:** This is another quantity that is often used to characterize module performance. The fill factor (FF) is the ratio of the power at the maximum power point to the product of $\mathbf{V_{OC}}$ and $\mathbf{I_{SC}}$

$$\text{Fill factor (FF)} = \frac{\text{Power at the maximum power point}}{V_{OC}\ I_{SC}} = \frac{V_R I_R}{V_{OC} I_{SC}}$$

So FF can be visualized as the ratio of two rectangular areas i.e. ratio of the rectangle area corresponding to MPP and the rectangle area corresponding to $\mathbf{V_{OC}}$ **&** $\mathbf{I_{SC}}$ (shown in dotted lines ) as shown in the earlier figure .

Fill factors of around 70–75% for crystalline silicon solar modules are typical.

## 4. Effect of irradiation and temperature:

I-V curves shift with change in cell temperatures and Insolation. Manufacturers often provide I –V curves that show how the curves shift as insolation and cell temperature changes. Figure below shows examples for a typical **(the Kyocera 120-W)** multi crystal (poly crystal) - silicon module described in the table above.

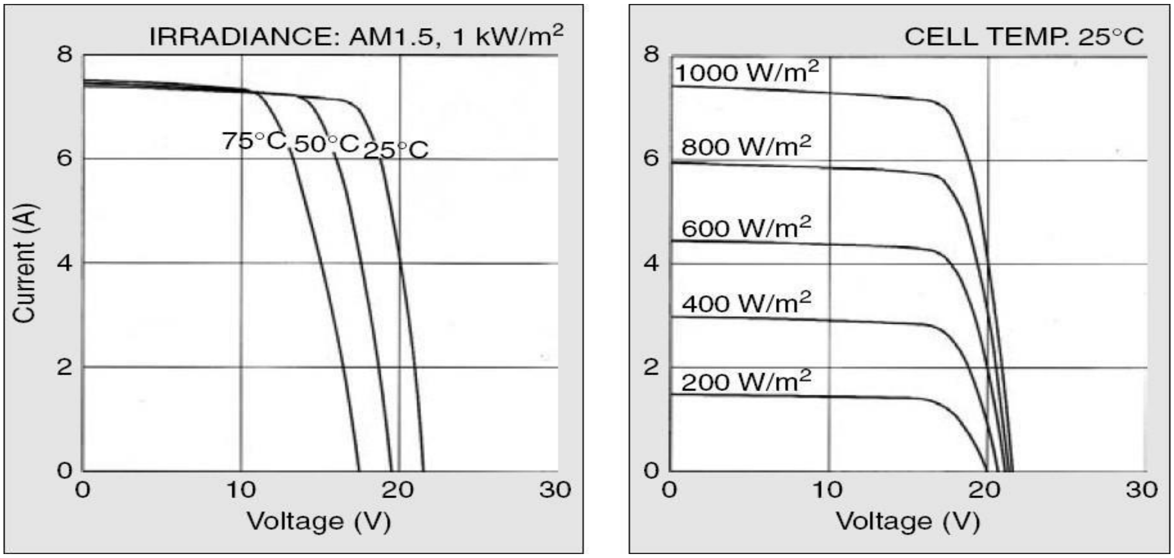


**Figure-9: Current-voltage characteristic curves under various cell temperatureand irradiance levels for a typical PV module.**

As can be seen in the figure above, as cell temperature **increases**, the open-circuit voltage **$V_{OC}$ decreases** substantially while the short-circuit current **$I_{SC}$ increases** only slightly thus effectively decreasing the maximum power and efficiency. Solar cells therefore perform better on cold, clear days than hot ones. Due to this significant shift in performance as cell temperature changes, the temperature needs to be included in any estimate of module performance.

Cell temperature varies not only because of ambient temperature change, but also because of change in insolation on the cell. Since only a small fraction of the insolation hitting a module is converted to electricity and carried away, most of that excess incident energy is absorbed and converted into heat.

## 5. Principles of Maximum Power Point Trackers:

Maximum Power Point Tracking, frequently referred to as MPPT, operates Solar PV modules in a manner that allows the modules to produce all the power they are capable of generating. MPPT is not a mechanical tracking system but it works on a particular tracking algorithm and it is based on electronic control. However

MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different. The voltage at which PV module produces maximum power is called 'Maximum Power Point' and this lies somewhere close to the knee point. We have already seen that this Maximum Power Point in theI-V characteristics of a Solar cell shifts with solar radiation and solar cell temperature (operating conditions).

We also know that the operating point of any power system i.e. the point at which maximum power is delivered by a source to a given load is the intersection point of the source line ( in this case the I-V characteristic of the Solar Module) and the load line( V-I characteristic of the Load). Let us consider a PV source having the I-V and P-V characteristics as shown in figure-9 (a) & (b) below and supplying power to three different loads $R_1$,$R_2$,and $R_3$. As the load resistance increases from $R_1$ to $R_2$ the operating point shifts from $A_1$ to $A_2$ and when load resistance increases from $R_2$ to $R_3$, the operating point moves from $A_2$ to $A_3$. As can be seen the maximum power is delivered by the module to the load when the load resistance is $R_2$. In figure (a) it is @ the knee point of the I-V curve and in figure (b) it is @ the peak power point of the P-V curve.

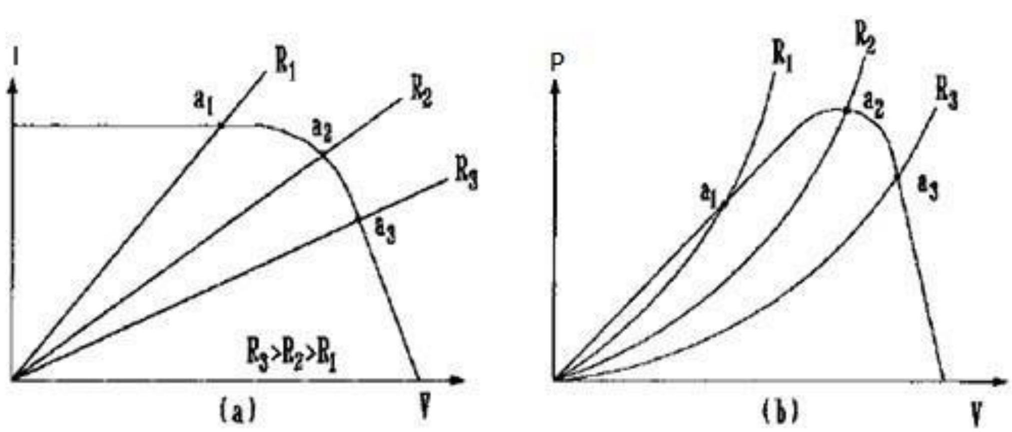


**Figure-9: Demonstration of the point that Maximum Power Transfer From agiven Solar cell @ given conditions takes place only with a specific load.**

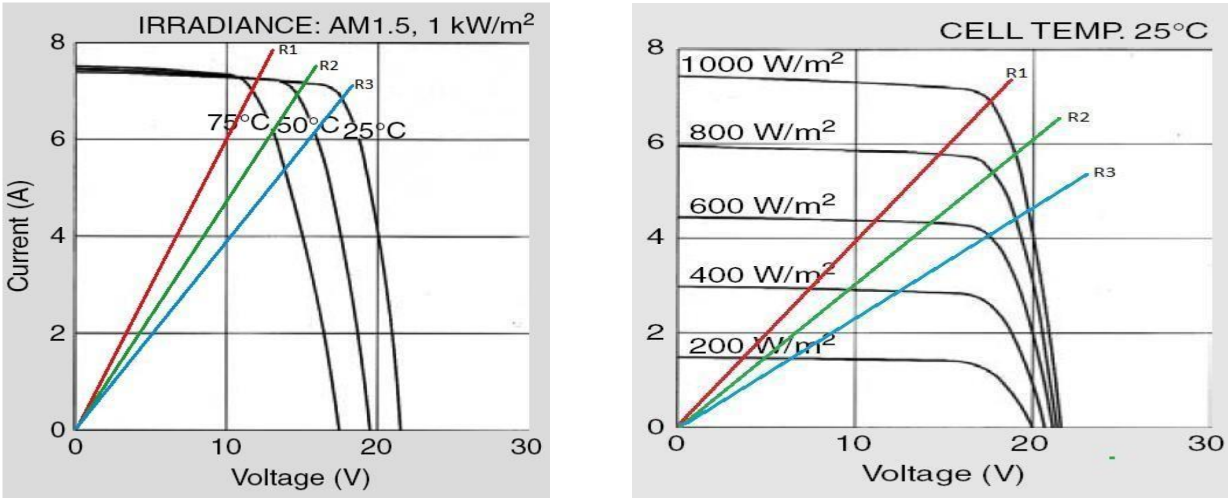


**Figure-10: (a) Effect of Temperature and (b) Insolation along with load on theshift of the Maximum Power Point.**

Further, when the temperature and solar radiation change along with load how the maximum power point shifts is shown in the figure-10 (a) and (b) above separately. These figures have been obtained by super imposing the differentload lines on the earlier curves showing how the MPP varies with insolation and cell temperature. These figures clearly demonstrate how tricky it is to match the source with load with so many variables i.e. Cell temperature, Insolation andLoad. From the above characteristics it can be observed that since a PV cell has an exponential relationship between current and voltage at higher voltages, maximum power generation and maximum power transfer to the load occur at the knee of the curve, when simultaneously the load resistance (V/I) is equal to the negative of the differential resistance at that point of the solar cell I-V characteristic.

Such critical matching of Source with the Load in so many variable conditions is precisely what is done by the MPPT acting as an interface between the Source and the Load.

Thus, in summary a MPPT can be considered as a high-efficiency DC-to-DC converter that functions as an optimal electrical interface which:

1. Has to first search and then establish the Input DC Voltage from a Solar module corresponding to the Maximum power point based on the prevailing operating conditions. And then
2. It has to convert this voltage into a DC Voltage again suitable to the varying Load conditions so as to extract the full power available from the Solar cell and deliver it to the load.

In order to carry out such complex functions Maximum power point trackers normally utilize microprocessor based controllers with sophisticated control algorithms.

Solar Power plants operate in both Off - Grid and ON - Grid modes. MPPTs make the best use of all the energy generated by the panels in both the cases as below:

- In the case of ON-Grid PV plants, MPPT is used to extract the maximum powerfrom a PV array, convert this to alternating current (AC) and forward the excess energy to the power grid after catering to the local Load. If the power is less, then it draws the additional power from the Grid.

- In the case of OFF - Grid PV plants where battery storage is necessary, MPPTs are used as charge controllers to extract the full power from the Solar cell and distribute between the load and for charging the battery as necessary.

## 6. PV Modules and Arrays:

**PV Modules:** An individual cell produces about one watt of power at about 0.5 V and they are of no practical use. Typically, it is a few square inches in size. Hence the basic building block for PV applications is a **module** consisting of a number of pre-wired cells in series, all encased in tough, weather-resistant packages in an area of several square feet. Such an encased panel is called a **Solar Module.**
Most solar PV panels have 30 to 36 cells connected in series. Each cell produces about 0.5 V in sunlight, so a panel produces 15V to 18 V. These panels are designed to charge 12-V batteries. A 30-cell panel (15 V) can be used to chargethe battery without a controller, but it may fail to charge the battery completely.

A 36-cell panel (18 V) will do better, but needs a controller to prevent overcharging.
The current depends on the size of each cell, and the solar radiation intensity. Most cells produce a current of 2 A to 3 A in bright sunlight. The current is the same in every cell because the cells are connected in series.
For cells wired in series, their voltages at any given current add. A typical module will have 36 cells.

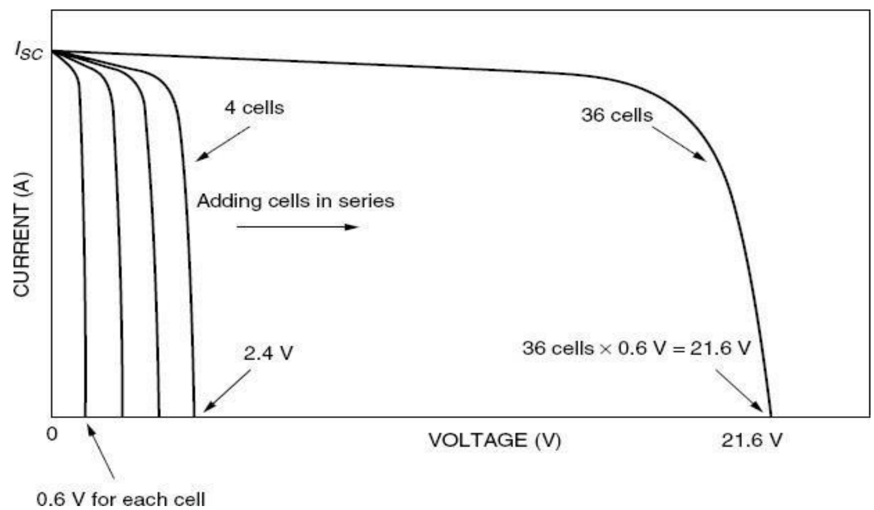


**Figure-11: For cells wired in series, their voltages at any given current add. A typical module will have 36 cells.**

**Arrays:** Multiple modules, in turn, can be wired in series to increase voltage and in parallel to increase current, the product of which is power.

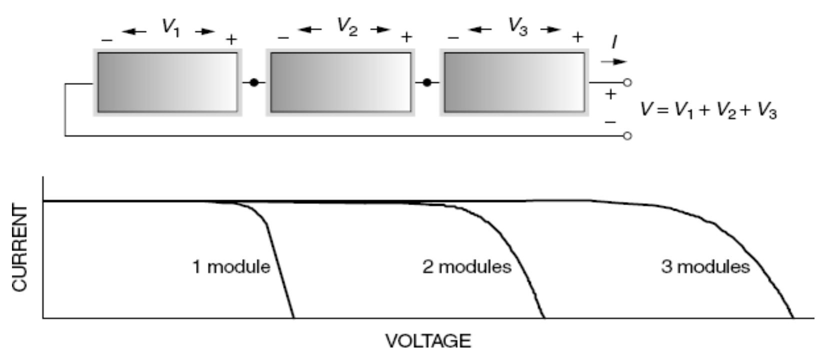


**Figure-12: Modules in series, at any given current the voltages add**

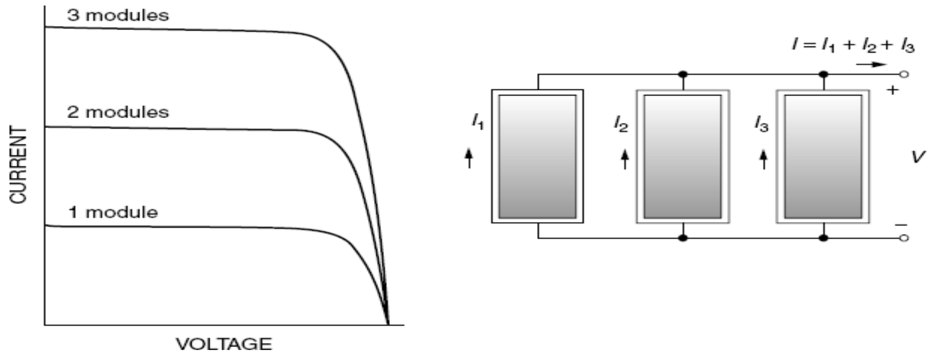


**Figure-13: Modules in parallel, at any given voltage the currents add.**

An important aspect in PV system design is deciding how many modules should be connected in series and how many in parallel to deliver the required energy. Such combinations of modules are referred to as an **array.** Figure below shows this distinction between cells, modules, and arrays.

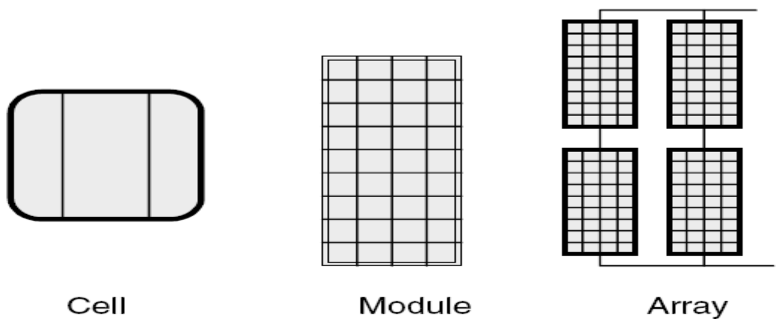


**Figure-14: Photovoltaic cells, modules, and arrays**

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Material in this portion is for information only. Not part of syllabus.

Figure below shows the actual construction of a module in a frame that can be mounted on a structure.

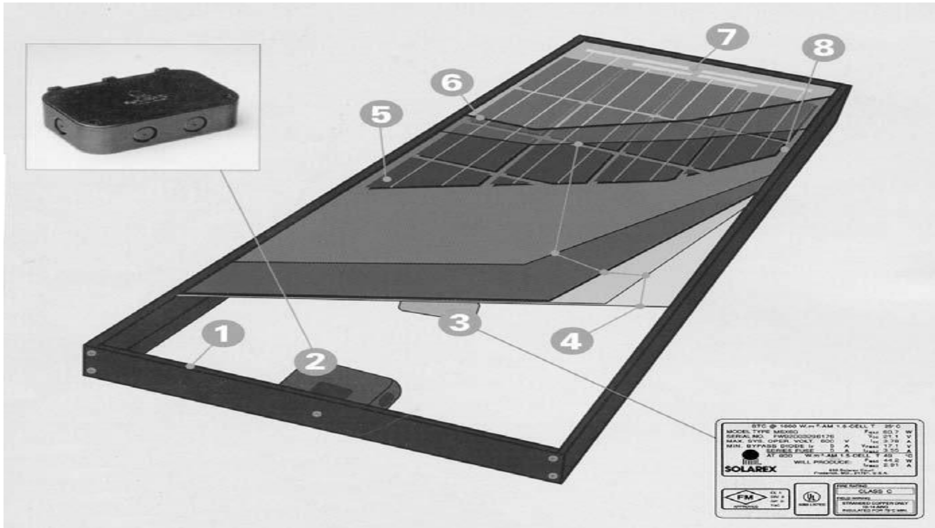


**Figure-15: Construction of pv module in Frame : 1) frame, 2) weatherproof junction box, 3) rating plate, 4) weather protection 5) PV cell, 6) tempered hightransmissivity cover glass, 7) outside electrical bus, 8) frame clearance.**

**Mounting of the Modules:**

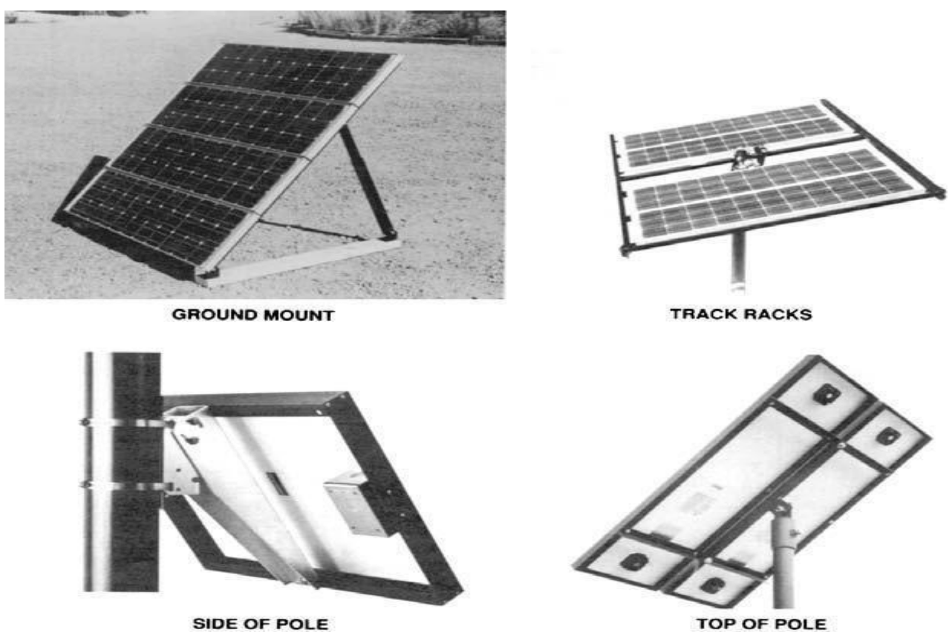


**Figure-16: PV module mounting methods**

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## 7. 0 Balance of systems:

The array of a set of PV modules by itself does not constitute the total PV power system. We need several other components and subsystems to have a complete solar power station. All other components and subsystems other than the main PV panels together are known as BOS (**B**alance **O**f **S**ystems).

The following are some of the major BOS components/subsystems: (1) Mounting Structure (2) Cables and Protection devices (3) Inverters (4) Energy Storage systems (Batteries) (5) Charge Controllers and will be explained briefly.

**Mounting Structure**

The PV module should be designed in such a way that it can withstand rain, hail, wind and other adverse conditions. The common aspects to be taken care of in the design and selection of the mounting structures are (i) Durability of the design (ii) Tilt angle (iii) Orientation and (iv) PV array shading. Correct and optimumTilting angle maximizes the efficiency of the solar PV module. Hence a welldesigned mounting structure apart from giving strength and capability to withstand high winds also serves as a PV module tilting structure which tilts the PV arrays at an angle determined by the latitude of the site location, to maximize the solar insolation falling on the panels. At any given location tilt is required in NS and EW directions to maximize the solar insolation on the panel. But normally tilt is given NS alone and in EW the Panel mount has to track the Sun from morning to evening. Normally low cost systems use fixed tilt in both axes. For EWif tracking feature is required it requires an electrical drive for the Mount. Similarly, shading has a significant effect on PV generation. Partial shading canreduce the system production up to 90 %. Thus, it is essential that the PV arraysare installed at a suitable location without any shading.

For PV array installation with multiple rows the shading de-rate factor should account for losses that may occur when a row shades an adjacent row.

## Cables and Protection Devices

The main purpose of cabling is to allow a safe passage of current. Appropriate cable sizing allows the current to be transferred within an acceptable loss limit to ensure optimal system performance. In order to establish connection between solar PV modules, charge controller, battery, Inverter and finally the Load, cables are needed. The size of the cable is determined based on the transmission length, voltage, flowing current and the conductor material. The cable in installation sites should be sized correctly. An undersized cable can lead not only to lower efficiency but also to fire hazards. In addition to the appropriate sizing, selection of relevant type of wire is also important in the case of solar PV application. For outdoor applications UV stabilized cable must be used, while normal residential wires/cables can be used indoors. This ensures the long term and safe functioning of the cable and hence reduction in the system ongoing maintenance.

## Inverters:

**Islanding** is the condition in which a distributed generator (DG) continues to power a location even though electrical grid power is no longer present. Islanding can be dangerous to utility workers, who may not realize that a circuit is still powered and proceed for service on live lines which is very dangerous. Additionally, without strict frequency control (without Grid frequency reference required for the local PV Plant is lost) the balance between load and generation in the islanded circuit is going to be violated, leading to abnormal frequencies and voltages. For those reasons, distributed generators must detect islanding and immediately disconnect from the circuit. This is called anti**-islanding**.

Some designs, commonly known as a **micro grid**, allow for intentional islanding. Incase of an outage, a micro grid controller disconnects the local circuit from thegrid on a dedicated switch and enables the distributed generator(s) to power the entire local load.

**Types of Inverters and Their Classification:**

Inverters can be classified based on three aspects. 1. Their basic design 2.Their topology, i.e. size, voltage and power level 3. Their utility based on the type of plant.

**Basic Design:**

Inverters can be classified by their output waveform into four categories: square wave, modified square wave, also called quasi-square wave, multilevel and sine wave (synthesized from a high frequency PWM). The square and quasi-square wave inverters are not recommended due to their poor quality waveform. Multilevel and sine wave inverters are considered to be the state of the art technology. The Multilevel inverter is based on low frequency and the sine wave inverter is based on high switching frequency. Multilevel inverters are the best available solution for high power applications. However, for medium and low power applications, there is not a clear tradeoff to make it more appealing than sine wave inverters, or vice versa. High frequency inverters favor compactness and reduced cost, while low frequency ones are claimed to have the best efficiency and robustness. The final choice of one inverter over the other depends on the application. In our application of stand-alone renewable energy systems (SARES), multilevel inverters have great potential with their reliability, surge power capacity and efficiency.

**Based on size:** Based on the size of the Solar Plant the solar PV inverters can be classified into (i) Centralized inverters (ii) String inverters (iii) Multi string invertersand (iv) Module integrated inverter.

**Centralized Inverters:**

In this category, a single large inverter is connected to many PV modules wired in series to form strings with up to 600 V/1,000 V of open-circuit voltage. All the solar PV modules are connected in strings, generating a sufficient high voltage to avoid further amplification and the strings are then connected in parallel to support high power to output as shown in the figure below.

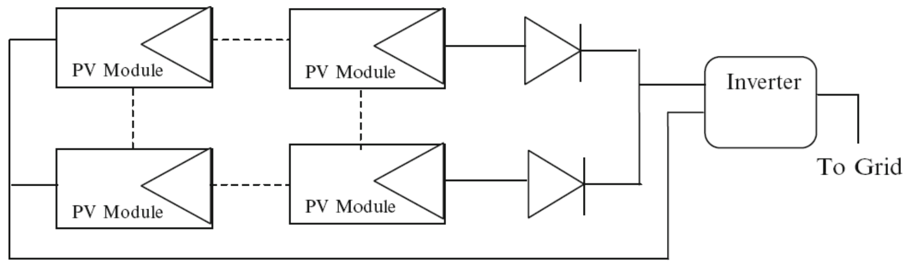


**Figure-17: Centralized Inverter**

The conversion efficiency of many central inverters is 95 % or higher, and they feature a relatively low unit cost per watt. However, central inverters have multiple drawbacks.

**String Inverters:**

This topology is introduced into the market relatively recently and is suitable for small loads. Figure below shows string of PV modules connected in series with an Inverter. With such a single string load current would be limited

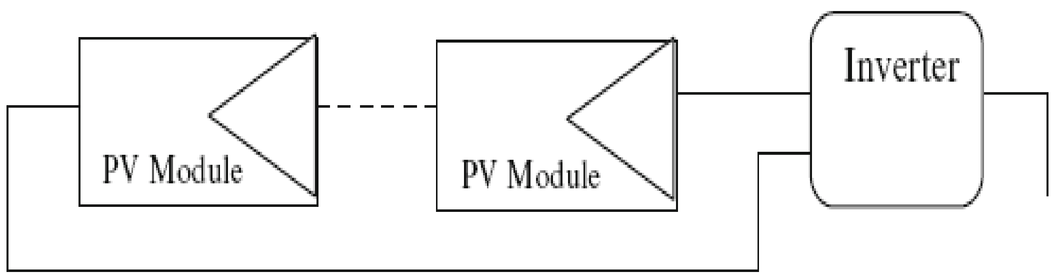


**Figure-18: String inverters**

**Multi-string Inverters:**

The above mentioned current limitation can be overcome n this configuration shown below. **DC-DC converter** is implemented for each string for MPP tracking and power combination of different string to a DC bus.

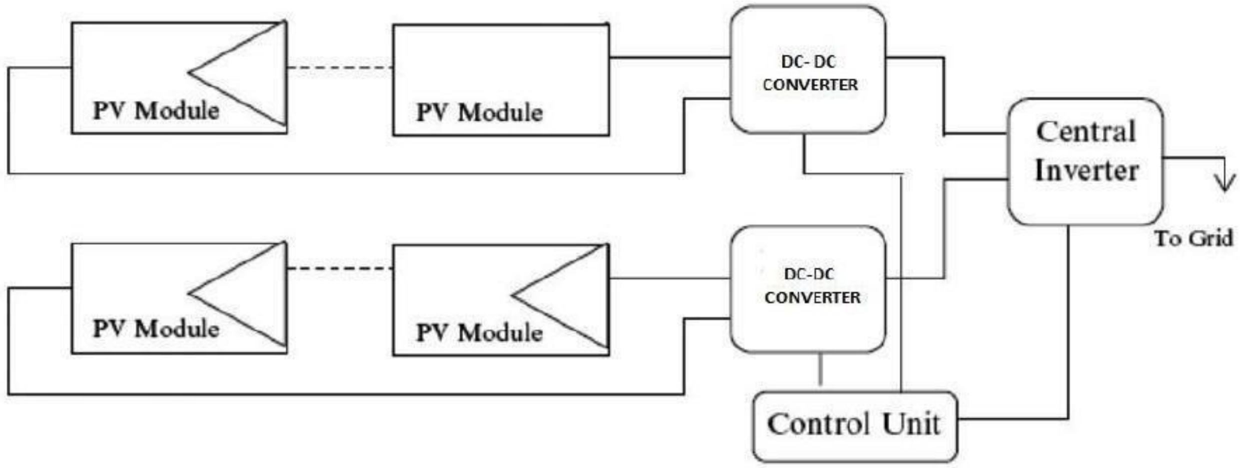


**Figure-19: Multi-string inverters**

Multi-string inverter features optimal MPP tracking for a single string of PVs. A bigpower stage works as a grid connected half bridge inverter without transformer. The multi-string inverter is useful when PV strings of different rated power, different orientation are combined.

**Module Integrated Inverter/Micro-inverters:**

Micro inverters are complete, environmentally protected integrated units consisting of solar cells, inverter, and other components, designed to generate ACpower with a single unit.

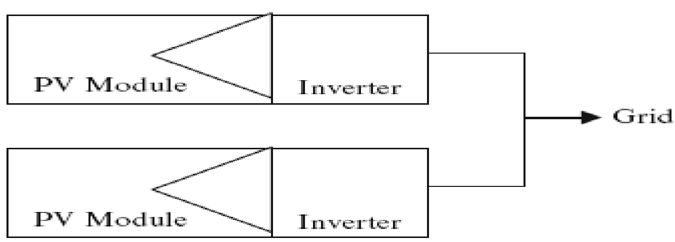


**Figure-20: Micro-Inverters**

The micro-inverter, also called AC module is the integration of PV and inverter into one electrical device. In an AC module, a micro-inverter is directly integrated with a PV panel, yielding a module that natively generates grid-compatible AC power.

**Batteries:**

In off-grid (Stand alone systems) and critical applications (such as back up in Grid connected systems), for storing the energy output from Solar PV systems energy storage systems are required. The most common medium of storage in PV systems are batteries or a battery bank depending upon the backup duration /capacity requirements of the specific system. There are many types of batteries suitable for use in a PV system for energy storage like lead acid batteries, alkaline batteries, nickel–cadmium batteries, and sealed batteries the most common type being lead acid batteries. One of the most expensive subsystems in the Standalone PV system is the batteries. Presently a lot of R&D work is going on in the field of batteries and other Energy storage systems for their effective and efficient use not only in Solar PV Systems but also in wind energy systems and Electric vehicles.

**The primary functions of batteries in a PV system:**

(a) Energy Storage Capability and Autonomy: to store electrical energy when it is produced by the PV array and to supply energy to electrical loads as needed or on demand.
(b) Voltage and Current Stabilization: to supply power to electrical loads at stable voltages and currents, by suppressing or 'smoothing out' transients that may occur in PV systems.
(c) Supply Surge Currents: to supply surge or high peak operating currents to electrical loads or appliances.

**Important aspects of batteries in PV system:**

**Sizing:** Batteries play a vital role in terms of total plant efficiency, performance and maintenance cost of standalone (OFF Grid) systems and at the same time take a substantial portion of the total cost of a Standalone Solar power plant. Lower sizing results in reduction of battery life due to higher Depth of Discharge (DOD %). Hence their sizing must be carried out carefully optimizing both cost and performance.

**Selection:** Selecting the suitable battery for a PV application and further their effective use depends on many factors and requires a comprehensive knowledge on the various types of batteries, their merits & demerits from the point of view of quality, reliability, charge discharge characteristics, expected nominal life and finally cost. Considerations in battery subsystem design also include the number of batteries in series and parallel, over-current and disconnect requirements. In the case of lead acid batteries, when used for high energy storage as a big bank, storage with proper ventilation is also to be addressed from safety point of view.

**Charge discharge rates:** A higher current discharge than the rating will dramatically reduce the battery life. This can be avoided by carefully sizing the battery according to the 'C-rating'. It signifies the maximum amount of current that can be safely drawn from the battery to provide adequate back up and without causing any damage. A discharge rate more than the C-ratings, may cause irreversible capacity loss due to the fact that the rate of chemical reactions taking place in the batteries cannot keep pace with the current being drawn from them. For such effective use and better performance, the batteries are charged and discharged using charge controllers.

**Charge controllers:**

A charge controller, charge regulator or battery regulator limits the rate at which electric current is added to or drawn from electric batteries. It prevents overcharging and overvoltage, which can reduce battery performance or lifespan, and may also pose a safety risk. To protect battery life, charge controller prevents battery from deep discharging or it will perform controlled discharges, depending on the battery technology. The terms "charge controller" or "charge regulator" may refer either to a stand-alone device, or to a control circuitry integrated within a battery pack, battery-powered device, or battery charger.

Solar Charge Controllers are controllers which regulate the power output or the DC output voltage of the solar PV panels to the batteries. Charge controllers take the DC output voltage as the input voltage and convert into same DC voltage but at a level required for battery charging. These are mostly used in off grid scenario and use Maximum Power Point Tracking scheme to maximize the output efficiency of the Solar PV Panel.

Working Principle**:** A solar-charge controller monitors voltage across the battery and disconnects the battery from the PV array or diverts the power away from the battery when it is fully charged. This can be achieved by short circuiting the PV array (shunt regulator) or by disconnecting the positive and negative terminals. (Open-circuited series regulator) In addition to a shunt/series regulator, an auto cut off switch is also provided, which disconnects the electrical load for very low battery voltage. This is referred to as a "low-voltage disconnect function."
The solar-charge controller (SCC) is provided between the solar PV panel and the batteries as shown in the figure below.

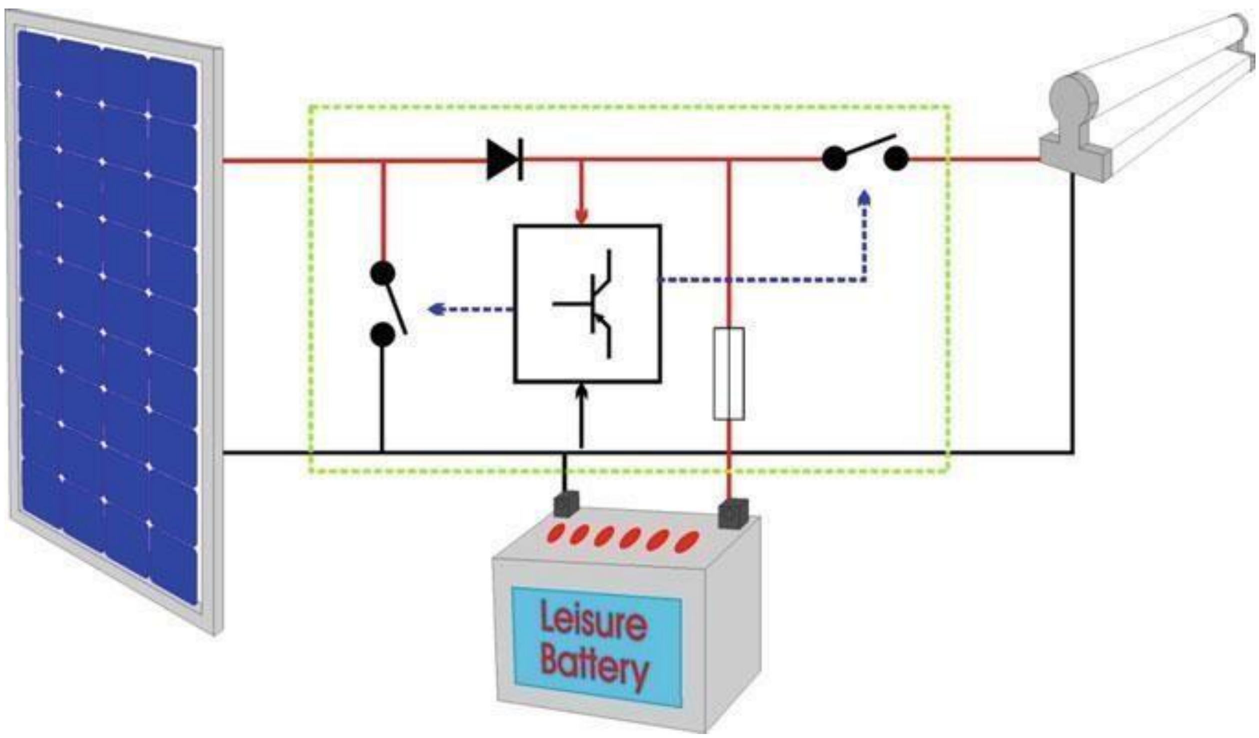


**Figure-21: Circuit diagram of a solar-charge controller**

# 8.0 Classification of PV systems:

Photovoltaic power systems can be classified according to several criteria based on their size, physical location, functional & operational requirements, their subsystem configurations, how the equipment is connected to other power sources , electrical loads etc. The two principal classifications are 'Grid- connected' or 'Utility-Interactive systems' and 'Stand-alone systems'. Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be combined with other energy sources and energy storage systems. When they are connected and operate with other Energy sources they are termed as 'Hybrid Systems'. It is difficult to draw a fine line between the various types of PV systems that arebeing designed and commissioned because of several attributes commonly shared by any system. However the most commonly adopted classifications are:

**Based on size and Location:**

1. Central PV Power Station System: One of the most important and essential requirement of such Plants is to cater to the large needs of the users of the normal Grid power to reduce the dependence on thermal power gradually and ina phased manner. Though DG power has its own advantages, such plants cannot be setup in urban areas by users of low income group who form a large part ofthe urban population and their need has to be met by CG only.

**2.** Distributed PV System: Distributed generation refers to solar power plants setup near the load centre i.e. where it will be used.. Distributed generation may serve a single user, such as a home or business, in which case it is also classified as 'Standalone 'or it may be part of a micro grid (a smaller grid that is also tied into the larger electricity delivery system), such as at a major industrial facility, a military base, or a large college campus in which case it is also termed as 'Grid Interactive' systems**.**

**Based on other criterion like configuration, connection with Grid, storage etc.:**

1. Stand-alone PV system
2. Grid Interactive PV System
3. Hybrid solar PV system

**Stand-alone PV system:**

**Important features:**

- Stand-alone Solar systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads.
- PV panels are connected in series/parallel to obtain the desired DC voltage and also to sustain the connected load while simultaneously charging the batteries to give the required backup power.
- The charge controller regulates the current output and prevents the voltage level from exceeding the maximum value for charging the batteries.
- During the sunshine hours, the load is supplied with DC power while simultaneously charging the battery.
- Battery bank sizing depends on a number of factors, such as the duration of an uninterrupted power supply required to the load when there is less or no radiation from the sun.
- The battery bank while giving back up facility results in around 20–30 % power loss due to heat when in operation.
- When designing a solar PV system with a battery backup, the designer must take this loss into account and also should plan a location with adequate space and ventilation for safe housing of the battery racks.
- Normally when Grid is close by, people will not go for a Standalone system with full battery backup since utility supply on Grid itself will serve as power backup when there is no adequate Sunshine. Only a small battery backup is normally provided as contingency to support essential loads.
- But in case of remote locations where nearby Grid access is not there Standalone PV systems must have battery backup except for direct online systems.

-  Further, the solar and wind power outputs can fluctuate on an hourly or daily basis. The stand-alone system must, therefore, have some means of storing energy, which can be used to supply the load during the periods of low or no power output as and when required.
-  The major application of stand-alone power systems are in remote areaswhere utility lines are uneconomical to install due to terrain, the '**right of way**' difficulties or the environmental concerns. Even without these constraints, building new transmission lines is expensive in far off areas.

Stand alone systems can be designed and configured in different ways with or without control functions like charge controller or MPPT, with or without battery backup etc based on user requirements and budget. This has become possible due to the enormous development in the field of Electronics and Computers which takes care of all complex monitoring and control functions. To understand and appreciate the versatility of such PV systems in terms of their capabilities, we will study one system with battery backup and several other control features.

**Standalone PV system with battery backup and some additional features:**

Figure-22 below shows a Standalone PV system with battery backup along with several features/ important subsystems like MPPT, Battery Charger etc.In such a stand-alone PV power system the peak power tracker senses the voltage and current outputs of the array and continuously adjusts the operating point using the switching Regulator to extract the maximum power under the given climatic conditions. The output of the array goes through this regulator to the inverter, which converts DC into AC. The array output in excess of the load requirement is used to charge the battery. The battery charger is usually a DC-DC buck converter. When the sun is not available, the battery discharges to the inverter to power the loads. The battery discharge diode $D_b$ is to prevent the battery from being charged when the charger is opened after a full charge or for other reasons. The array diode $D_a$ is to isolate the array from the battery, thus keeping the array fromacting as load on the battery when it is not generating power.

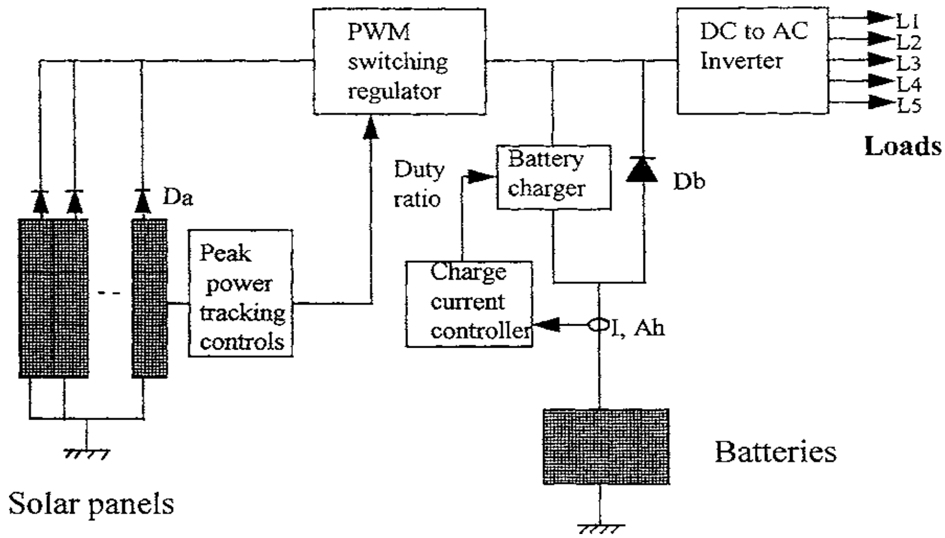


**Figure-22: Photovoltaic stand-alone power system with battery backup andother subsystems like battery charger, Charge controller, MPPT etc.**

**Grid interactive PV systems:**

**Important features:**

- A **Grid-connected Photo Voltaic (PV) system** is a Solar PV Power generating system that is connected to the utility Grid. A grid-connected PV system consists of a Grid Interface system apart from the normal solar panels, Inverters and a power conditioning unit. They range from small residential and commercial roof top systems to large utility-scale Solar Power Stations.. A grid-connected system will include an integrated battery system as well but of a very small capacity to serve as a backup for essential monitoring and control functions.
- Grid-connected or utility-interactive PV systems are designed to operate in parallel and interconnected with the electric utility grid. The most important subsystem in grid-connected PV systems is Power Conditioning Unit (PCU). It generally includes MPPT, charge controller and most importantly the grid interface unit apart from the Inverter. Apart from the inverter, the PCU mainly consists of a Grid interface between the PV system, AC output circuits and the

electric utility network, typically at an on-site distribution panel or service entrance.

- This allows the AC power produced by the PV system to either supply on-site electrical loads or to back-feed the grid when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility.
- This interface also automatically stops supplying power to the grid when the utility grid is not energized. This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or repair.
- The grid interface also incorporates synchronization circuitry that allows the production of sinusoidal waveforms in synchronization with the electrical service grid.

- One of the important and useful feature of a grid-connected system is net metering. Net meters have a capability to record consumed or generatedpower in an exclusive summation format. The recorded power registration is the net amount of power consumed—the total power used minus the amount of power that is produced by the solar power system and fed into the grid.Net meters are supplied and installed by utility companies that provide Grid- connection service systems. Net metered solar PV power plants are subject to specific contractual agreements and are subsidized by state governmental agencies.

The wind and photovoltaic power systems have made a successful transition from small stand-alone systems to large grid-connected systems with several safety and consumer friendly features like ‘Ant islanding’ and ‘net meetering’. In nutshell, the grid supplies power to the site loads when needed, or absorbs the excess power from the site when available.

**Typical Grid Interactive PV system:**

Typically a Grid Interactive PV system comes with battery backup as shown in the figure-23 below. When an outage occurs, the unit disconnects from the utility and powers specific loads. If the outage occurs in daylight, the PV array will be able to assist the load in supplying the power.

The major component is the Power Conditioning Unit (PCU) shown as a single big block in the figure. As already explained the PCU consists of several other important subsystems like MPPT, Charge controller, Interfacing & Controller section etc. apart from the inverter.

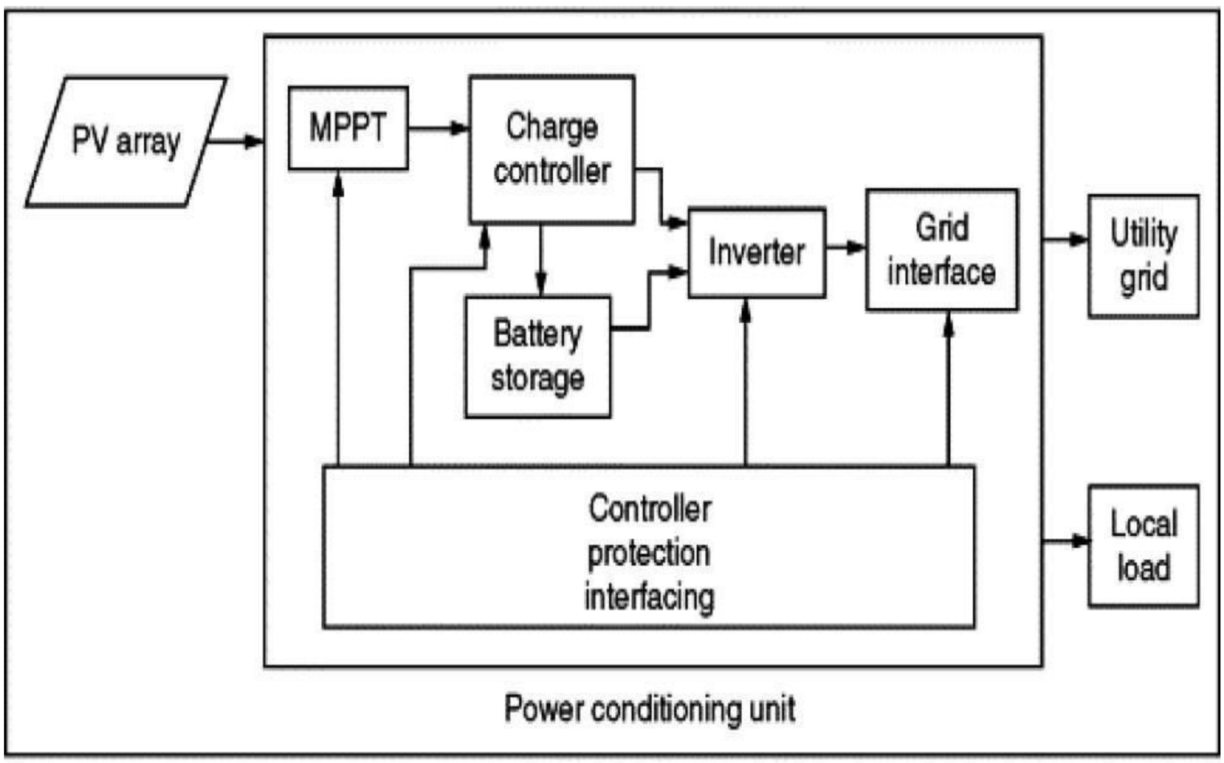


**Figure-23: Grid Connected PV system with battery backup**

The inverter is the key to the successful operation of the system, and it is also the most complex hardware. The inverter requirements include operation over a wide range of voltages and currents and regulate output voltage and frequency while providing AC power with good power quality which includes low total Harmonic distortion and high power factor, in addition to highest possible efficiency for all solar irradiance levels.

Inverters can be centralized inverters for the whole array of PV or separate string inverters for each PV module.

The special features like (i) Grid Interface Requirements (ii) Synchronizing with Grid etc. related to "Grid Interactive systems" will be covered at the end in Unit-5 after covering Wind electrical systems since these aspects are common to both Solar and Wind Electrical systems.

## 8.3 Hybrid solar PV system:

Hybrid Solar PV systems generally refer to the combination of more than one power source. The certainty of meeting load demands at all times is greatly enhanced by the hybrid system using more than one power source. Most hybrid systems use diesel generator as second source along with PV or Wind Turbine power systems which act as the primary power sources, since Diesel Generator ( mostly abbreviated as DG Power ) provides more predictable power on demand.

Though almost all solar PV systems generally use battery bank to store energy output from the panels to accommodate a pre-defined period of insufficient sunshine, there may be still exceptional periods of poor weather when another alternative source such as a Diesel Generator is required for guaranteed power availability. The batteries meet the daily short term load fluctuations & PV source power short falls, while the Diesel Generator takes care of the long-term load fluctuations & PV source power short falls. For example, the diesel generator is used in the worst case weather condition, such as extended overcasts in case of PV Hybrid systems and or during windless days or weeks in case of Wind power systems.

## PV-Wind- DG Hybrid systems:

Though PV-hybrid systems are combined with other power sources - typically diesel generators as explained, occasionally another renewable supply such as a wind turbine is also used if suitable and favorable site conditions for both Solar and Wind power generation are available at the same place. This configuration is normally used in remote locations where large power plants are required to supply power to the Grid on a totally commercial scale/basis.

In the case of PV – Wind Energy systems one major advantage is optimum utilization of the vacant space between the Wind turbine towers by locating the PV modules in-between. But PV modules should have a adequate ‘Shadow effect’ mitigating diodes.

In this combination of Hybrid system the PV generator and the Wind Generator together would usually be sized to meet the base load demand, taking into consideration the duration of time in which each of these systems will be available independently and together. Like for example Day time and night time, summer and rainy season etc. This arrangement offers all the benefits of PV in respect of low operation and maintenance costs, but additionally ensures a secure supply.

Figure below shows the simple block diagram of a typical Solar PV hybrid system along with DG and Wind Power systems.

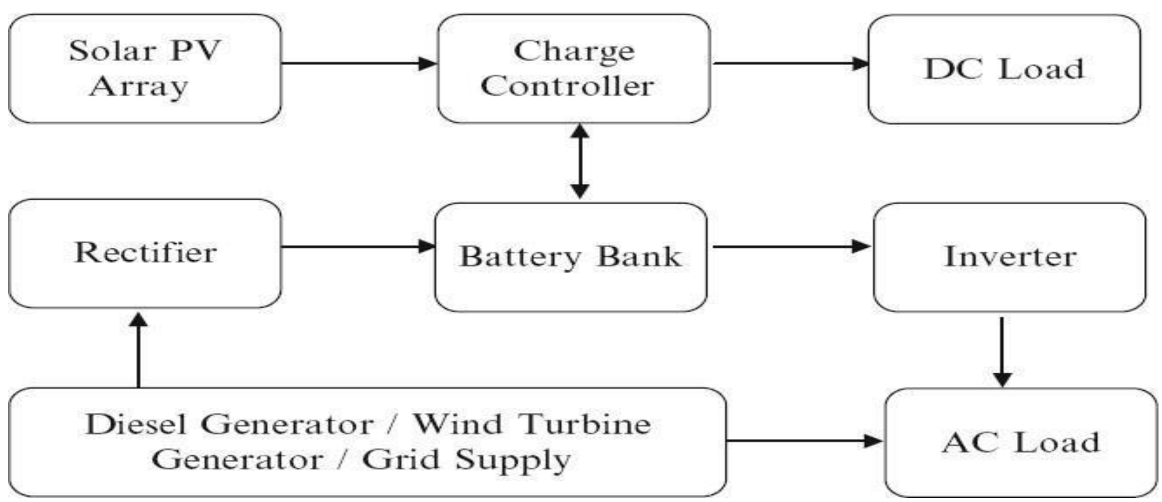


**Figure-24: Block diagram of PV - DG - Wind Hybrid system**

# 9. Important Formulae:

**1. Shockley diode equation**:

$$I_d = I_0(e^{qV_d/kT} - 1)$$

where $\mathbf{I_d}$ is the diode current (A), $\mathbf{V_d}$ is the voltage across the diode terminals from the p-side to the n-side (V), $\mathbf{I_0}$ is the reverse saturation current (A), **q** is the electron charge ($1.602 \times 10^{-19}$C), **k** is Boltzmann's constant ($1.381 \times 10^{-23}$ J/K), and**T** is the junction temperature (K).

Substituting the above constants into the exponent of equation above for $\mathbf{I_d}$ and taking the junction temperature of $25^0$ which is a standard we get

$$I_d = I_0(e^{38.9V_d} - 1) \qquad \text{(at } 25^\circ\text{C)}$$

**2. Solar cell I-V relation:**

$$I = I_{SC} - I_0\left(e^{qV/kT} - 1\right)$$

Where '$\mathbf{I_{SC}}$' is the short circuit current of the Solar Cell obtained with load terminals shorted (i.e. V=0) and all other terms being same as defined for simple P-N Junction diode.

When the load terminals of the PV cell are left open, **I** = 0 and we can solve the above equation for the open-circuit voltage $\mathbf{V_{OC}}$ :

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

And at $25^0$C, the above two equations become

$$I = I_{SC} - I_0(e^{38.9\ V} - 1)$$

And

$$V_{OC} = 0.0257\ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

## 10. Important questions:

1. (a) Draw the equivalent circuit of a Solar cell and from that explain the terms **'$I_{SC}$'** & **'$V_{OC}$'**. Derive expressions for the current **'I'** delivered to a load & **'$V_{OC}$'** in terms **'$I_{SC}$'** and **'$I_0$'** (Reverse Saturation current). Using these expressions draw the Dark current and Light current versus V.
   (b) Starting from these basic I-V curves and with additional curves explain what is Maximum Power Point and where it occurs.
2. Define and explain the terms: (i) Cell efficiency and (ii) Fill factor
3. Explain the effect of 'Irradiation' and 'Temperature' on the I-V characteristics of a solar cell.
4. (a)Explain clearly and in detail what MPPT is with the help of relevant diagrams.
5. (a) What are PV Modules and Arrays in Solar PV systems?
   (b) Explain clearly with the help of suitable figures how the current and Voltage levels of PV modules are increased by interconnecting them.
6. (a) Mention what are the 'BOS' and explain briefly the important systems.
   (b) Explain in detail the various criteria on which the Inverters can be classified for use in PV solar systems.
7. Explain briefly (i) Batteries (ii) Charge Controllers
8. (a)Explain the important features of 'Stand Alone Solar Power System'
   (b) With the help of a suitable block diagram explain the operation of such a Standalone system with battery backup and other control features.
9. (a)Explain the important features of 'Grid Connected Solar Power System'
   (b) With the help of a suitable block diagram explain the operation of such a System with battery backup and other Interface and Synchronization features.
10. (a) Explain briefly the concept of a Hybrid Solar System
    (b) With the help of a simple Block diagram explain the operation of a PV - DG - Wind Hybrid system

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# UNIT-III

# FUNDAMENTALS OF WIND TURBINES

## CONTENTS:

**Introduction: Basic Background of Wind Turbines**

1. **Power contained in wind**
2. **Efficiency limit for wind energy conversion**
3. **Design of wind turbine rotor: (i) Diameter of the rotor (ii) Choice ofnumber of blades**
4. **The tower**
5. **The transmission system and gear box**
6. **Power speed characteristics**
7. **Torque speed characteristics.**
8. **Wind turbine control systems: (i) Pitch angle control (ii) Stall control (iii) Yaw control**
9. **Control strategy**
10. **Summary points and Important Relations**
11. **Illustrative examples**
12. **Important questions**

**Introduction-Basic background of wind Turbines** : For ease of understanding of the subject covered in this course, the essential basic/background information required is covered in this introduction. This is not part of syllabus.

**---------------------------------------------------------------------------------------------------------**

Wind energy is one of the most abundantly available and exploitable forms of renewable energy like Solar. Winds blow from a region of high atmospheric pressure to one of low atmospheric pressure.The difference in pressure is caused by (a) the fact that the earth's surface is not uniformly heated by the sun and (b) the earths rotation. Essentially wind energy is a byproduct of Solar energy , available in the form of Kinetic energy of air.

Wind power has been in use for centuries before the invention of steam engine in sailing ships, pumping water and grinding grain. Subsequently economic utilisation of fossil fuels has pushed its use into back seat.

However Denmark which lacked adequate fossil fuels and water resources pioneered in the development of wind mills for the Generation of electricity in 1890s. Subsequently world wide interest in developing wind power plants has grown due to the depletion of fossil fuels , the effects of world wars and the push to reduce environmental pollution. Further, the aviation technology resulted in an improved understanding of forces acting on the blades moving through air. This resulted in the development of wind turbines with two or three blades. Then onwards by the efforts of countless scientists and engineers from various disciplines , today we have viable technologies to tap wind power in very cost effective and efficient way. We will be studying such technologies relevant to Electrical engineers in this course.

**Types of wind turbnes :**

Wind turbines can be broadly classified in to two types according their axis of Rotation.

*(1)* Horizontal Axis Wind Turbines (HAWT):can further be divided into three types

- Dutch type grain-grinding wind mills
- Multi blade water pumping wind mills
- High-Speed propeller type wind mills

*(2)* Vertical axis wind turbines: come in two different designs.

- Savonious rotor and Darrieus rotor

In the above types, HAWT High-Speed propeller type wind mills are the type most commonly used today for Wind Turbines in Electrical Power generation and is the main content in this course. However for completeness and comparison where ever necessary a brief introduction to the other four types is also given here.

**Dutch Wind mills**:

Originally developed in Denmark for grain grinding they operate on the thrust exerted by wind and are called Thrust operated Wind mills (as against our High Speed Propeller type wind mills which operate on Lift Force just like Aero planes). The blades which are generally four are inclined at an angle to the plane of rotation. The blades are made of sails or wooden slats as shown in the figure below. The blades are oriented in the direction of the wind manually.

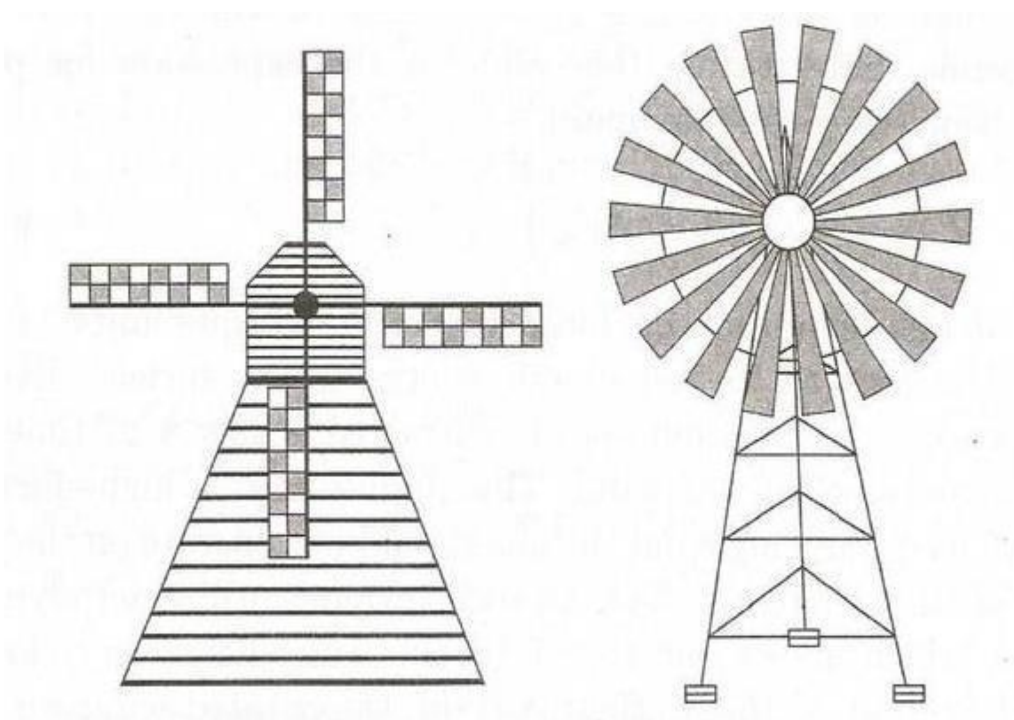

**Figure-1 : Dutch wind mill and Multiblade water pumping wind mill**

## Multi blade Water-Pumping Wind mills:

Water pumping wind mills have large number of blades , generally wooden or metallic slats driving a reciprocating pump. As the mill has to be placed directly over a well, the criterion for site selection is water availability and not windiness. Therefore , the mill must be able to operate at slow winds. The large number of blades give a high Torque , required for driving a centrifugal pump, even at low winds. Hence sometimes these are called fan –mills. The blades are made of flat steel plates working on the thrust of wind. The orientation is generally achieved by a ‘tail vane’.

## High Speed Propeller type wind Machines:

The Horizontal Axis wind Turbines that are used today for Electrical Generators do not operate on Thrust force. They operate mainly on the Aerodynamic forces that Develop when wind flows around a blade of aerofoil design. Wind turbines that operate on Thrust are inherently less efficient.

To understand how a modern wind turbine works , let us first see how an aerofoil/blade works. For an understanding of the blade which works on the principle of aerofoil let us give the following basic definitions related to the blade and the aerodynamic forces that act on it to give the rotation.

## Basic Definitions related to a Blade/Aerofoil :

Aerofoil: A structure with curved surfaces designed to give the most favorable ratio of lift to drag in flight, used as the basic form of the wings, fins, and tail planes of most aircraft.

Leading edge: This is the point at the front of the aerofoil that has maximum curvature.

Trailing Edge: This is defined similarly as the point of maximum curvature at the rear of the aerofoil.

Chord Line: This is a straight line connecting the leading and trailing edges of the aerofoil.

Chord Length: Chord Length, is the length of the chord line of the blade and is the characteristic dimension of the aerofoil section.

Blade length: Is the height of the blade.

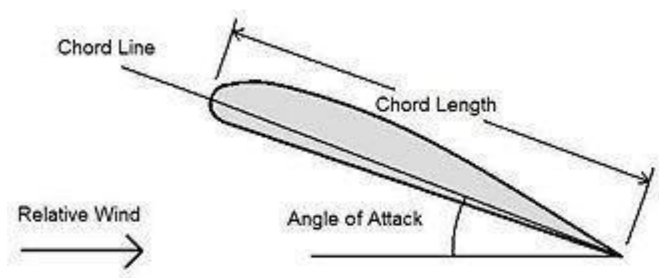


**Figure -2: Cross section of an aerofoil**

Pitch angle (α): The angle between the chord of the aerofoil section and the plane of rotation, also called as 'setting angle'.

Relative Velocity: The velocity of the air flow relative to the blade.

Angle of Inclination (I): The angle between the relative velocity vector and the plane of rotation.

Angle of incidence (i): The angle between the relative velocity vector and the chordline of the aerofoil. It is also called 'angle of attack'. It is clear that $i = I - \alpha$.

Lift force: It is the component of aerodynamic force in the direction perpendicular to the relative wind. It is given by $\mathbf{F_L = (\rho\ A_b\ \omega^2\ C_L)/2}$ Newton, where $\mathbf{C_L}$ is the dimensionless lift co-efficient and $\mathbf{A_b}$ is the blade area in square meters.

Drag force: It is the component of aerodynamic force in the direction of relative wind. It is given by $\mathbf{F_D = (\rho\ A_b\ \omega^2\ C_D)/2}$ Newton, where $\mathbf{C_D}$ is the dimensionless lift co-efficient and $\mathbf{A_b}$ is the blade area in square meters.

Total force (F): The total aerodynamic force of a blade is the vector sum of the lift force and the drag force.

*Relative velocity* The velocity of air flow relative to the blade, $\vec{w} = \vec{v} - \vec{u}$

**Operation of High Speed Propeller type wind Machines:**

Suppose an aerofoil say an aero plane wing is moving in a stream of wind as shown in the figure below (figure 3).

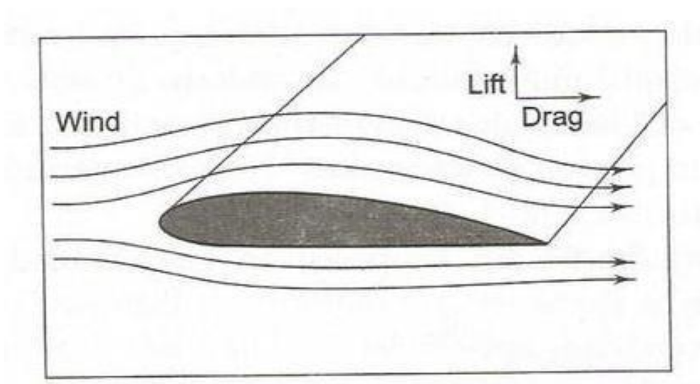


**Figure -3: Flow of Wind over an Aerofoil blade**

The wind stream at the top of the aerofoil has to traverse a longer path than that at the bottom, leading to a difference in velocities. This gives rise to a difference in pressure (Bernoulli's principle ) from which 'lift force' results. There is another force that tries to push the aerofoil in the direction of the wind. This is called the 'drag force'. The net force on the aerofoil is then determined by the resultant of these two forces. (fig-4)

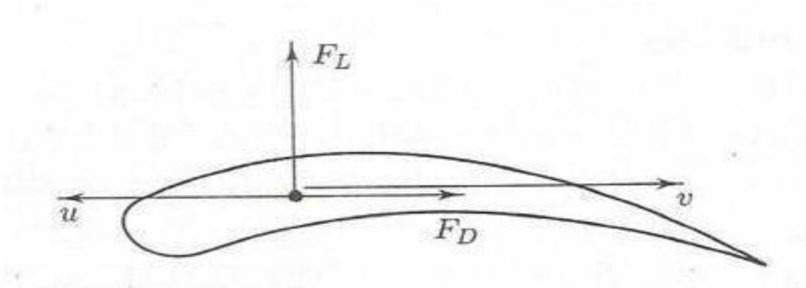


**Figure-4: The aerodynamic forces in an aerofoil moving in the direction of the wind. 'u' is the aerofoil velocity, 'v' is the wind velocity , '$F_L$' is the lift force and'$F_D$' is the drag force.**

In this example, the aerofoil and the wind move along the same axis. But in our case of wind turbine Rotor, these forces are determined by the wind speed as seen by the aerofoil, called the 'relative wind'. This is given by the vector summation of the wind velocity and the negative of the aerofoil velocity.
Since it is difficult to visualize the forces acting upon the blades in a wind mill rotor, Extending the basic aerofoil working principle in an aero plane to the wind turbine we will just state the following points :

- The lift force '$F_L$'will now be perpendicular to the relative wind and the Drag force '$F_D$' parallel to it.
- The magnitude of these two forces will also be proportional to that of the relative wind velocity. ( see figure-5 below )
- We can see from the figure below (Fig-5) that the lift force and the Drag force have opposing components along the direction of motion.
- If the lift Force dominates the drag ,there will be a resultant force along the direction of motion, giving a positive push to it.
- In fact ,this is the force that creates the torque in a modern wind turbine. The blades are of aerofoil section, which move along the stream of wind.
- They are so aligned that the Drag force is minimized and the lift force maximized. This gives a net positive torque and make the rotor rotate as shown in the figure below. ( Fig - 6)

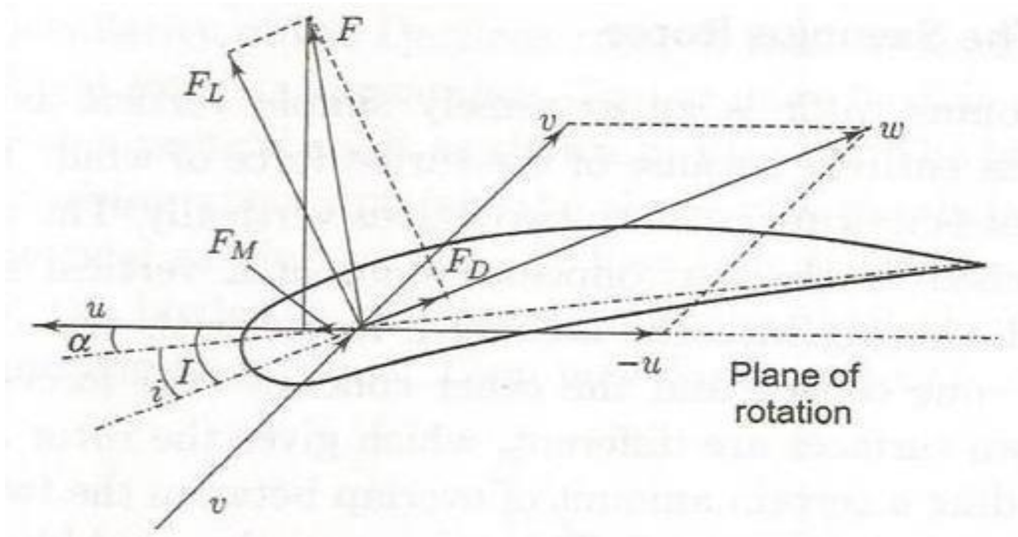


**Figure - 5: The relative wind direction and the aerodynamic forces. Note the production of the resultant force '$F_M$'along the direction of motion. 'w' is therelative wind direction, '$F_L$'is the lift force, '$F_D$'is the drag force, '$F_M$' is the moment force,'I'is the inclination angle, 'i'is the angle of incidence and 'α' is thepitch angle.**

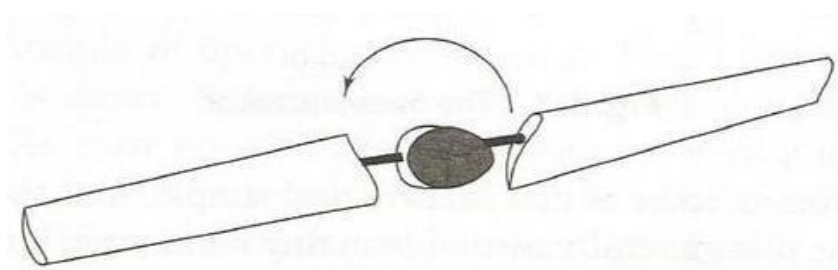

**Figure - 6: Arrangement and angle of Blades in a propellor- type of windTurbine.**

There is another component of the two forces i.e that perpendicular to the Direction of Blade motion. This force is called 'Thrust Force'. This component tries to topple the tower and is a problem at high wind speeds.

**Upwind Turbine:** The rotor on an upwind turbine is in the front of the unit, positioned similar to a propeller driven airplane. This is the most common type of turbines. To keep it oriented into the wind, a yaw mechanism such as a tail is needed.

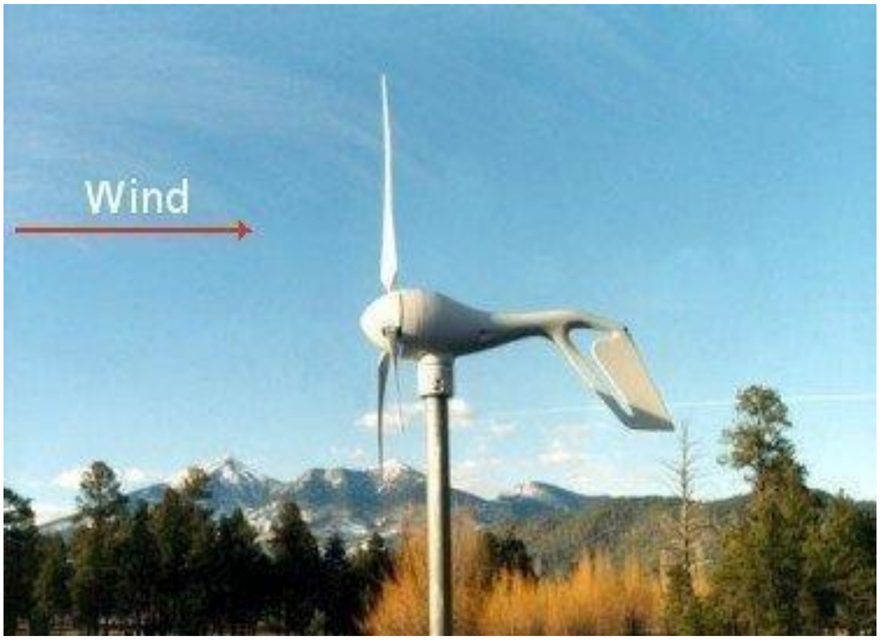


**Figure-7: Upwind wind Turbine**

**Advantage:** The reduced tower shading. The air will start to bend around the tower before it passes it so there is some loss of power from the interference, just not to the same degree as in the downwind turbine. Operating the rotor upwind of the tower produces higher power as it eliminates the tower shadow on the blades. This also results in lower noise, lower blade fatigue, and smoother power output.

**Disadvantage:** The extended nacelle that is required to position the rotor far enough away from the tower to avoid any problems with a blade strike. The blades themselves must be somewhat stiff to avoid bending back into the tower. This will mean the point where the blade attaches to the rotor hub will be stressed during high, gusty wind conditions.

**Down wind turbine**: Has its rotor on the back side of the turbine. The nacelle typically is designed to seek the wind, thus negating the need for a separate yaw mechanism.

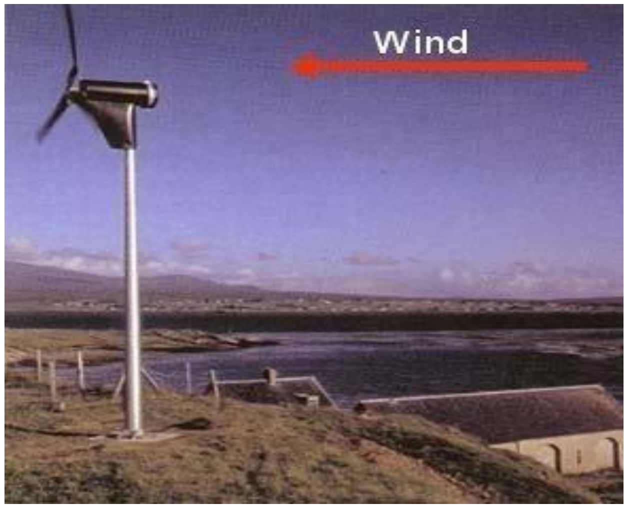


**Figure-8: Downwind wind Turbine**

**Advantages:**

1. The rotor blades can be flexible since there is no danger of a tower strike.

2. They are less expensive to make.

3. They can relieve stress on the tower during high or gusty wind conditions since the flexing allows some wind load to be transferred directly to the blades instead of the tower.

**Disadvantage:**

The flexible blade advantage can also be a disadvantage as the flexing may fatigue the blades. Tower shadow is problem with a downwind machine since the rotor blade is actually placed behind the tower. This can cause turbulence and increased fatigue on the unit.

**The Savonious Rotor :** It is a simple vertical axis wind turbine that works on the Thrust force of wind. It is drum cut into two halves and attached to the two opposite sides of a vertical shaft as shown in the figure below. . As the wind blowing into the structure meets with two different surfaces ,one convex and one concave , the forces exerted on the two surfaces are different thus giving the Rotor a Torque.

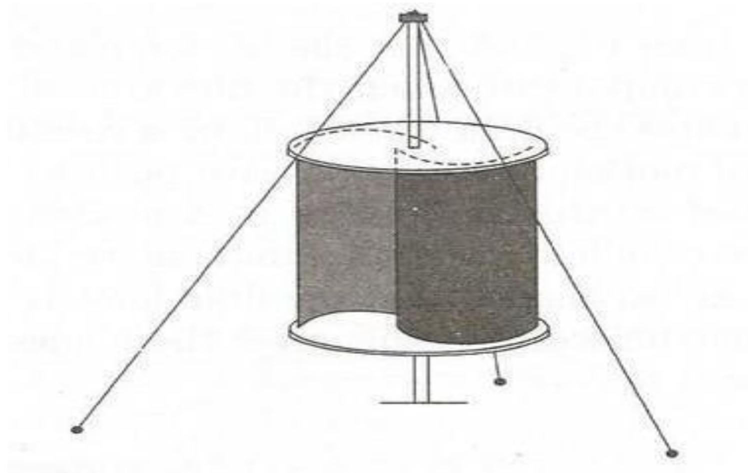

**Figure-9: The Savonious Rotor**

**The Darrieus Rotor:** This is a Vertical axis Lift force operated device invented by G.J. Darrieus of U.S.A. Two or more flexible blades are attached to a vertical shaft as shown in the figure below. The blades bow outwrads , taking approximately the shape of a parabolaid and are of symmetrical aerofoil section.For this machine the Torque is zero when the rotor is stationary. Hence the starting torque isprovided by an electrical machine which initially runs as a Motor and then as a Generator.

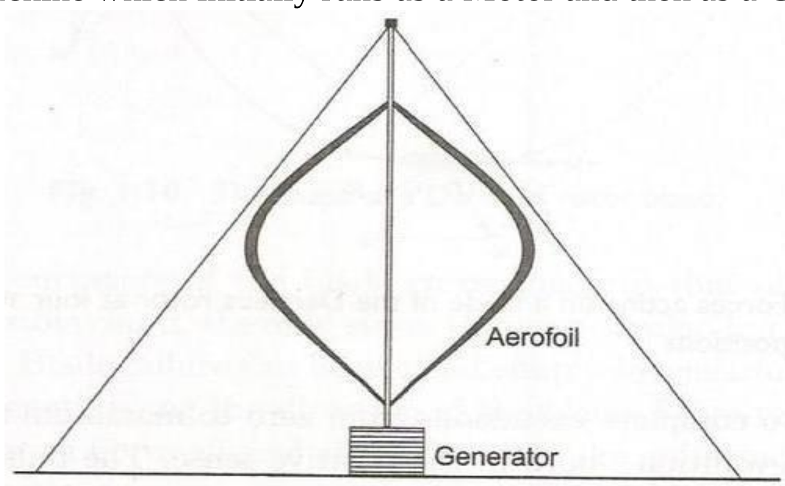


**Figure-10: The Darrieus Rotor**

**------------------------------------------------------------------------------------------------------**

**1. Power contained in wind:** Power contained in wind is given by the kineticenergy of the flowing air mass per unit time. That is,

The kinetic energy in air of mass “m” moving with speed V is given by the following in SI units:

Kinetic Energy= ½(m $v^2$) joules (1)

The power in moving air is the flow rate of kinetic energy per second. Therefore:

Power=1/2(mass flow rate per second)$V^2$ (2)

If we let P = mechanical power in the moving air

ρ= air density, kg/$m^3$ (at 15◦C and 1 atmosphere, ρ = 1.225 kg/m3)

A = area swept by the rotor blades, $m^2$

V = velocity of the air, m/s

Then, the volumetric flow rate is A·V, the mass flow rate of the air in kilogramsper second is ρ·A·V, and the power is given by the following:

$$P = \frac{1}{2}(\rho A V) \cdot V^2 = \frac{1}{2}\rho A V^3 \ watts. \tag{3}$$

This is the power in the upstream wind. It varies linearly with the density of the air sweeping the blades, and with the cube of the wind speed. All of the upstream wind power cannot be extracted by the blades, as some power is left in the downstream air which continues to move with reduced speed.

Two potential wind sites are compared in terms of the specific wind power expressed in watts per square meter of area swept by the rotating blades. It is also referred to as the power density of the site, and is given by the following expression:

$$Specific\ Power\ of\ the\ site = \frac{1}{2}\rho \cdot V^3\ watts\ per\ m^2\ of\ the\ rotor\ swept\ area \tag{4}$$

## 2. Efficiency limit for wind energy conversion:

The actual power extracted by the rotor blades is the difference between the upstream and the downstream wind powers. That is, using Equation (2):

$$P_o = \frac{1}{2}\ mass\ flow\ rate\ per\ second \cdot \left\{V^2 - V_o^2\right\} \tag{5}$$

Where $P_o$ = Mechanical power extracted by the rotor, i.e., the turbine outputPower
V = upstream wind velocity at the entrance of the rotor blades$V_o$
= downstream wind velocity at the exit of the rotor blades.

The air velocity is discontinuous from V to $V_o$ at the "plane" of the rotor blades in the macroscopic sense (we leave the aerodynamics of the blades which is beyond our scope). The mass flow rate of air through the rotating blades is, therefore, derived by multiplying the density with the volume of air flow per second which is equal to the product of Turbine Area (A) and average velocity $[(V+V_0)/2]$. That is:

$$mass\ flow\ rate = \rho \cdot A \cdot \frac{V + V_o}{2} \tag{6}$$

The mechanical power extracted by the rotor, which is driving the electrical generator, is therefore:

$$P_o = \frac{1}{2}\left[\rho \cdot A \cdot \frac{(V + V_o)}{2}\right] \cdot \left(V^2 - V_o^2\right) \tag{7}$$

The above expression can be algebraically rearranged ( by multiplying and dividing the first term in the square brackets by **'V'** and the second term in normal brackets by $\mathbf{V^2}$) **:**

$$P_o = \frac{1}{2}\rho \cdot A \cdot V^3 \frac{\left(1 + \frac{V_o}{V}\right)\left[1 - \left(\frac{V_o}{V}\right)^2\right]}{2} \tag{8}$$

The power extracted by the blades is customarily expressed as a fraction of the upstream wind power as follows:

$$P_o = \frac{1}{2}\rho \cdot A \cdot V^3 \cdot C_p \tag{9}$$

Where $$C_p = \frac{\left(1+\frac{V_o}{V}\right)\left[1-\left(\frac{V_o}{V}\right)^2\right]}{2} \qquad (10)$$

And $C_p$ is the fraction of the upstream wind power, which is captured by the rotor blades. The remaining power is discharged or wasted in the downstream wind. The factor $C_p$ is called the **power coefficient** of the rotor or the rotor efficiency.

For a given upstream wind speed, the value of $C_p$ depends on the ratio of the downstream to the upstream wind speeds, that is ($V_o/V$). The plot of power coefficient versus ($V_o$ /V) shows that $C_p$ is a single, maximum-value function (Figure-1). It has the maximum value of 0.59 when the ($V_o/V$) is one-third. The maximum power is extracted from the wind at that speed ratio, when the downstream wind speed equals one-third of the upstream speed. Under this condition:

$$P_{\max} = \frac{1}{2}\rho \cdot A \cdot V^3 \cdot 0.59 \qquad (11)$$

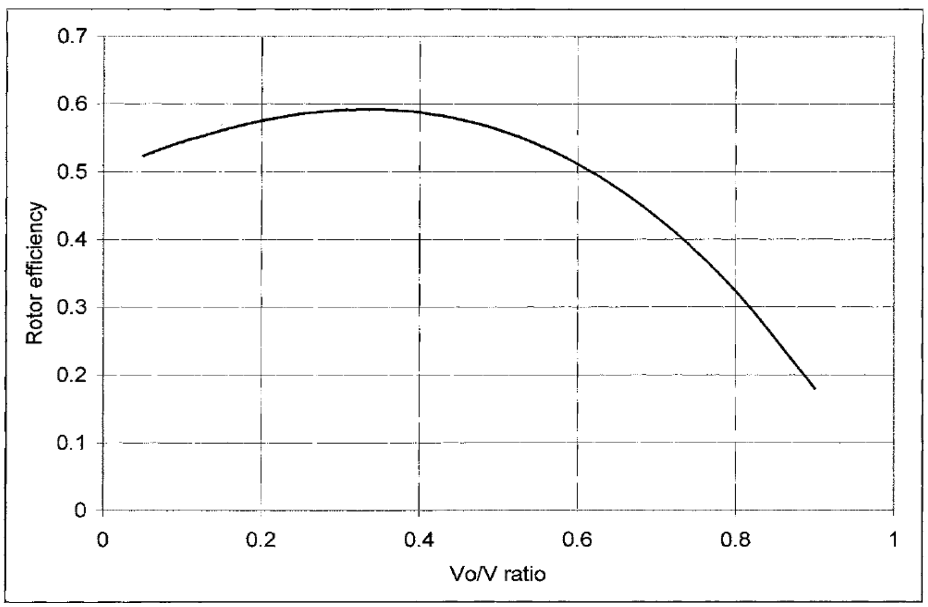


**Figure - 1: Rotor efficiency versus $V_o$/V ratio has single maximum. Rotor efficiency is the fraction of available wind power extracted by the rotor and fedto the electrical generator.**

The theoretical maximum value of $C_p$ is 0.59. This limit is called '**Betz Limit**'. In practical designs, the maximum achievable $C_p$ is below 0.5 for high-speed, two-blade turbines, and between 0.2 and 0.4 for slow speed turbines with moreblades as shown in the figure below. (Figure - 2).

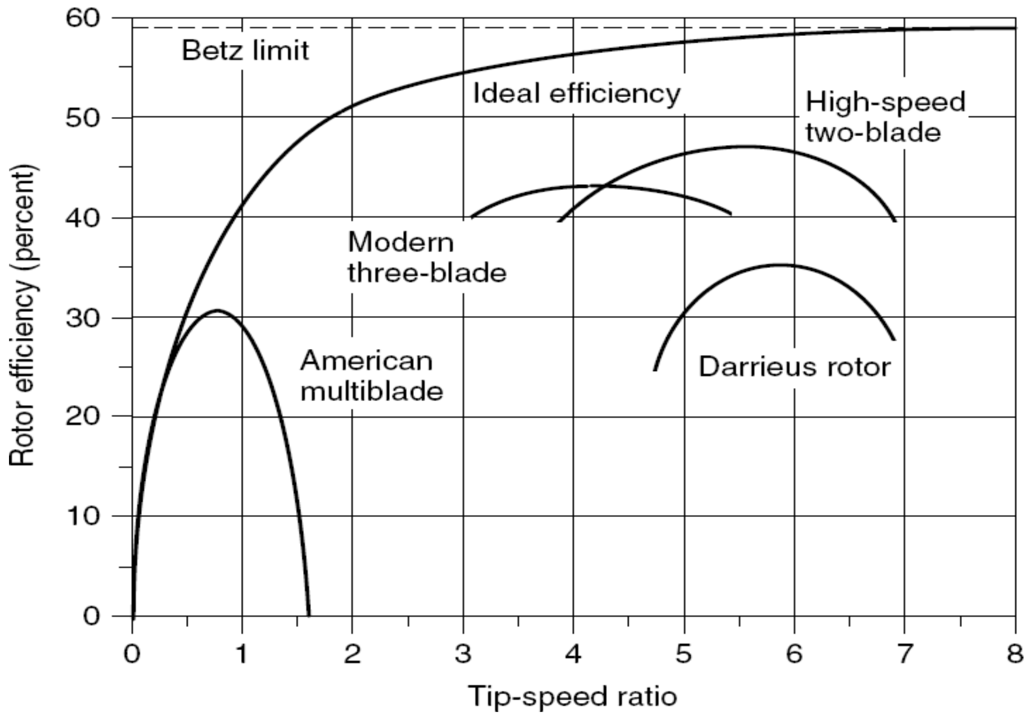


**Figure-2: Rotor efficiency versus tip speed ratio for rotors with different numberof blades. Two-blade rotors have the highest efficiency.**

If we take 0.5 as the practical maximum rotor efficiency, the maximum power output of the wind turbine becomes a simple expression:

$$P_{\max} = \frac{1}{4} \cdot \rho \cdot V^3 \text{ watts per m}^2 \text{ of swept area.} \tag{12}$$

**Some Relevant Terms and their Definitions:**

Before proceeding further, we must get acquainted with the terms frequently used in this notes and in the literature on wind energy.

**Solidity:**

Solidity of a wind Rotor is the ratio of the projected blade area to the area of the wind intercepted. The projected blade area does not mean the actual blade area. It is the blade area met by the wind or projected in the direction of the wind.

The **Solidity** is defined as the ratio of the solid area to the swept area of the blades. The modern 2-blade turbine has low solidity ratio. Hence, it requires little blade material to sweep large areas.

In our course we will be studying '**H**orizontal **A**xis **W**ind **T**urbines (HAWT)' alone and for them solidity lies between 0.01 to 0.1.

Solidity has a direct relationship with Torque and speed. High solidity rotors have high torque and low speed. Low solidity rotors on the other hand, have high speed and low torque and are typically suited for electrical power generation.

**Rotor Swept Area:**

As seen in the power equation, the output power of the wind turbine varies linearly with the **rotor swept area**. For the horizontal axis turbine, the rotor swept area is given by:

$$A = \frac{\pi}{4} D^2 \qquad (13)$$

where **'D'** is the rotor diameter.

The wind turbine efficiently intercepts the wind energy flowing through the entire swept area even though it has only two or three thin blades with solidity between 5 to 10 percent.

**Tip speed ratio:**

The tip speed ratio (TSR denoted by **λ**) of a wind turbine is given by:

$$\lambda = (2\pi R N)/V \qquad (14)$$

where '**λ**' is the TSR (non dimensional), '**R**' is the radius of the swept area (in

meters), '**N**' is the rotational speed in revolutions per second and **'V'** is the wind speed (without rotor interruption in meters/second).
In high speed horizontal axis rotors and Darrieus rotors, the outer tip actually turns much faster than the wind speed owing to the aerodynamic shape. Consequently, the TSR can be as high as 9. It can be said that high solidity rotors have in general low TSRs and vice versa.

**Power Coefficient:**

The power coefficient $C_p$ of a wind energy converter is given by:

**$C_p$ = (Power output from the wind turbine)/(Power contained in the wind)** (15)

The power coefficient differs from the efficiency of a wind machine in the sense that the latter includes losses in mechanical transmission, electrical generation etc. whereas the former is just the efficiency of conversion of wind energy into mechanical energy of the shaft. In high- speed horizontal-axis machines the theoretical maximum power coefficient is given by the Betz limit.

## 3. Design of wind turbine rotor:

The design of the wind turbine rotor is basically aerodynamics related and its study in detail is beyond our scope. However a basic knowledge of the underlying basic principles of a wind turbine Rotor design is essential even for an Electrical engineer. We must also remember certain technical conclusions arrived at from a detailed analysis and study. Hence we will study them briefly in this topic.

The design of a WT Rotor basically involves many aspects like the design of the blade profile, selection of the number of blades, the Rotor diameter, choice of pitch angle , height of the tower and the type of transmission system & gear box. We will study some of them briefly one by one.

**Diameter of the Rotor:**

The diameter of the rotor is determined from the operating wind speed and the rated power output. The generated power is given by:

$$= \frac{1}{2}\rho A V_\infty^3 \eta_e \eta_m C_p$$
$$= \frac{1}{8}\pi \rho D^2 V_\infty^3 \eta_e \eta_m C_p \quad (16)$$

Where $P_o$ is the power contained in the wind, $\eta_m$ is the efficiency of the mechanical transmission and $\eta_e$ is the efficiency of electrical generation. If the rated P (W), V (m/s) , and $C_p$ are known ,the diameter in meters can be found out.

In the absence of the above data, the following simple formulae can be used for the initial estimation of the maximum aerodynamic power:

$P = 0.15D^2V^3$ for slow rotors
$P = 0.20D^2V^3$ for fast rotors

**Choice of the number of blades :**

It is obvious that the efficiency of power transfer from wind depends on the proper choice of the number of blades. There will be little power extraction if the blades are so close to each other or rotate so fast that every blade moves into the turbulent air created by the preceding blade. It will also be less than optimum if the blades are so far apart or move so slowly that much of the air stream passes through the wind turbine without interacting with a blade. Thus the choice of the number of blades depends on the TSR.

A large number of blades implies high solidity - hence high torque and low speed. On the other hand , a small number of blades implies low torque and high speed. Therefore a large number of blades are used in wind turbines for pumping water or other mechanical functions that require a high starting torque. For modern electricity generating-wind turbines,the empirical measurement of 'd' and the requirement of a high TSR leads to a small number of blades , generally only two or three.

Though both two blade and three blade designs are equally popular , their choice depends on certain factors. The two blade designs have less nacelle weight and are much simpler to erect. Three blade turbines involve 33% more weight and cost , though the power coefficient increases only by 5-10%. On the other hand, the three blade design has smoother power output and a more balance gyroscopic force and therefore less blade fatigue and lesser chances of failure.

## 4. The Tower

In a horizontal axis wind turbine, the tower supports the hole machinery, including the blades, the gearbox the generator and the control equipment. It therefore requires high strength,which is achieved with a steel or concrete structure based on tubular or lattice construction. It is necessary to avoid amplification of vibration through careful design of the resonant frequencies of the tower,blades,rotor ,etc. vis-a-vis the wind fluctuation frequencies.

In general, for medium and large turbines, the height of the tower is slightly greater than the Rotor diameter. Small turbines should have taller towers in comparison with their rotor diameters; otherwise the turbine would be too close to the ground surface and would experience poor wind speeds. Turbines with rated output between 10kW and 100 kW have tower heights in the range of 20-30 m;300kWt o 500kW machines would have towers 35m to 40 m high.

## 5. Transmission System and GearBox

In general , the optimal speed of rotation of an electrical generator is much higher than the optimal speed of a wind turbine. In order to ensure that a low speed of the turbine produces a high rotational speed at the Generator, a gear box is inserted in the transmission system. The arrangement in side the generator housing (known as nacelle) is shown schematically in the figure below.

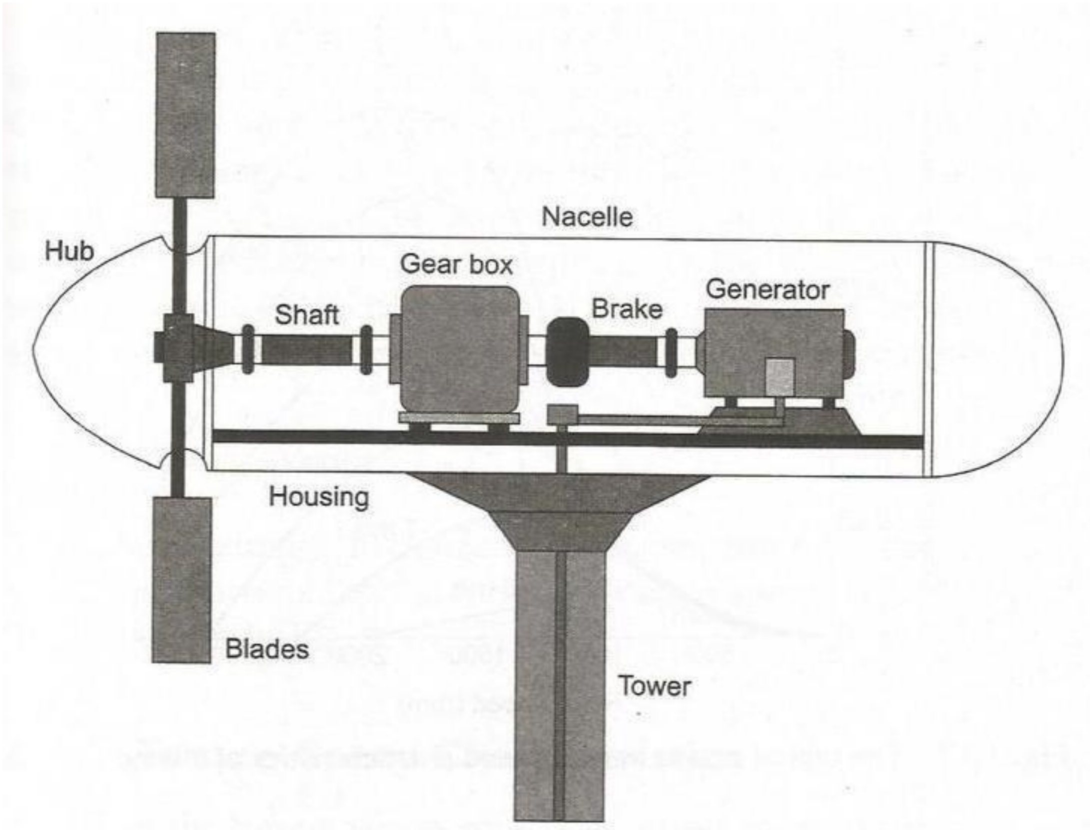


**Figure - 3 : The Shaft ,Gearbox,Generator and Brake inside the Nacelle**

If the generator has a fixed gear ratio , the transmission system is relatively simple and inexpensive. However, in this case the efficiency suffers at low or high wind speeds . It has been found that for a particular site ( with particular wind speed distribution characteristics), one particular choice of the gear ratio gives the highest system efficiency and the curve falls off on both sides of this optimal gear ratio. Therefore a judicious choice of the gear ratio is very important. Generally a speed ratio of 20-30 is chosen for wind electrical systems.

For variable speed wind turbine , a better overall efficiency may be obtained witha two speed gearbox which can switch from a low gear ratio at high wind speeds to a high gear ratio at low wind speeds so that the speed variation at the generator side is kept minimum.

## 6. Power - Speed Characteristics:

The wind turbine power curves shown in the figure - 4 below illustrate how the mechanical power that can be extracted from the wind depends on the rotor speed. For each wind speed there is an optimum turbine speed at which the extracted wind power at the shaft reaches its maximum.

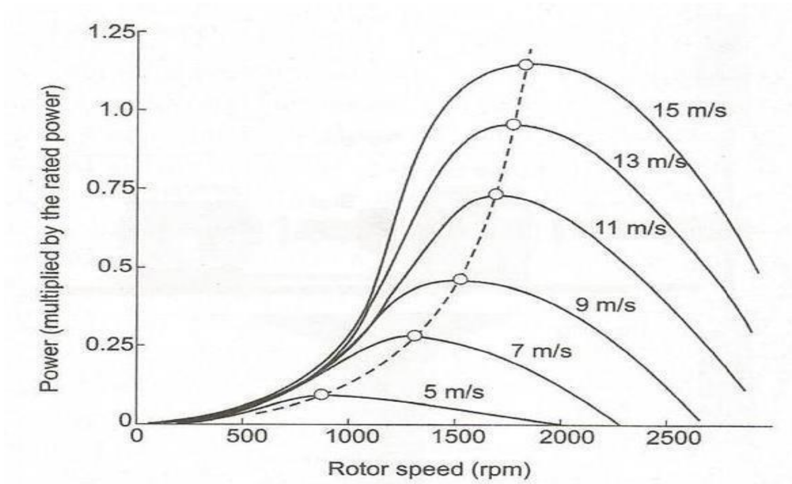


**Figure- 4: Typical power vs speed characteristics of a wind turbine**

Such a family of wind turbine power curves can be represented by a single dimensionless characteristic curve , namely , the $C_P$-λ curve as already shown in the figure - 2 where the power coefficient is plotted against the TSR. For a given turbine , the power coefficient depends not only on the TSR but also on the blade pitch angle. Figure 1-5 shows the typical variation of the power coefficient with respect to the TSR(λ) with blade pitch control.As can be seen from these curves for a given windpseed and TSR the power coefficient can be increased by controlling the pitch angle.

From the equations of power contained in wind and the definition of $\mathbf{C_P}$ , the mechanical power transmitted to the shaft is given by:

$$P_m = \frac{1}{2}\rho C_p A V_\infty^3 \qquad (17)$$

Where $C_P$ is a function of the **TSR '$\lambda$'** and the **pitch angle '$\alpha$'**. For a wind turbine with a radius **'R'**, the above equation (17) can be expressed as

$$P_m = \frac{1}{2}\rho C_p \pi R^2 V_\infty^3 \qquad (18)$$

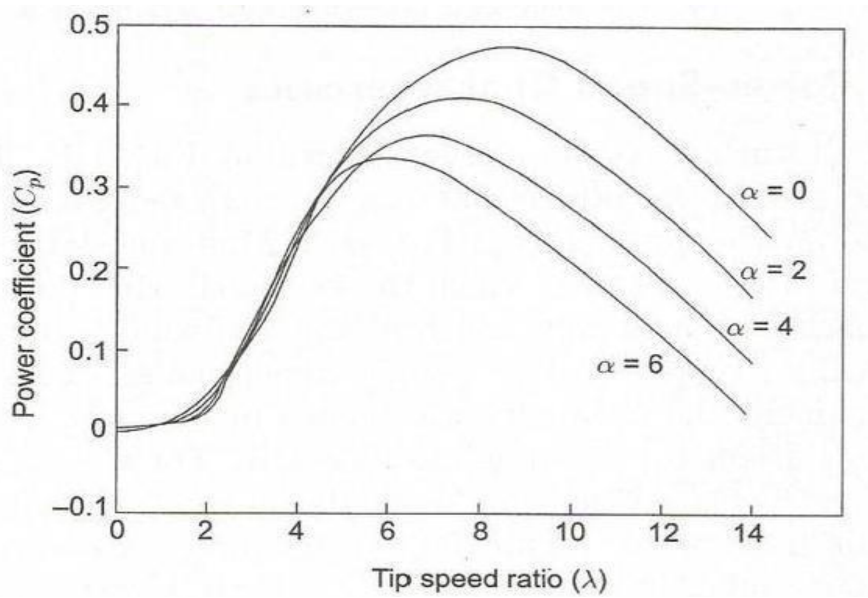


**Figure - 5: Typical curves of Power coefficient vs. TSR for various Pitch angles**

For a given wind speed , the power extracted from the wind is maximised if $C_P$ is maximised. The optimum value of $C_P$, say $C_{Popt}$,always occurs at a definite value of $\lambda$ say(= $\lambda_{opt}$). This means that for varying wind speed, the rotor speed should be adjusted proportionally to adhere to this value of $\lambda$ (= $\lambda_{opt}$) for maximum mechanical output power from the turbine. Using the relation $\lambda = \omega R/V$ ($2\pi NR/V$) in equation (1-18) , the maximum value of the shaft mechanical power for any wind speed can be expressed as :

$$P_{max} = ½\, \rho C_{popt} \pi \,( R^5/\lambda_{opt}^3)\omega^3 \qquad (19)$$

Thus the maximum mechanical power that can be extracted from wind is proportional to the cube of the rotor speed i.e.$P_{max}$a $\omega^3$ as shown in figure-4

## 7. Torque - Speed Characteristics

Studying the Torque versus rotational characteristics of any prime mover is very important for properly matching the load and ensuring stable operation of the electrical generator. The typical torque-speed characteristics of a two blade propeller type wind turbine are shown in the figure below (1-6). The profiles of the Torque-Speed characteristic curves shown in this figure follow from the power curves, since Torque and Power are related as: $\mathbf{T_m = P_m/\omega}$ --------------------- (20)

From equation - 19 , at the optimum operating point ($C_{p,opt}$, $\lambda_{opt}$ ), the relation between aerodynamic torque and rotational speed is then given by :

$$T_m = \frac{1}{2}\rho C_{p,\mathrm{opt}}\pi \left(\frac{R^5}{\lambda_{\mathrm{opt}}^3}\right)\omega^2 \quad (21)$$

It is seen that at the optimum operating point on the $\mathbf{C_P - \lambda}$ curve, the torque is quadratically related to the rotational speed.

The curves in figure - 6 given below show that for the propellor turbine, for any wind speed , the torque reaches a maximum value at a specific rotational speed and this maximum shaft torque varies approximately as the square of the rotational speed.

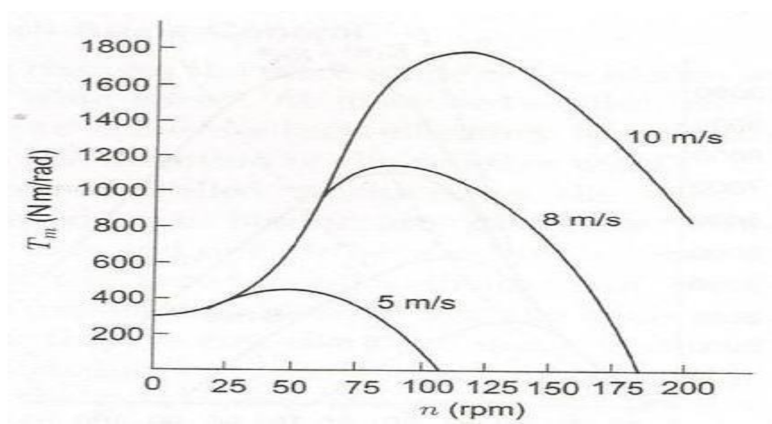


**Figure - 6: Torque - Speed Characteristics of Two blade Propeller type Rotor**

In the case of electricity production the load torque depends on the electrical loading and by properly choosing the load (or power electronics interface) the torque can be made to vary as the square of the rotational speed. The choice of the constant of proportionality of the load is very important as shown in the figure-7 below. At the optimal value,the load curve follows the maximum shaft power. But at a higher value the load torque may exceed the turbine torque for most speeds. Consequently the machine would fail to speed up above a very low value. If the constant K is lower than the optimum value the machine may overspeed at the rated wind speed activating the speed limiting mechanism. Thus the proportionality constant of the load needs to be selected from a rather narrow range , about 10-20% of the optimum power curve. Note that the point of maximum torque is not the same as that of maximum power.

As the power output is the product of torque and speed , it also has a maxima that varies as the cube of the rotational speed. The matching characteristics of the load can make the load curve pass through the maximum power points at all wind speeds. For generators that feed power to the Grid the T-S characteristics are tuned using power electronics controls.

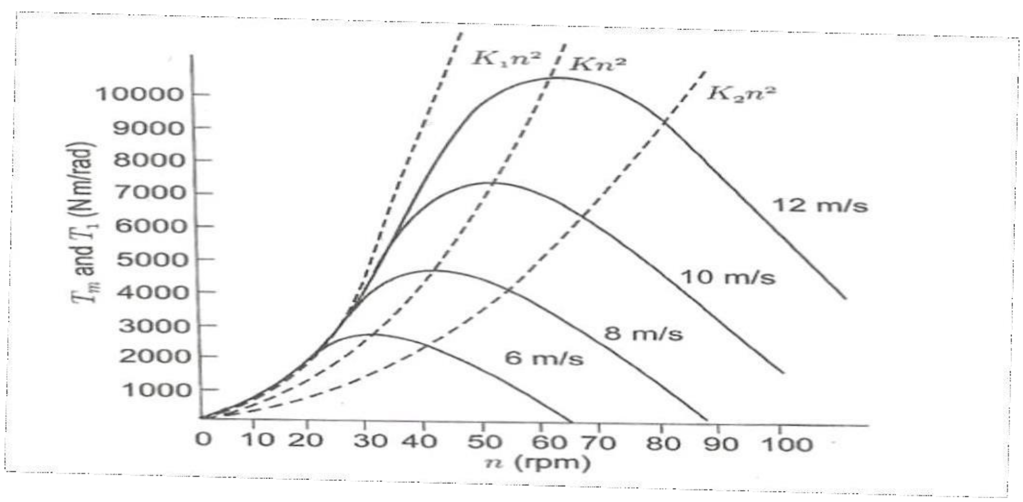


**Figure - 7: Torque Speed Characteristics of a wind turbine with T ⍺ $n^2$ load for different values of the proportionality constant 'K'**

## 8. Wind Turbine Control Systems

Wind turbines require certain control systems. Horizontal-axis wind turbines have to be oriented to face the wind. In high winds it is desirable to reduce the drive train loads and protect the generator and the power electronics equipment from overloading, by limiting the turbine power to the rated value up to the furling speed. At gust speeds, the machine has to be stalled. At low and moderate wind speeds, the aim should be to capture higher power as efficiently as possible.

Along with many operating characteristics, the technical data sheet of a turbine mentions its output at a particular wind speed, generally known as the rated wind speed. This is the minimum wind speed at which the wind turbine produces its designated output power. For most turbines, this speed is normally between 9 and 16 m/s. The choice of the rated wind speed depends on the factors related to the wind speed characteristics of a given site, which are discussed in the next unit. The Generator rating is chosen so as to best utilize the mechanical output of the turbine at the rated wind speed.

Wind turbines can have four different types of control mechanisms, as discussed in the following sections.

**Pitch Angle Control:**

This system changes the pitch angle of the blades according to the variation of wind speed. With pitch control, it is possible to achieve a high efficiency by continuously aligning the blade in the direction of the relative wind.

On a pitch-controlled machine, as the wind speed exceeds its rated speed, the blades are gradually turned about the longitudinal axis and out of the wind to increase the pitch angle. This reduces the aerodynamic efficiency of the rotor, and the rotor output power decreases. When the wind speed exceeds the safe limits for the systems, the pitch angle is so changed that the power output reduces to zero and the machine shifts to the ‘stall’ mode. After the gust passes, the pitch angle is reset to the normal position and the turbine is restarted. At normal wind speeds, the blade pitch angle should ideally settle to a value at which the output power equals the rated power.

The Pitch angle control principle is shown in the figure-8 below. The input variable to the pitch controller is the error signal which is the difference between the output electrical power and the reference power. The pitch controller operates the blade actuator to alter the pitch angle. During operation below the rated speed, the control system commands to pitch the blade at an angle that maximizes the rotor efficiency. The generator must be able to absorb the mechanical power output and deliver to the load. Hence, the generator output power needs to be simultaneously adjusted.

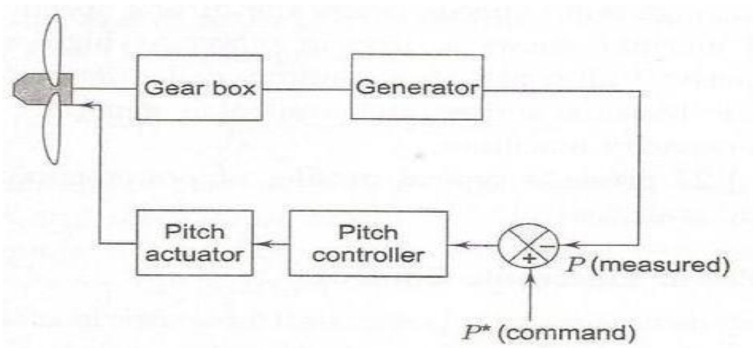


**Figure - 8: The feedback loop for pitch angle control**

Cotinuous pitch control is relatively expensive to incorporate and the cost-benfit trade-off does not justify its use in small wind machines. However, the stalling mechansiam must be incorporated to prevent damage of the turbine during turbulent weather conditions.

**Stall Control:**

**Passive stall control**

Stall control is generally applied to limit the power output at high winds to constant-pitch turbines driving induction generators connected to the network.

The rotor speed is fixed by the network, allowing only 1-4% variation. As the wind speed increases, the angle of attack also increases for a blade running at a near constant speed. Beyond a particular angle of attack, the lift force decreases,causing the rotor efficiency to drop. This is an intrinsic property and does not need any complex control /actuation system. The lift force can be further reduced to restrict the power output at high winds by properly shaping the rotor blade profile to create turbulence on the rotor blade side not facing the wind.

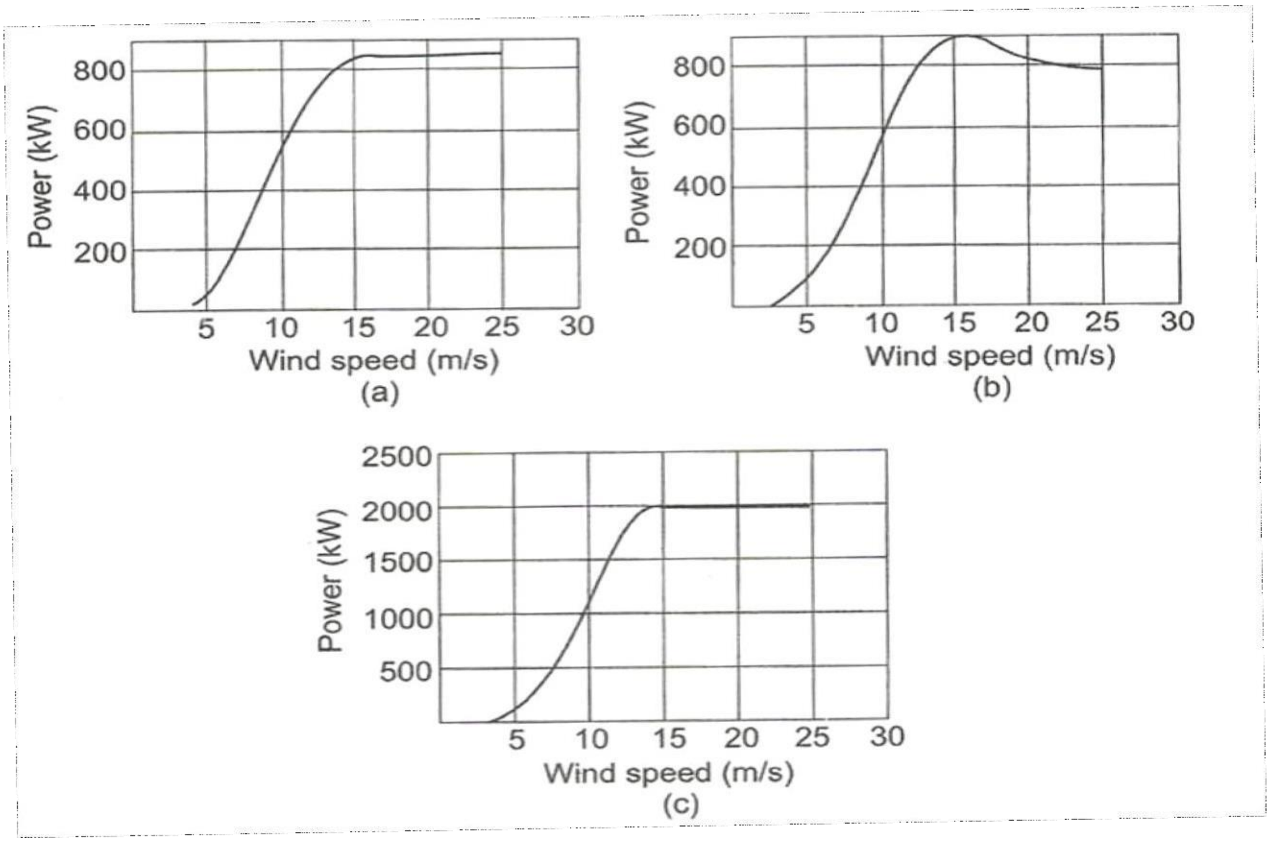


**Figure - 9: Typical power profile: (a) pitch control (b) passive stall control (c) active stall control**

**Active stall control**

In this method of control, at high wind speeds the blade is rotated by a few degrees in the direction opposite to that in a pitch-controlled machine. This increases the angle of attack, which can be controlled to keep the output power at its rated value at all high wind speeds below the furling speed. A passive controlled machine shows a drop in power at high winds. The action of active stall control is sometimes called deep stall. Owing to economic reasons, active stall control is generally used only with high-capacity machines.

Figure-9 above presents typical profiles of power curve for pitch control and stall control.

**Yaw Control:**

This control orients the turbine continuously along the direction of wind flow. In small turbines this is achieved with a tail-vane. In large machines this is achieved using motorized control systems activated either by a fan-tail (a small turbine mounted perpendicular instrument to the main turbine) or, in case of wind farms,by a centralized instrument for the detection of the wind direction. It is also possible to achieve yaw control without any additional mechanism, simply by mounting the turbine downwind so that the thrust force automatically pushes the turbine in the direction of the wind.

The yaw control mechanism can also be used for speed control. The rotor is made to face away from the wind direction at high wind speeds, thereby reducing the mechanical power. However, this method is seldom used where pitch control is available, because of the stresses it produces on the rotor blades. Yawing often produces loud noise, and it is desirable to restrict the yawing rate in large machines to reduce the noise.

## 9. Control Strategy

**Speed Control:** For every wind turbine, rotor speed control is necessary for three reasons:

- To capture maximum possible energy.
- To protect the rotor, the generator and the power electronic equipment from

overloading at high wind.

- When the generator is disconnected accidentally or for a scheduled event, losing the electrical load. Under this condition, the rotor speed may run away, destroying it mechanically, if it is not controlled.

There are five different ranges of wind speed, which require different speedcontrol strategies as shown in figure - 10 below.

1. Below a cut-in speed, the machine does not produce power. If the rotor has a sufficient starting torque, it may start rotating below this wind speed. However, no power is extracted and the rotor rotates freely. In many modern designs the aerodynamic torque produced at the standstill condition is quite low and the rotor has to be started (by working the generator in the motor mode) at the cut-in wind speed.
2. At normal wind speeds, maximum power is extracted from wind. We know that the maximum power point is achieved at a specific (constant) value of the TSR. Therefore, to track the maximum power point, the rotational speed has to be changed continuously in proportion to the wind speed.
3. At high winds, the rotor speed is limited to a maximum value depending on the design limit of the mechanical sub systems. In this region, the $C_p$ is lower than the maximum, and the power output is not proportional to the cube of the wind speed.
4. At even higher wind speeds, the power output is kept constant at the maximum value allowed by the Electrical generator.
5. At a certain cut-out or furling wind speed, the power generation is shut down and the rotation stopped in order to protect the system components.

The last three control regimes can be realized with yaw control, pitch anglecontrol (if these are installed ), and eddy-current or mechanical brakes.

In the intermediate-speed range, the control strategy depends on the type of electrical power generating system used, and can be divided into two basic categories.

(a) The constant-speed generation scheme, and
(b) The variable-speed generation scheme.

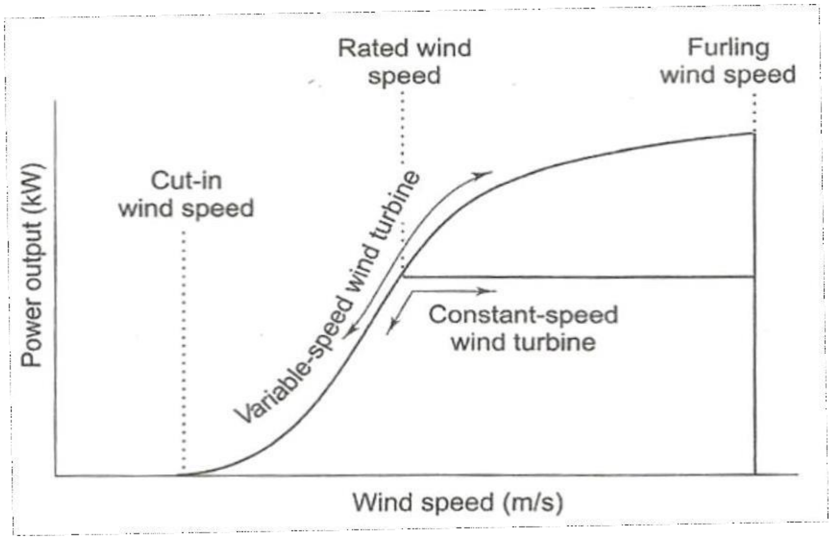


**Figure - 10 : Typical Power versus wind speed characteristics of variable speedwind machines**

The constant-speed generation scheme is necessary if the electrical system involves a grid-connected synchronous generator (the details are given in subsequent units). In the case of grid-connected squirrel cage induction generators, the allowable range of speed variation is very small, requiring an almost constant rotational speed.

However, constant-speed generation systems cannot maximize the extraction of the power contained in wind. We can see from Fig.1. 2 that the power coefficient reaches a maximum at a specific value of TSR for every type of wind turbine. Therefore, to extract the maximum amount of power from the wind, the turbine should operate at a constant TSR, which means that the rotational speed should be proportional to the wind speed. Hence the extraction of maximum power requires a variable-speed generation system with the speed control aimed at keeping a constant TSR.

Such systems can yield 20-30% more power than constant-speed generation systems. With the development of induction generators and power electronic converters, designers are favoring variable-speed generation systems. We will, therefore, discuss the control strategies for such systems in greater detail.

The constant-TSR region, which encompasses the largest range of wind speeds, is generally achieved by regulating the mechanical power input through pitch control or the electrical power output by power electronics control. In many cases a combination of both is employed.

## 10. Summary points and Important Relations

- Thrust-operated wind turbines are inherently less efficient than lift- operated wind turbines.
- The wind turbines we discuss in this course are all Horizontal axis propellor type and Lift operated.
- The important mechanical characteristics of wind turbine such as power-speed characteristics and torque-speed characteristics, which will be needed in the later units, are treated here.
- Finally, the control systems necessary for running a wind turbine are discussed.

- Power 'P' contained in the wind is given by :

$$P = \frac{1}{2}(\rho A V) \cdot V^2 = \frac{1}{2}\rho A V^3 \ watts.$$

- Two potential wind sites are compared in terms of the specific wind power expressed in watts per square meter of area swept by the rotating blades. Itis also referred to as the power density of the site, and is given by the following expression:

$$Specific\ Power\ of\ the\ site = \frac{1}{2}\rho \cdot V^3 \ watts\ per\ m^2\ of\ the\ rotor\ swept\ area$$

This is the power in the upstream wind.

- The power extracted by the blades is expressed as a fraction of the upstream wind power as follows.

$$P_o = \frac{1}{2}\rho \cdot A \cdot V^3 \cdot C_p$$

Where $$C_p = \frac{\left(1+\frac{V_o}{V}\right)\left[1-\left(\frac{V_o}{V}\right)^2\right]}{2}$$

And $C_p$ is the fraction of the upstream wind power, which is captured by the rotor blades and is called the 'power coefficient' of the rotor or 'rotor efficiency'. For a given upstream wind speed, the value of $C_p$ depends on the ratio of the downstream to the upstream wind speeds, that is ($V_o$/V).
With $C_p$ as 0.5 the maximum power becomes:

$$P_{max} = \frac{1}{4} \cdot \rho \cdot V^3 \text{ watts per m}^2 \text{ of swept area.}$$

- The generated power in terms of rotor diameter 'D' is given by:

$$\begin{aligned} P &= P_0 \eta_e \eta_m C_p \\ &= \frac{1}{2}\rho A V_\infty^3 \eta_e \eta_m C_p \\ &= \frac{1}{8}\pi \rho D^2 V_\infty^3 \eta_e \eta_m C_p \end{aligned}$$

Where $P_o$ is the power contained in the wind, $\eta_m$ is the efficiency of the mechanical transmission and $\eta_e$ is the efficiency of electrical generation. ($V_\infty$ is same as V i.e. upstream wind speed)

- **Rotor Swept Area:** For the horizontal axis turbine, the rotor swept area is given by:

$$A = \frac{\pi}{4} D^2$$

where **'D'** is the rotor diameter.

- **Tip speed ratio:** (TSR) denoted by λ of a wind turbine is given by :

$$\boldsymbol{\lambda = (2\pi RN)/ V}$$

where λ is the TSR (non dimensional), R is the radius of the swept area (in meters), N is the rotational speed in revolutions per second and V is the wind speed (without rotor interruption in meters/second)

- **The power coefficient $C_p$**: of a wind energy converter is given by:
  **$C_p$ = (Power output from the wind machine)/(Power contained in the wind)**

- For a given wind speed , the power extracted from the wind is maximised if $C_P$ is maximised. The optimum value of $C_P$, say $C_{Popt}$,always occurs at a definite value of λ say(= $\lambda_{opt}$). This means that for varying wind speed, the rotor speed should be adjusted proportionally to adhere to this value of λ (= $\lambda_{opt}$) for maximum mechanical output power from the turbine. Using the relation λ = ωR/V(2πNR/V) in the equation:

$$P_m = \frac{1}{2}\rho C_p \pi R^2 V_\infty^3$$

the maximum value of the shaft mechanical power for any wind speed can then be expressed as :

$$P_{max} = \tfrac{1}{2}\, \rho C_{popt} \pi \,( R^5/\lambda_{opt}^3)\omega^3$$

**Thus the maximum mechanical power that can be extracted from wind is proportional to the cube of the rotor speed i.e.$P_{max}$a $\omega^3$**

- Torque and power are related as: $T_m = P_m/\omega$

  Hence from the above equation: $P_{max} = \tfrac{1}{2}\, \rho C_{popt} \pi \,( R^5/\lambda^3_{opt})\omega^3$

  at the optimum operating point ($C_{popt}$, $\lambda_{opt}$ ), the relation between aerodynamic torque and rotational speed is given by :

$$T_m = \frac{1}{2}\rho C_{p,\mathrm{opt}} \pi \left(\frac{R^5}{\lambda_{\mathrm{opt}}^3}\right)\omega^2$$

**It is seen that at the optimum operating point on the $C_P$-λ curve, the torque'$T_m$'is proportional to the square of the rotor speed i.e.$T_m \alpha\ \omega^2$**

## 11. Illustrative Examples

**Example - 1: (We should not Use Average Wind speed)** Compare the energy at15◦C, 1 atm pressure, contained in 1 $m^2$ of the following wind regimes:

a) 100 hours of 6-m/s winds (13.4 mph),

b) 50 hours at 3 m/s plus 50 hours at 9 m/s (i.e., an average wind speed of 6 m/s)

**Solution:**

a) With steady 6 m/s winds, all we have to do is multiply power given by equation (1.3) times hours:

Energy at (6 m/s) = $\frac{1}{2}\rho A V^3 t = \frac{1}{2}.\ 1.225\ kg/m^3 \cdot 1\ m^2 \cdot (6\ m/s)^3 \cdot 100\ h$
= 13,230 Wh

b) With 50 h at 3 m/s

Energy at (3 m/s) = $\frac{1}{2}\rho A V^3 t = \frac{1}{2}.\ 1.225\ kg/m^3 \cdot 1\ m^2 \cdot (3\ m/s)^3 \cdot 50\ h$
= 827 Wh

And with 50 h at 9 m/s contains

Energy at (9 m/s) = $\frac{1}{2}\rho A V^3 t = \frac{1}{2}.\ 1.225\ kg/m^3 \cdot 1\ m^2 \cdot (9m/s)^3 \cdot 50\ h$
= 22,326 Wh

Making a total energy of 827 + 22,326 = 23,152 Wh

Important Point to be noted: Though the average wind velocity of 50 hours of 3m/s plus 50 hours of 9m/s is same as the average of 100 hours of 6m/s the energy during the same period of 100 hours is not the same in the two cases. This is because of the fact that the power contained in the wind is proportional to the cube of the velocity. So in such cases we have to take the average of $V^3$ and not average of V while calculating the total energy. This aspect will be dealt with in detail in unit -2 while studying wind statistics.

**Example - 2 :** Find the diameter of a wind turbine to generate 4kW at a wind speed of 7 m/s and a rotor speed of 120 RPM . Assume a power coefficient of 0.4, efficiency of mechanical transmission of 0.9 and efficiency of generator 0.95.

**Solution:** Applying the above equation for Generator power in terms of Rotor diameter we get:

Generator Power P $= \frac{1}{8}\pi\rho D^2 V_\infty^3 \eta_e \eta_m C_p$

$4.0 = (1/8) \times \pi \times 1.225 \times D^2 \times 7^3 \times 0.95 \times 0.9 \times 0.4$

Solving which we get D = 8.42 m

**Example - 3: How Fast Does a Big Wind Turbine Turns ? :** A 40-m diameter (D) , three bladed wind turbine produces 600 kW at a wind speed of 14 m/s. Air density is the standard 1.225 kg/m$^3$. Under these conditions,

a) At what rpm does the rotor turn when it operates with a TSR of 4.0?

b) What is the tip speed of the rotor?

c) If the generator needs to turn at 1800 rpm, what gear ratio is needed to match the rotor speed to the generator speed?

d. What is the efficiency of the complete wind turbine (blades, gear box, generator) under these conditions?

**Solution:**

**a)** The tip speed ratio of a wind turbine is given by λ = (2πRN)/ V or (πDN /V) where λ is the TSR (non dimensional), D is the diameter of the swept area (in meters), N is the rotational speed in revolutions per second and V is the wind speed without rotor interruption in meters/second).

From which we get **N = λ.V/πD**

Substituting the given values we get:

**Rotor Speed** N = (4x14)/40π = 0.446 RPS or **26.7 RPM**

**b)** The tip speed of each blade is given by: **Tip speed** = (πDN)m/s
= 40.π.0.446
= **56 m/s**

The same answer could have been obtained from the other simpler relation also. i.e. Tip speed is given by: λ = Tip Speed ( m/s)/(wind speed without rotor interruption in meters/second) or

**Tip Speed** = $\lambda$ x Wind speed = 4x14 = **56 m/s**

**c)** If the generator needs to spin at 1800 rpm, then the gear box in the nacelle must increase the rotor shaft speed by a factor of
**Gear ratio** = Generator rpm / Rotor rpm = 1800 / 26.7 = **67.4**

**d)** From (1.3) the power in the wind is given by: P = ½$\rho AV^3$Substituting the given values we get:

$$P = ½ .1.225. \pi . ¼ .40^2 \times 14^3 = 2112 \text{ kW}$$

So the overall efficiency of the wind turbine, from wind power to final electrical power =600 / 2112 = 0.284 = **28.4%**

## 12. Important questions

1. Derive an expression for the Power contained in wind.
2.Derive an expression for the limit on efficiency in wind energy conversion (Derive an expression for "Betz limit "in wind energy conversion and explain in detail with relevant plot).

3. Define and explain the terms: Solidity, Rotor Swept Area, Tip speed ratio, Power Coefficient in wind energy systems.

4. Explain the following subsystems of a Wind Turbine: (a) Tower (b) Nacelle and the subsystems in side.

5. (a) From an understanding of the Power coeffcient of wind turbne draw the Power- speed curves of a wind turbine and explain the same.

(b) Using a separate plot show the $C_p$ versus TSR curves for different Pitch angles and explain the dependence of these curves on the Pitch angle.

(c) From the same concept that $C_{Popt}$ always occurs at a definite value of $\lambda$ say(= $\lambda_{opt}$) derive an expression for $P_{max}$ in terms of $C_{Popt}$ & $\lambda_{opt}$ and prove that $P_{max}$ is proportinal to $\omega^3$

6.Explain with suitable plots the Torque speed characteristics of typical Propellor type wind turbines. Uisng the plots along with load-torque characteristics explain the importance of matching them with suitable proportionality constant K.

7. (a) Explain the need for the control systems in wind Turbines.

(b) Explain in detail the need and functioning of the following control systems in Horizontal Axis Wind Turbines. (i) Pitch angle control (ii) Stall control (iii) Yaw control

8. With the help of Typical Power versus wind speed characteristics of variable speed wind machines show and explain the different speed control regions and the strategy of control adopted in those regions.

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# UNIT-IV: CLASSIFICATION OF WIND POWER GENERATION SCHEMES & SELFEXCITED INDUCTION GENERATORS

**CONTENTS**

## Introduction:

This unit consists of two parts. In the first part we will study the classification of wind power generation schemes in four important ways based on three important criteria:

***(a)*** Use of Wind Turbine in **Fixed speed** mode vs. **Variable speed**

***(b)*** Choice of Generator: Induction Generator in **Single out put mode**,(Squirrel cage Induction Generator) Wound Rotor Induction Generator in **double output mode**, ( Doubly Fed Induction Generator) and **Synchronous Generator**( Both wound field and Permanent magnet type)

***(c)*** **Grid connected** versus **Self excited** mode of operation in the case of Induction Generator since it does not have its own field power supply.

This has been explained in detail since a clear understanding of the possible modes of operation and the criteria is essential for choosing the required configuration of a wind generation system based on the site conditions and power requirements.

In part two, operation of an Induction Generator in self excited mode is explained in detail starting from Basic working principle of an Induction Generator, limitations in this mode of operation and methods to overcome these limitations.

## 1. Criteria for Classification of wind power generation schemes

**Fixed and Variable Speed Wind Turbines:** We know from our earlier study in unit-3 that:

- The power contained in the wind at a particular site is proportional to the cube of the wind speed. Ideally, the maximum power that a turbine can extract is 0.593 (**the Betz coefficient or Power coefficient**) times the power contained in the wind. However, the maximum extractable power from a practical turbine is limited to 35-40% of the wind power.

- For a given turbine, this limit is achievable for a specific **tip speed ratio** i.e. ratio of the turbine's rotational speed to the wind speed. At other ratios, the turbine output reduces.
- So, with constant change in wind speed, which is a natural occurrence, it is desirable for the turbine speed to be adjustable to the wind speed in order to maximize the output i.e. we have to have variable-speed operation of wind turbines along with suitable Electrical Power Generation systems i.e. suitable Generators along with Power electronics. We also have studied that this variable turbine speed operation is possible with pitch angle control.
- Besides increased output, variable-speed turbine operation has many other advantages, in contrast to the constant-speed operation of generators in conventional power generating stations. But this operation requires additional Power electronics to convert the variable voltage and variable frequency output that comes from the Electrical generators which cannot be connected to the Grid directly. However this is not a limitation with theenormous development of Power electronics systems.
- However if Generator output is to connected to the Grid directly then the wind turbine is to be operated at a **constant speed** and it is to be connected to the Generator through a speed increasing gearbox so as to achieve the required frequency of 50 Hz. This is also possible with the same pitch angle control when the turbine speed changes with change in wind speed.

So we can summarize that, for classification of wind power Generation schemes, based on wind turbine speed two options are available **(i) Variable speed Turbines: to maximize capture of wind power from the turbine and (ii) Constant speed turbines : to avoid power electronics and connect the generator directly tothe grid.**

**Types of Electrical Power Generators:**

For wind power generation normally the following Generators are used: (i) Squirrel cage Induction generators in single output mode (ii) Wound rotor Induction generators in double output mode normally known as **D**oubly **F**ed **I**nduction **G**enerators **(DFIG)** (iii) Synchronous Generators (Wound field & Permanent Magnet).

**Self Excited Vs Grid Connected Induction Generators:**

In the above type of Generators, Squirrel Cage Induction Generators can be used in two modes: (i) Stand alone or Self Excited mode and (ii) Grid Interactive or Grid connected mode.

Further, in the Nacelle, Gear box can be used to convert the rotor speed to the required speed so that the Generator output can be connected to the Grid directly. Or without Gear box, the generator output at any frequency and voltage can be converted to Grid compatible voltage and frequency using Power Electronic converters and Inverters. This criterion is explained where ever it is required in the respective systems.

## 2. Classification of Wind Power Generation Schemes

Taking into account all the above options i.e. (a) Turbine speed: Variable versus Constant (b) Electrical generators : (i) Squirrel cage Induction Generator (ii) Doubly Fed Induction Generator (iii) Synchronous Generator ( Both wound field and Permanent magnet ), wind power Generation schemes can be broadlyclassified into the following four. After indicating in each classification the type of turbine and the type of Generator that can be chosen, each of them is further narrowed down to Self excited Vs. Grid connected.

**Constant Speed (Wind Turbine), Constant frequency (Generator output):**

This generation scheme is based on fixed-speed technology. The horizontal-axis wind turbine, whose speed can be controlled by using a pitch-control mechanism, operates at a constant speed at all operating wind speeds and drives, through a gear box, a Synchronous or an Induction generator **that is 'Grid connected'**. The main advantage in this scheme is with a fixed speed from the Gear box output, we can use directly an Induction Generator or a Synchronous Generator with a frequency and voltage corresponding to that of the Utility. This way there is no necessity for any Converter/Inverter in between the Turbine and the Generator.

A constant-speed wind turbine can achieve maximum efficiency only at one speed that gives the tip speed ratio the value corresponding to the maximum power coefficient $C_{popt}$. Its main weakness lies in its poor energy capture from the available wind power at other wind speeds. Moreover, a pitch-control mechanism adds considerably to the cost of the machines and stresses the operating mechanism and the machines.

This is a 'Constant **Speed', 'Grid connected' 'Squirrel cage Induction Generator'** based system and is covered in the next unit.

**Near-constant-speed, constant-frequency**

In this scheme, Induction Generators feed power to the utility network at variable slip. Here also the generators are driven by horizontal-axis wind turbines througha fixed ratio Gear box, but with a less stringent pitch angle controller, which can maintain small values of slip.

This also broadly comes under **'Constant Speed', 'Grid connected', 'Induction Generator'** but with a slightly higher permissible slip.

**Variable-Speed, variable-frequency**

This scheme employs **capacitor self-excited three-phase Induction Generators** forsmall-scale power generation as a source of isolated supply to feed frequency-insensitive loads directly.

Otherwise, this type of system requires efficient power electronic ac/dc/ac converters for interfacing with the utility systems. Converters using power electronic devices have good dynamic performance, and can provide high-quality sine wave current in the generator and the Power network. They can also help to control the real as well as the reactive power of the system. Furthermore, when a number of wind generators operate in parallel, the converters can optimize the output of each machine in order to increase the total power output, by allowing different machines to operate at different speeds.

This uses '**Variable speed' 'Self excited' 'Induction Generator'** and is covered in detail in this unit starting from Basic working principle of an Induction Generator, limitations in this mode of operation and methods to overcome these limitations.

**Variable-speed, Constant-frequency**

Wind turbines are basically variable-speed prime movers. This category implies a **wide and continuous range of variable-speed operation of the turbine and the processing of power ultimately at the synchronous frequency of** the utility system. Variable-speed operation of the wind turbines offers several benefits. So there is a general trend now towards generation schemes employing variable-speed turbines. There are many reasons for such a choice, which may be briefly summarized as follows.

This uses **'Variable speed' 'Grid Connected'** '**doubly fed Induction Generators' and Synchronous Generators (Both Wound field and Permanent Magnet)'**.Thisis covered in detail in the next unit.

**Advantages of Variable speed wind Turbines:**

a) Continuous operation of the wind turbines at the optimum Tip Speed Ratio (TSR) is possible by changing the rotor speed with the wind velocity. This increases energy capture even under low wind conditions.
b) Reduction in the size and weight of the gear box, or its total elimination, together with the associated noise
c) The possibility of the power smoothening due to the inertial energy storage in the turbine rotor as the wind gusts above the average level. With reduction in the wind speed, the power flow level in the network can be maintained by deriving additional energy from the inertia of the system.
d) The time trace of the power output of the constant-speed wind turbine is characterized by high-frequency fluctuations superimposed on slow power variations owing to the wind turbine control system. On the other hand, in variable speed systems, the time trace of the power output of a variable- speed system is considerably smoother due to the rotor flywheel effect.
e) Variable-speed operation can be carried out with or without a gear box (direct drive). The main advantage due to the absence of a gear box is Low maintenance, higher efficiency at low wind speeds, etc. The disadvantages area large diameter machine and/or a large electronic converter

## 3. Operation of Induction Generators in Self excited mode

Basic schematic of a Self-Excited Induction Generator is shown in the figure below.

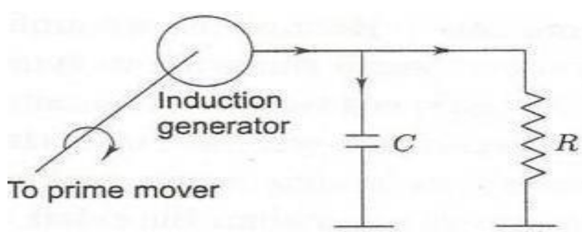


**Figure - 1: Self Excited Induction Generator**

A capacitor, when connected across the induction machine as shown, helps build up the terminal voltage. But the building up of the voltage also depends on factors such as speed, capacitor value, and load. The operation of such a system is explained in detail.

**Induction Generator - Basic Principle of operation:**

An induction machine can be made to work as both a Motor and a Generator. The extended Torque-Speed characteristic curve of an Induction Machine showing both the motoring and Generating operational regions is shown in the figure below (3-2) It can be seen from the figure, that if an induction motor is driven at aspeed greater than '$n_{sync}$' by an external prime mover, the direction of its inducted torque will reverse and it will act as a generator.

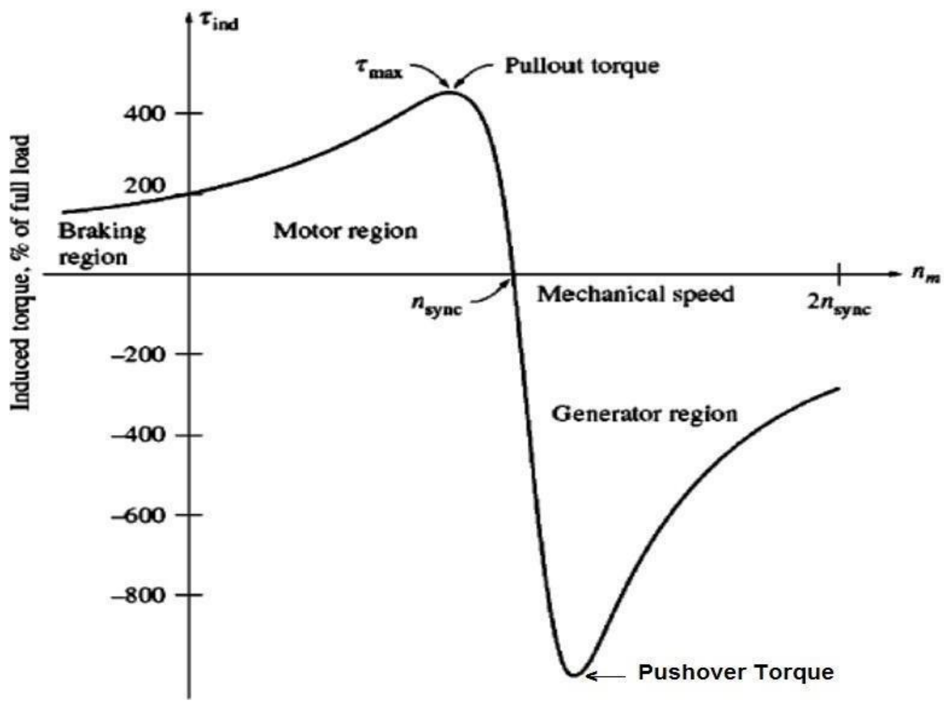


**Figure - 2: Induction motor torque-speed characteristic curve, showing the extended operating ranges (braking region and generator region). Note thepushover torque.**

As the torque applied to its shaft by the prime mover increases, the amount of power produced by the induction generator increases. As shown in the figure above (3-2), there is a maximum possible induced torque in the generator mode of operation. This torque is known as the **pushover torque** of the generator. If a prime mover applies a torque greater than the pushover torque to the shaft of an induction generator, the generator will over speed.

As a generator, however an induction machine has some limitations. Because it lacks a separate field circuit, an induction generator **cannot** produce **reactive power**. In fact, it consumes reactive power, and an external source of reactive power must be connected to it at all times to maintain its stator magnetic field. **This external source of reactive power must also control the terminal voltage of the generator. With no field current, an induction generator cannot control its own output voltage. Normally, the generator's voltage is maintained by the external power system to which it is connected.**

The one great advantage of an Induction Generator is its simplicity. An Induction Generator does not need a separate field circuit and does not have to be driven continuously at a fixed speed. As long as the machine's speed is some value greater than **'$n_{sync}$'** for the power system to which it is connected, it will function as a generator. The greater the torque applied to its shaft (up to a certain point), the greater its resulting output power. The fact that no stringent regulation is required makes this generator a good choice for windmills, heat recovery systems, and similar supplementary power sources attached to an existing power system. In such applications, the required power-factor correction can be provided by capacitors, and the generator's terminal voltage can be controlled by the external power system.

## Induction Generator - Stand alone operation: (Self excited mode)

It is also possible for an induction machine to function as an isolated generator, independent of any power system, as long as capacitors are available to supply the reactive power required by the generator and by any attached loads. Such isolated operation of an induction generator is shown in the figure -3 below.

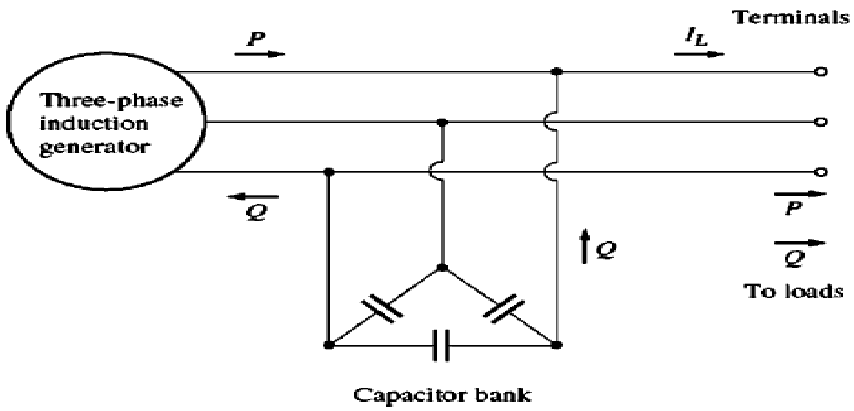


**Figure - 3: An Induction Generator operating alone with a Capacitor bank tosupply reactive power**

The magnetizing current $I_M$ required by an induction machine as a function of terminal voltage can be found by running the machine as a motor at no load and measuring its armature current as a function of terminal voltage. Such a magnetization curve is shown in figure - 4(a) below. To achieve a given voltage level in an Induction Generator, external capacitors must supply the magnetization current corresponding to that level.

Since the reactive current that a capacitor can produce is directly proportional to the voltage applied to it, the locus of all possible combinations of voltage and current through a capacitor is a straight line. Such a plot of voltage versus current for a given frequency is shown in figure – 4(b) below.

If a three-phase set of capacitors is connected across the terminals of an induction generator, the no-load voltage of the induction generator will be the intersection of the generator's magnetization curve and the capacitor's load line. The no-load terminal voltage of an induction generator for three different sets of capacitance is shown in Figure - 4(c) below.

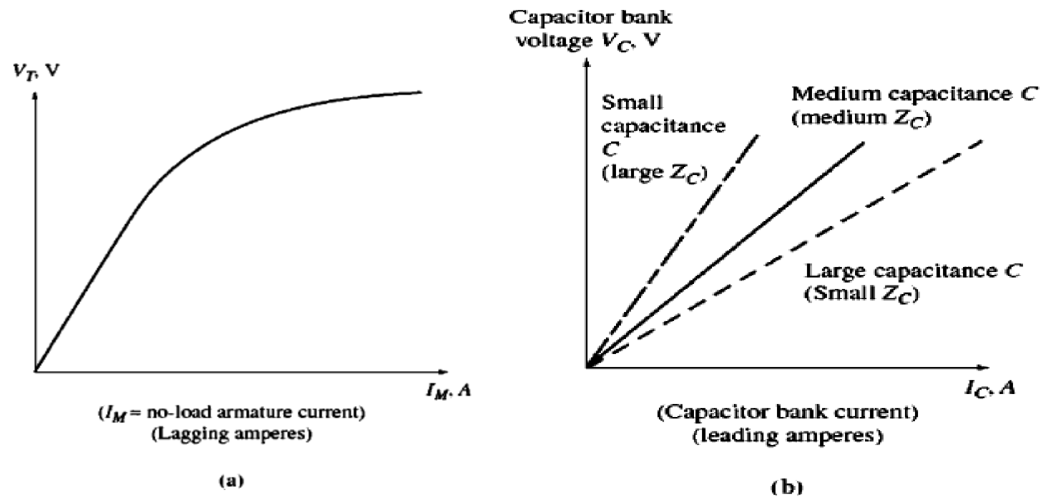


**Figure - 4 : (a) The magnetization curve of an induction machine. It is a plot of the terminal voltage of the machine as a function of its magnetization current (which lags the phase voltage by approximately 90°) (b) Plot of the voltage current characteristic of a capacitor bank. Note that the larger the capacitance the greater it's current for a given voltage. This current leads the phase voltageby approximately 90°.**

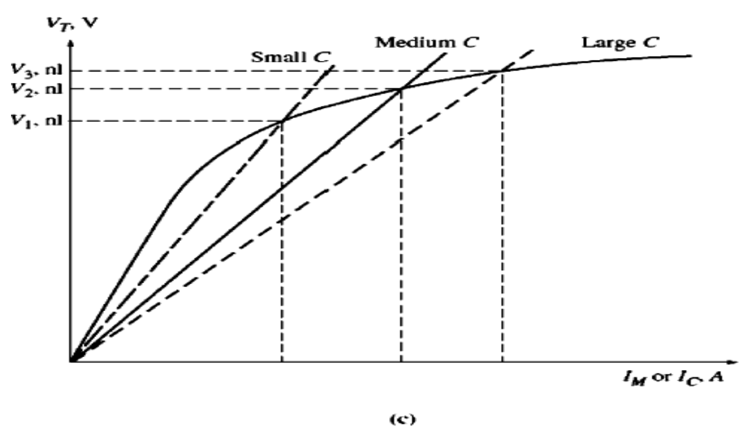


**Figure - 4(c): The no-load terminal voltage for an isolated induction generator can be found by plotting the generator terminal characteristic and the capacitorvoltage current characteristic on a single set of axes. The intersection of the twocurves is the point at which the reactive power demanded by the generator is exactly supplied by the capacitors, and this point gives the no-load terminal voltage of the generator.**

## Initial Voltage build up in a Self Excited Induction Generator:

How does the voltage build up in an Induction Generator when it is first started? When an induction generator first starts to turn, the residual magnetism in its rotor induces a small voltage in the stator windings. That small voltage produces a capacitive current flow, which increases the voltage across the stator and also across the capacitor (since capacitors are connected just across the stator terminals), further increasing the capacitive current, and so forth until the voltageis fully built up. If no residual flux is present in the induction generator's rotor, then its voltage will not build up, and it must be magnetized by momentarily running it as a motor. This is explained step by step below which can be visualized with the help of the figure 3.5 below.

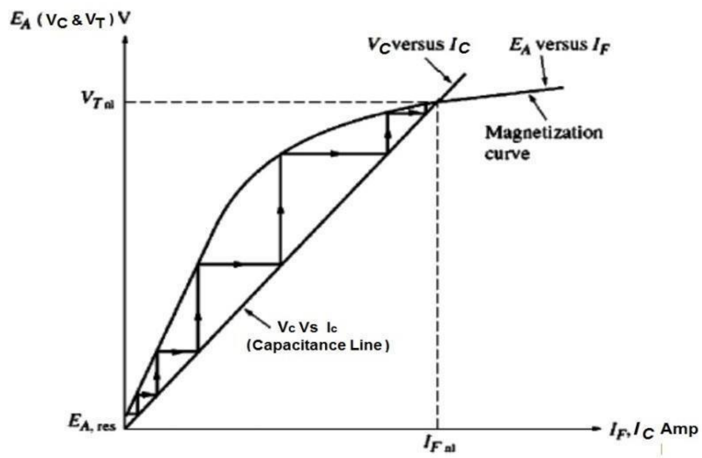


**Figure - 5: Voltage Build up in a self excited Induction Generator**

- When the Rotor is rotated, the Residual flux in the Rotor bars induces small voltage in the Stator coils.
- The increased Voltage in the stator coils increases the capacitor voltage and thus in turn capacitive current. This increased current increases the Rotor induced flux which in turn increases the stator induced Voltages and so forth.
- This cumulative process continues to build the Stator Voltages to the required level (while charging the Capacitors also to the same level). This build up is limited by the saturation characteristics of the Stator/Rotor.

Important concepts of Self Excitation in a Standalone Induction Generator:

- Excitation required for the IG Stator windings is provided by the Charged Capacitor of adequate size.
- Voltages are induced in the Stator Coils due to continuous exchange of energy between the Stator coils and the externally connected Capacitances by a process similar to Resonance.
- To initiate the excitation process, at least a small Residual flux in the Rotor is required.

The following further important qualitative relations also should be borne inmind:

- The induced voltage in the stator coils is directly proportional to the Capacitance at a given Speed.
- The induced voltage in the stator coils is directly proportional to the Speed with a given Capacitance.
- So, effectively Voltage will increase with both increase in Speed and Capacitance.
- For every Speed there is a minimum Capacitance for self excitation.
- For every Capacitance there is a minimum Speed for self excitation.

**Limitations of Induction Generator in Self Excited mode of operation:**

Self-excited Induction Generators working in isolation with variable-speed wind turbines have the following limitations:

- Poor voltage and frequency regulation. Voltage varies wildly with changes in load, especially reactive load.
- Typical terminal characteristics of an induction generator operating alone witha constant parallel capacitance are shown in the figure - 6 below.

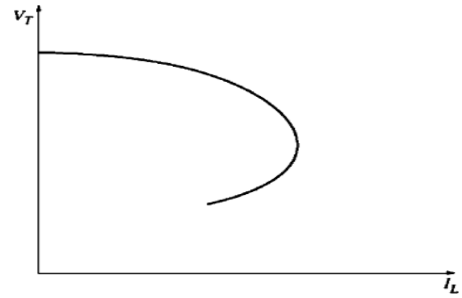


**Figure - 6: The terminal voltage - current characteristic of an induction generator for a load with a constant lagging power factor.**

- In the case of inductive loading, the voltage collapses very rapidly. This happens because the fixed capacitors must supply all the reactive power needed by both the load and the generator, and any reactive power divertedto the load moves the generator back along its magnetization curve, causing a major drop in generator voltage.
- It is therefore very difficult to start an Induction Motor on a power system supplied by an Induction Generator. Special techniques must be employed to increase the effective capacitance during starting and then decrease it during normal operation.
- But still generally, squirrel cage induction machines are chosen due to their ruggedness, low cost, and low maintenance.

## 4. Methods to overcome the limitations:

A number of methods are however available for regulating the voltage of the self-excited induction generator, each with their advantages and limitations. The application of power semiconductor devices, controlled converter circuits, and control algorithms has resulted in suitable regulating schemes for self-excited variable-speed squirrel cage generators.

We will study in this unit two such schemes for Voltage regulation in Self excited Induction Generators used in Variable speed Generation systems.

**Controlled firing angle scheme with AC-side capacitor:**

A method to obtain DC power **at a controllable voltage** from a **variable-speed generation** system is shown in the figure below (Figure 5.4). Initially, the necessary self-excitation is provided by the Residual magnetic flux & capacitor bank and the output of the generator is connected to a three-phase controlled rectifier. The attention here is focused on controlling the DC voltage, which is of prime importance, by changing the firing angle of the devices instead of changing the capacitors.

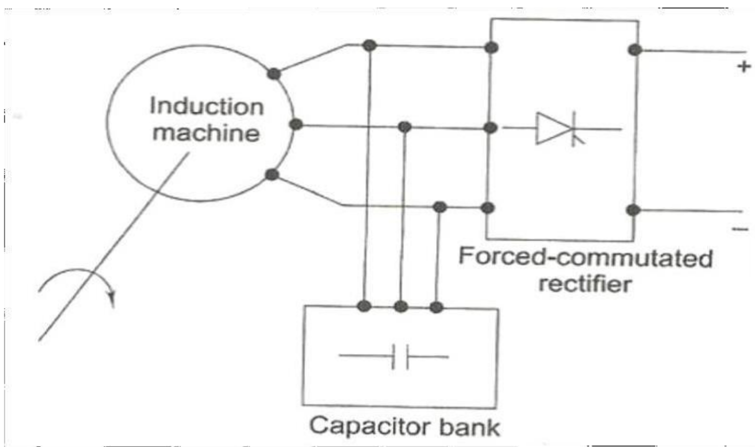


**Figure - 7: Self-excited Induction Generator with an A.C side capacitor andForced-Commutated Rectifier**

When a load is applied there is a fall in the DC voltage level due to the reduction in the net excitation given by the converter reactive current. To maintain the required output voltage regulation, the firing angle is advanced. When the limit is reached (ideally diode-bridge operation), the exciting capacitance has to be augmented.

The required change in the delay angle for maintaining a constant DC voltage is very sensitive to the speed change. At a higher speed, when the no-load voltage rises sharply, a large delay angle is required for maintaining a constant dc voltage. With a fixed excitation capacitor, the useful speed range for a constant DC voltage, employing a line-commutated controlled rectifier, is extremely restricted. The lower end of the speed range is limited by the minimum excitation speed and the upper end by the excessive rise in the induced voltage and the large delay angle required. In order to increase the speed range, the capacitance value needs to be changed. In this regard the scheme is not self-contained. To obtain a wide speed range, two or more sets of capacitor banks are needed. Therefore, the basic problems of a self-excited Induction Generator are only partially solved, but not completely.

For the same excitation capacitance, the useful speed range can be increased if a forced-commutated rectifier is used in place of a line-commutated rectifier. The basic principle is enunciated by the voltage and the current waveforms shown in the figure below.

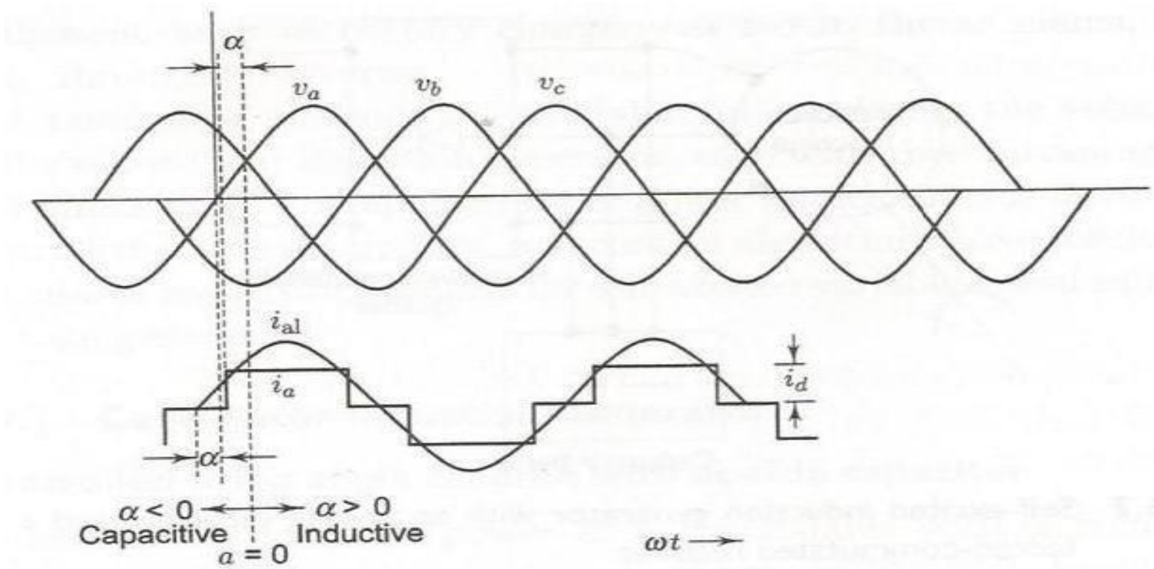


**Figure - 8: Input Voltage and Current waveforms**

It assumes sinusoidal converter input voltages, ripple-free output current, and ideal switching elements. Advancing the firing angle (i.e., negative delay angle) produces a capacitive effect at the machine terminals since the rectifier input current now leads the corresponding voltage. This is in tune with the requirements of a self-excited induction generator, where the effective excitation capacitance must increase with increasing load current. At high speeds and light loads, the firing angle can be delayed (i.e., α made positive) so that the rectifier appears as an equivalent RL load to reduce the effective VAR supplied to the machine and thereby avoid high voltage at the machine terminals.

**Inverter/converter system with DC-side capacitor:**

In conventional **self- excited variable-speed induction generators** with a bank of capacitors connected across the machine terminals, **the value of capacitance required is almost inversely proportional to the square of the prime mover speed,** calling for impracticably large values of capacitance at low speeds. Even then, further stages of power conversion are needed to feed conventional DC/AC loads due to the variable magnitude and frequency of the generated voltages. These problems can be overcome to a large extent by using a Power Converter with a large DC-side capacitor connected between the Induction Generator and the power network. This power conversion equipment comprises two fully controllable pulse width modulated voltage source inverters to provide independent control of the net generator current. Both of them have bidirectionalsinusoidal operation. The power flow into and out of bridge 1 (connected on the Grid side and not shown in the figure below ) and the voltage of the dc link can be controlled by controlling the phase and the magnitude of the modulating signal relative to the network voltage. Bridge 2 (connected on the Generator side) can be controlled by the conventional scalar variable-voltage/variable-frequency method. This scheme is outlined below with reference to a DC load.

The scalar method shown in Figure 5.4 gives the control scheme of an induction generator-static inverter system with a DC load and capacitor. The frequency of the inverter is adjusted to give a small negative slip. Assuming that the capacitor voltage builds up to a steady value, the working of the system can be described as follows. The PWM inverter converts the dc voltage into ac voltage, which supplies the necessary magnetizing ampere-turns to establish the air-gap flux of the machine. If the slip is made negative, the mechanical power gets converted into electrical power, which, through the feedback diodes of the inverter, supplies the load connected across the capacitor. At the same time, it also replenishes the charge that has been drained from the capacitor.

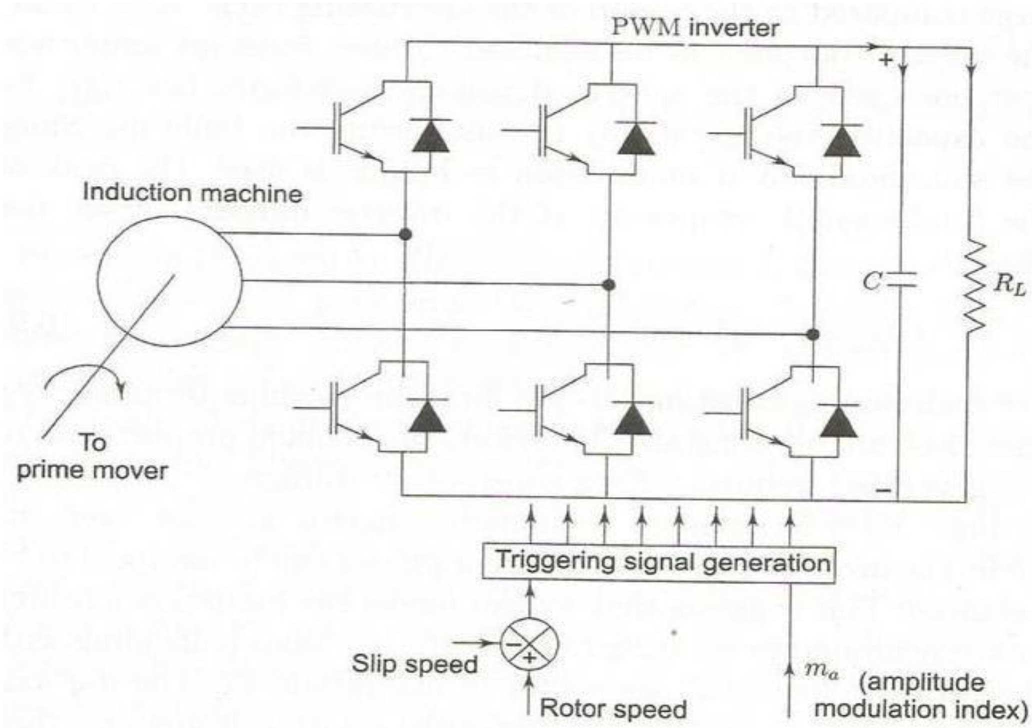


**Figure - 9: Self excited Induction Generator with a DC side Capacitor and aConverter /Inverter system**

An increase in the load tends to decrease the capacitor voltage, which can be compensated by *increasing the slip, i.e., reducing the inverter frequency. Again, in order to maintain a nearly constant dc voltage at reduced prime mover speed,it is necessary to **reduce the modulation index ($m_a$) of the inverter in proportionto the speed. Thus, to have a fairly constant dc voltage for varying loads and prime mover speeds, the slip as well as '$m_a$' should be controlled. Although the output of the system is dc, its near constant value makes it easier both forsupplying it to DC loads and for feeding it to AC loads through an Inverter.

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*By increasing slip , Rotor power ( Slip Power )increases and hence decrease in capacitor voltage can be compensated.

** In a PWM inverter the line to line voltage **'$V_{LL}$'** can be shown to be proportional to the modulation Index **'$m_a$'** and **'$V_{DC}$'**( link voltage) **i.e. $V_{LL}$= K. $m_a$ .$V_{DC}$** where **'$m_a$'** the modulation Index is defined as **the ratio of modulating sine wave amplitude '$V_m$' to the carrier ( triangular wave ) wave amplitude '$V_t$'.**

**Hence to maintain constant $V_{DC}$ which falls due to higher load current, '$m_a$' is tobe reduced while simultaneously slip is increased.**

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The system has several advantages: (a) A single large dc capacitor is sufficient, instead of several banks of ac capacitors. (b) The value of the DC capacitor is not critical provided it is sufficiently large, and (c) The output voltage can be maintained constant over a wide range of speeds.

For maintaining constant air-gap flux, the machine terminal V/f should be almost constant. Therefore, $m_a$ is made proportional to the generated frequency for a constant DC voltage.

## 5. Summary – Important Concepts /Relations:

- This chapter explains in detail classification of various methods of Wind power generation based on the possible use of wind turbine in variable speed and constant speed in conjunction with Induction Generators, DFIGs, Synchronous generators ( both wound field and Permanent magnet) highlighting the various advantages and disadvantages.
- Self-excited Induction Generators working in isolation with variable-speed prime movers, such as wind turbines have Poor voltage and frequency regulation. Voltage varies wildly with changes in load, especially reactive load.

- In this unit these limitations were explained in detail.
- Two effective methods to overcome these limitations and get controlled output also have been explained. They are :
    - Controlled firing angle scheme with AC-side capacitor:
    - Inverter/converter system with DC-side capacitor:

## 6. Important Questions:

1. (a) Name and explain the four basic schemes of Electrical power generation with wind turbines.

(b) Elaborate in detail the advantages of Variable speed - constant frequency scheme.

2. (a) Explain the basic principle of operation of an Induction Generator showing the Torque –Speed Characteristic of an Induction Machine beyond the Synchronous speed.
(b) Explain step by step the process of self excitation in a squirrel cage Induction Generator with capacitors on the stator side with the help of the open circuit magnetization curve and the capacitance lines.
(c) Highlight important concepts of Self Excitation in a Standalone Induction Generator along with a summary of qualitative relations.
3. Explain the limitations of Cage Rotor Induction Generator in standalone operation. (In self excited mode)

4. Explain how the above limitations can be overcome to obtain DC power at a controllable voltage using Controlled firing angle scheme with ac-side capacitor from a Cage Rotor Induction Generator.

5. Explain with the help of a suitable block diagram the method to obtain DC power at a controllable voltage with DC-side capacitor from a (SCIG) Squirrel CageInduction Generator.

*******

# UNIT-V

# GRID INTEGRATION OF WIND TURBINE

**SYSTEMSCONTENTS:**

**Introduction:** This unit consists of two parts. In first part we will study operation of Grid connected Induction generators and Synchronous generators. In second part we will study the general technical features of Integration of Wind turbines tothe Grid like interface requirements, synchronizing procedures, effect of Connecting wind Generators on the network etc.

**1. Grid connected Induction generators operation:** As we know, there aretwo ways of exciting an Induction Generator Viz. **(a) Grid Connected** and **(b) Self excited**.

Out of these two systems we have already studied **(b)** operation of **Self excited Induction Generators** in the previous unit (Unit-4).We will study in this unit **(a)** operation of **Grid Connected Induction Generators**. A simple schematic is shown in the figure below. Here the stator terminals are directly connected to the Bus and the Rotor is driven by a Prime mover at speeds higher than the Synchronous speed.

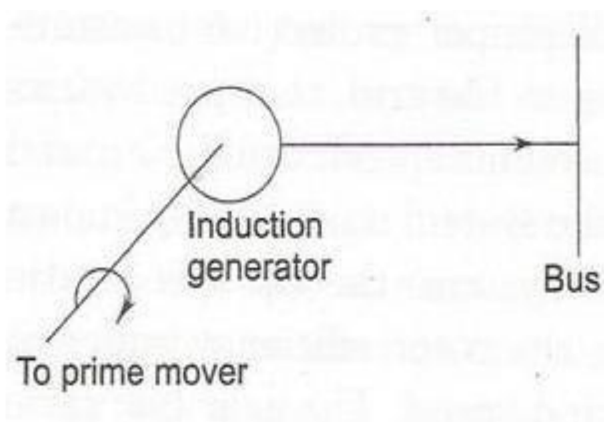


**Figure - 1: Grid Connected Induction Generator**

**Single-Output System - Fixed-Speed**

The term Single Output implies the use of a Squirrel Cage Induction Generator **(SCIG)**, which provides the power output only through the stator winding. Figure below (5.2) illustrates the configuration. It requires a grid-connected Squirrel **C**age

**I**nduction **G**enerator coupled to a turbine through a gear box. The gear box steps up the rotor speed to a value matching a 50 or 60 Hz utility network. (1500 or 1800 RPM for a 4 pole machine)

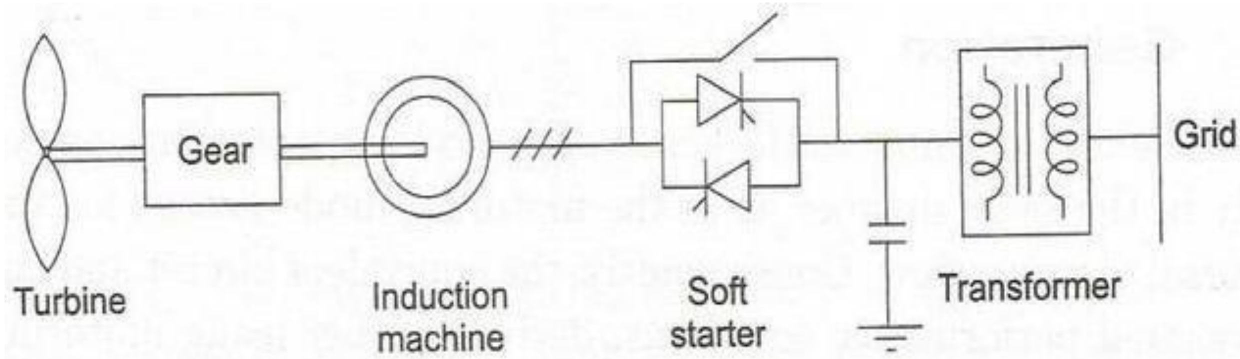


**Figure - 2: Fixed Speed Wind Turbine system with a Squirrel Cage InductionGenerator.**

The Induction Generator always draws reactive power from the network. Capacitors are used to compensate this lagging VAR. These capacitors may cause the induction machine to self-excite, leading to over voltages at the time of the disconnection of the wind turbine Generator from the electrical system if proper protective measures are not taken. Because of its coupling to the grid, the speed Varies over a very small range above synchronous speed, usually around 1%. As the speed variation is small, the system is commonly known as a **fixed-speed** system. For such a system, the tip speed ratio **'λ'** varies over a wide range in inverse proportion to the wind speed , making the rotor efficiency suffer at wind speeds other than the rated wind speed. The gear box ratio is selected for optimum **'$C_P$'** for the most frequent wind speed. In a well-designed system, fixed- speed operation can extract about 80% of the energy available from a fully variable speed system over a year. Fixed-speed wind turbines employing either blade pitch regulation or stall regulation are used to limit the power at high wind speeds. It is necessary to do so because if the input mechanical power is more than the power corresponding to the Pull-out torque, the system becomes unstable.

Appreciable generation at low wind speeds requires reduced rotor speed. To achieve this, one can use a two-speed cage-type Induction generator with a stator winding arrangement for two different numbers of poles. The large number of poles is for low wind speed and the small number of poles is for high wind speed. An appropriately designed two-speed system can extract as high as 90% of the energy obtainable from a 100% variable-speed system over a year. With a two-speed system, the audible noise at lower wind speed is reduced.

Usually, the turbine accelerates the induction machine to synchronous speed using wind power. The machine is then connected to the grid. The direct connection of an induction machine to the Supply produces high inrush current, which is undesirable, particularly in the case of electrical networks with low fault tolerance levels. Such a connection can also cause torque pulsations, leading to gear box damage. In order to reduce the magnetizing current surge, soft-start circuits utilizing phase-controlled anti parallel thyristors (ac voltage controllers), as illustrated in figure 4.2, are frequently employed to control the applied stator voltage when the induction machine is connected to the network. A few seconds later, when normal current is established, these starting devices are bypassed. Such AC voltage controllers can also be used for connecting the machine to the grid during acceleration from zero speed to the operating speed.
Advantages: of a grid-connected, fixed-speed squirrel cage generator is its lower capital cost, Simple System configuration, and robust mechanical design.
Disadvantages: As the rotor speed is nearly constant, fluctuations in Wind speed result in torque (and hence power) excursions, which may lead to unwanted grid voltage fluctuation and mechanical strain on the turbine components. Wind gusts in particular lead to large torque variations.

**Double-Output System – Variable Speed:**

The wound rotor induction machine, commonly known as the **D**ouble **O**utput **I**nduction **G**enerator **(DOIG)** or **D**oubly **F**ed **I**nduction **G**enerator **(DFIG)** is finding increasing application, particularly in the megawatt range, in **variable-speed** wind energy conversion systems. When compared with motoring operation, the power handling capability of a wound rotor Induction machine as generator theoretically becomes nearly double. The rotor of generator is coupled to the turbine shaft through a gear box so that a standard (1500/1800 rpm) wound rotor induction machine can be used. The gear ratio is so chosen that the machine's synchronous speed falls nearly in the middle of the allowable speed range of the turbine (nearly 60 – 110 % ).Above the rated wind speed, power is limited to the rated value by pitching the blades.

To start with the basic operation of a **D**ouble **O**utput **I**nduction **G**enerator (**DOIG**) can be explained with the help of the power flow diagram shown below. As we know, in an Induction Machine, when the Rotor is moved at a super synchronous speed (speed greater than the synchronous speed) the slip 's' is negative and the Machine works as a Generator. In this mode, the air gap power **$|P_{ag}|$** is lesser than the input mechanical Power **$|P_m|$.** As can be seen from the power flow diagram below, the input mechanical power **$P_m$** gets split into air gap power **$P_{ag}$** and slip power **$s.P_{ag}$.** Air gap power, after meeting stator copper losses **$P_{cu1}$** goes out through stator as output power **$P_1$.** In the case of a Squirrel Cage Induction Generator the slip power **$s.P_{ag}$** gets wasted as heat. But in the case of a wound rotor Induction Generator the slip power after meeting Rotor copper losses **$P_{cu2}$** can be taken as output power **$P_2$** from Rotor side and fed into the Grid in which case it is called a **DOIG**.

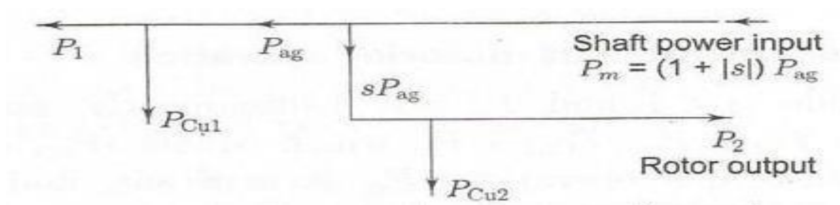


**Figure - 3: Power Flow Diagram in a Double Output Induction Generator**

With a slip-ring induction machine, power can be fed into the supply system over a wide speed range by appropriately controlling the rotor power from the variable-frequency slip power. The provision for bidirectional flow of power through the rotor circuit is achieved by the use of a slip-ring induction motor with an AC/DC/AC converter connected between the slip-ring terminals and the utility grid. The system is known as a **D**ouble **O**utput **I**nduction **G**enerator **(DOIG)** because power can be fed both from both the Stator and Rotor.

Figure 5.4 below shows the main components of a solid-state system for the controlled flow of slip power at variable speed through a current source converter/inverter.

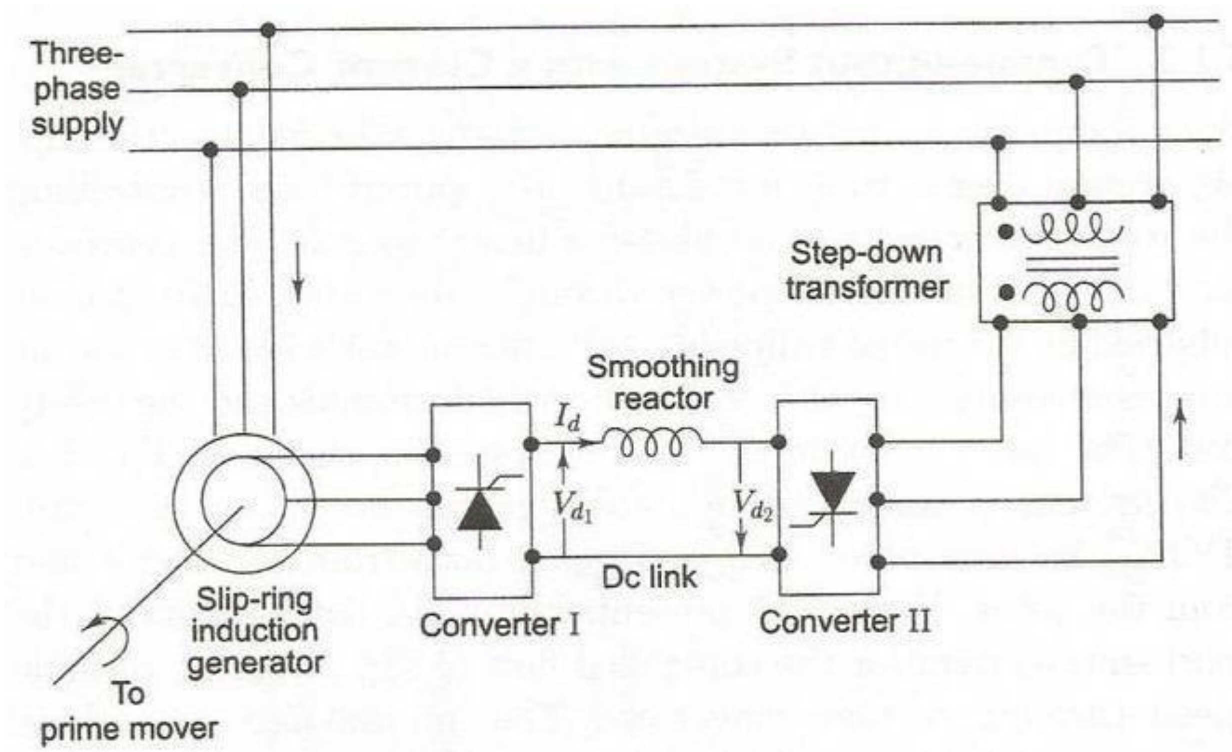


**Figure - 4: Double Output Induction Generator with Current Source Inverter**

The stator is directly connected to the fixed-frequency utility grid while the rotor collector rings are connected via back-to back current source inverters and a transformer/filter to the same utility grid. As the rotor power is a fraction of the total power of the generator, a rotor converter rating of nearly 35% of the rated turbine power is sufficient. For the transfer of electrical power from the rotor circuit to the supply, converters I and II are operated, respectively, in rectification and inversion modes.

Line-commutated converters cannot generate leading VAR, and so, for maximization of the power output, in converter-I **'$\alpha_1$'** should be set at $0^0$ (rectification mode) in the super synchronous region above the rated speed $n_r$ (Fig. 3.6) to draw power out of the rotor.

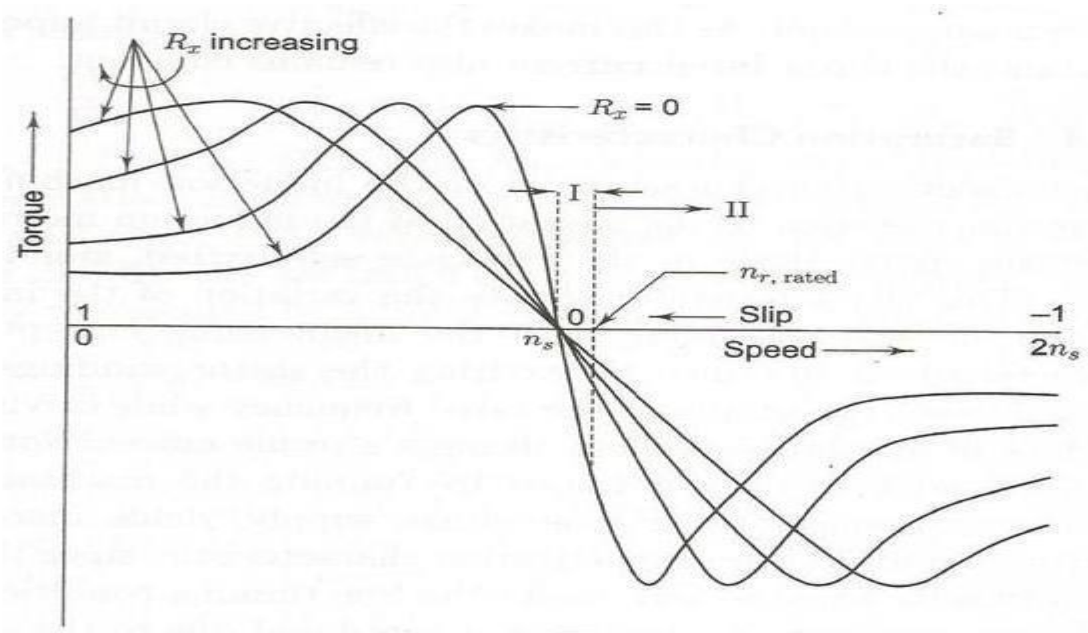


**Figure - 5: The Torque Speed Characteristics of an Induction Machine showingthe effect of Rotor Resistance variation in both Sub synchronous and super synchronous speeds.**

The grid-side converter-II enables power flow to the grid, keeping dc-link voltage level constant by controlling its firing angle **'$\alpha_2$'**. The intermediate smoothing reactor is needed to maintain current continuity and reduce ripple in the link circuit. The step-down transformer between converter-II and the supply extends the control range of the firing delay angle '**$\alpha_2$**' of converter-II.

## 2. Grid connected Synchronous Generators operation:

When it comes to **Synchronous Generators**, since they have their own field supplythe requirement of self excitation does not come into picture and all of them are Grid connected only. The only difference is if Gear box is used the Generator itself is connected to the Grid and if Frequency converter is used then it is connected tothe Grid. With the enormous development of Power electronics and its ability to control supply of both active and reactive power, in modern systems Frequency Converters are mostly used. This avoids use of gear box or at least reduces its size which in turn reduces the Nacelle weight. So we will study in this unit Operation of Grid connected Synchronous generators with Power electronics control.

**Wound-field synchronous Generator:**

**Introduction:**

In wind electric power generation systems, two types of wind turbines are generally used. These are variable-speed and constant speed turbines. The high power variable speed Synchronous Generator (750 kW to 2MW), with field windings on the Rotor is a serious competitor for the wound Rotor Induction Generator in variable speed wind turbine systems. In particular, direct drive variable-speed systems use Synchronous Machines. As the name indicates, unlike in a wound Rotor Induction Generator, the Rotor of a Synchronous Generator runs in synchronization with the field produced by the Stator winding currents.

**Operation of a Synchronous Generator in a variable-speed wind energy conversion scheme:**

A Synchronous Generator can also be employed in a variable-speed wind energy conversion scheme. To match the utility frequency, such systems use an Inverter. In the case of a self-excited squirrel cage induction generator under variable-

speed operation, the amount of lagging VAR required for voltage regulation is supplied by switched capacitors, controlled rectifiers with fixed capacitors, or frequency-controlled Generator-side voltage source inverters. In the case of a Synchronous Generator, the generated voltage can be controlled more easily by using a voltage regulator in the field circuit. It requires no shunt capacitors/controlled inductors to achieve voltage regulation.
Figure 3.7 illustrates a power generation scheme at the grid frequency, employinga variable-speed Synchronous generator with excitation control. The conversion scheme for the variable output of the Synchronous generator consists of an uncontrolled diode-bridge rectifier, a filter capacitor, a smoothing DC-link choke, and a line-commutated thyristor bridge inverter. The diode and the thyristorbridges generate harmonic currents and voltages, and their interaction results in considerable power fluctuation through the dc link. This interaction is considerably reduced by means of the capacitor filter at the output of the diode bridge. **The control strategy is based on the speed cube law for optimal power output from the wind turbine.**

We know that the EMF generated in a Synchronous Generator is given by $\mathbf{E_A = K\varphi\omega}$. Since the flux $\boldsymbol{\varphi}$ generated in the SG is proportional to the field current $\mathbf{I_f}$ (assuming magnetic linearity) we can see that the generated EMF is proportional to the product of the field current $\mathbf{I_f}$ and the speed $\boldsymbol{\omega}$. If the dc-link current $\mathbf{I_{dc}}$ and the field current $\mathbf{I_f}$ are made proportional to speed, i.e.,

$$\mathbf{I_{dc} = k_{dc}\omega}$$

And

$$\mathbf{I_f = k_f\omega}$$

Then

- The generated EMF will be proportional to $\boldsymbol{\omega^2}$ (since $\mathbf{E_A = K\varphi\omega = K.I_f .\omega = K.K_f . \omega^2}$)
- And the fundamental component of the generator current will be proportional to $\boldsymbol{\omega}$ (Since fundamental component of the generator current will be proportional to $\mathbf{I_{dc}}$ which in turn is proportional to $\boldsymbol{\omega}$ ).

However the generated power will be less than that given by the cubic power versus speed characteristics (**$p \propto \omega^3$**) owing to the synchronous reactance of the machine, which causes a phase difference between Generated EMF and the fundamental component of the stator current.

The output of the Synchronous Generator in the dc link given by

$$\mathbf{P_{dc} = V_{dc}I_{dc}}$$

This is generated power minus the stator copper loss and the diode-bridge loss. Therefore, in order to make **$P_{dc}$** follow the cubic law in speed, the field current is required to have a component dependent on **$V_{dc}$**.( to compensate for the loss in power due to drop in synchronous reactance )

In the system illustrated in Fig.3.10, the turbine (or the generator) speed and the DC-link voltage are chosen as the input variables and the DC link current **$I_{dc}$** and the Generator field current **$I_f$** as the output variables.

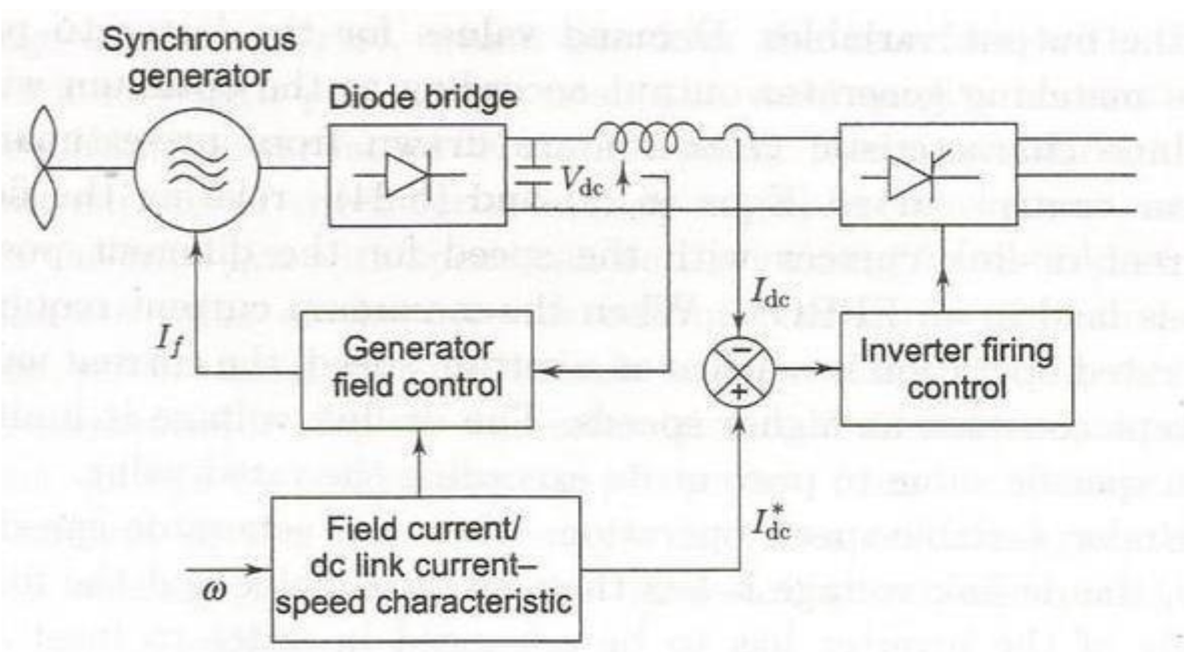


**Figure - 6: Control Scheme for a Synchronous Generator with variable SpeedDrive and Utility Interface**

The values of $\mathbf{I_{DC}}$ and $\mathbf{I_f}$ required to provide matching Generator output as per the optimum wind turbine characteristic (**$p \propto \omega^3$**) are taken from the pre estimated linear control relations (equations 3.23 and 3.2) relating $\mathbf{I_f}$ and $\mathbf{I_{DC}}$ with the speed **ω** for different power levels and are stored in the EPROM . i**.e. the values of $\mathbf{K_f}$ and $\mathbf{K_{dc}}$ that are required for various values of power levels are pre estimated and stored in the EPROMs as a look up table.**
When the maximum current required for rated operation is reached at a certain speed, and then onwards current value is kept constant at higher speeds. The dc-link voltage is limited to a specific value to prevent its exceeding the rated value.

**Permanent Magnet Synchronous Generator:**

**Introduction:**

Wind turbines run at inconveniently low speeds, typically 25-50rpm. A speed-increasing gear box is required to run induction machines and conventional Synchronous machines at 1500 rpm for operation with the utility network. Additional cost, weight, power loss, regular maintenance, and noise generation are some of the problems associated with the gear box required to increase the speed.
There are two methods by which the gear box can be avoided. If a standard Generator with number of poles say 4 is used , then a power electronic converter (Converter /inverter) has to be used which first converts the low frequency AC ( which would be 1Hz with P = 4 and Ns = 30 RPM ) from the generator to DC and then converts the DC to 50 Hz AC. Otherwise a Synchronous generator should have higher number of poles say around 240 such that with input synchronous speed of 25 RPM it produces 50 Hz electrical output which can be directly connected to the Utility Grid. But such large number of poles necessitate large diameter Generator since Synchronous machines cannot be built with pole pitches less than 150 mm. Consequently it’s size and weight will become abnormally large and heavy and hence it is not practically possible to accommodate in the Nacelle. Therefore, low-speed, direct-coupled generators

with low pitch requirement are required particularly for turbines with large diameters.

Permanent magnet (PM) excitation considerably brings down the pole pitch requirement, which can be less than 40 mm. This allows the rotor to be within an acceptable diameter, which makes the housing of the generator inside the Nacelle possible. Even then a Power converter or at least a smaller gear box ( withsmaller ratio and hence smaller size and weight ) are required.

**Constructional features:**

Several rotor configurations of Permanent Magnet Synchronous Machines have been developed. Some typical ones are illustrated here.

In the surface-type permanent magnet machine, high-energy, rare-earth magnets such as neodymium-iron-boron (Nd-Fe-B) are mounted on the rotor surface, as shown in Fig. 3.11.

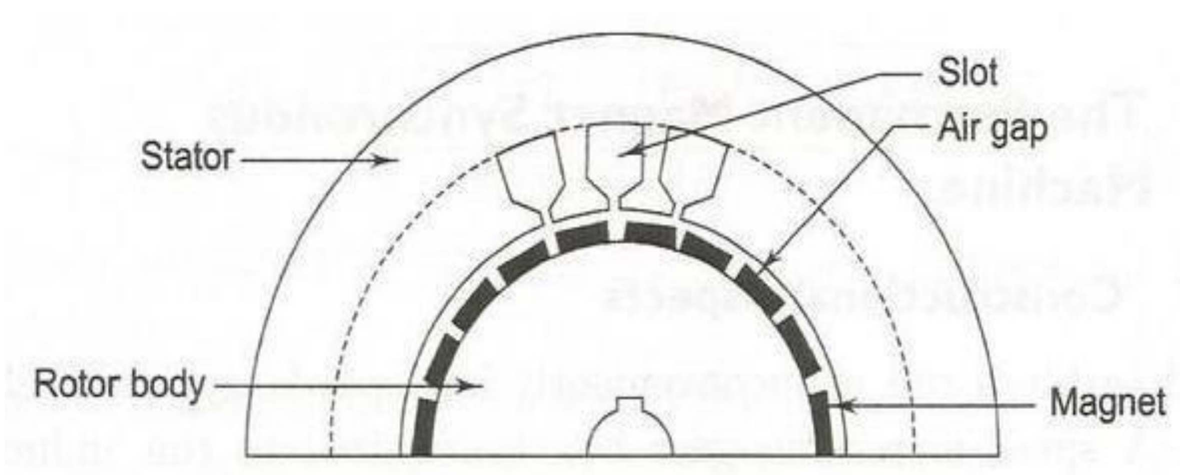


**Figure - 7: Cross sectional view of a Surface mounted PM Machine**

In an interior-type machine, as shown in Fig. 3.12, cheaper ferrite magnets are circumferentially oriented between flux-concentrating pole pieces.

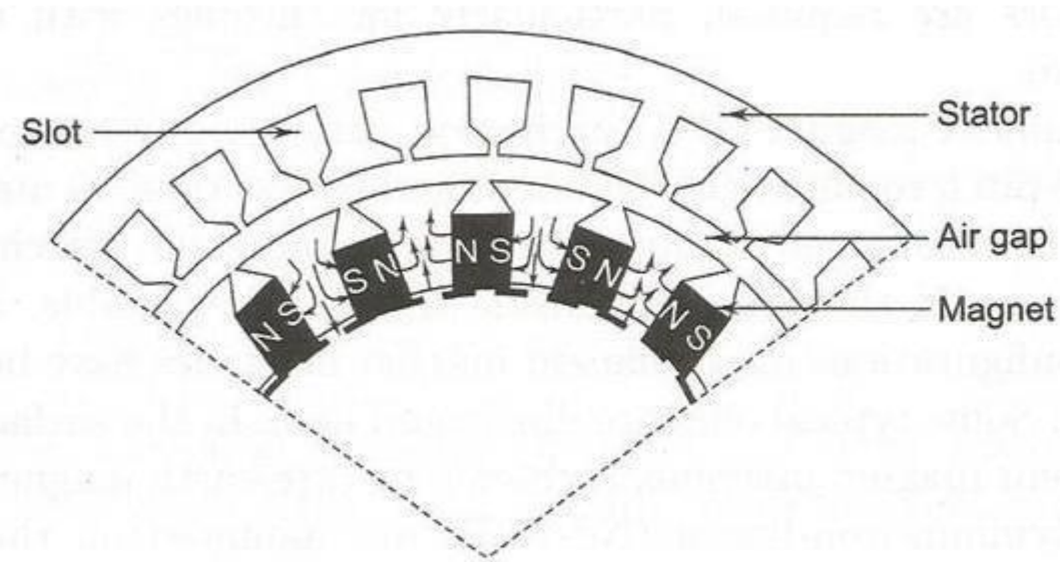


**Figure - 8: Cross sectional View of an Interior type (Buried) PM Machine(Circumferential Magnet motor)**

**Properties:** The surface-type machine has lower structural integrity and mechanical robustness. The surface type gives equal 'd' and 'q'-axis reactances while the latter (Interior type ) has a somewhat greater q-axis reactance than the d-axis reactance. In per-unit terms, both the reactance values are small because of the large number of poles. This provides the PM machines high peak torque capability to resist higher-than-rated torque for short periods during wind gusts and repeated torque pulsations of up to 20% of the rated torque.

**Steady-state Equations:**

The generated EMF $\mathbf{E_g}$ of a permanent magnet generator can be expressed as:

$$\mathbf{E_g = K_E\ \omega}$$

Where $\boldsymbol{\omega}$ is the angular frequency of the generator (Rad/sec) and is related to the mechanical speed as $\boldsymbol{\omega = P\ \omega_r/2}$ (where $\boldsymbol{\omega_r}$ = Generator mechanical speed in Radians per second)
Assuming unity power factor and referring to the figure shown below in Fig. 3.10,

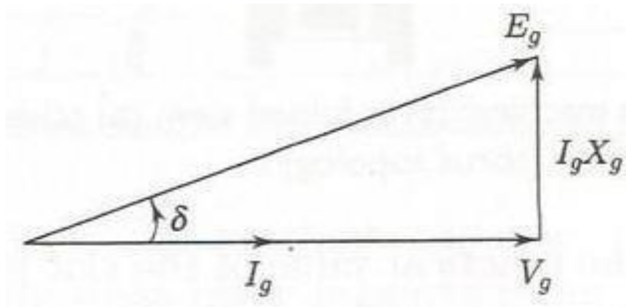


**Figure - 9: The Phasor diagram of a PM Synchronous Generator**

The relationship between the stator terminal voltage $\mathbf{V_g}$ and the current $\mathbf{I_g}$ is

$$\mathbf{E_g = V_g + j\, I_g\, X_S}$$

The generated power can be expressed as

$$\mathbf{P_g = 3V_gI_g = 3(E_g\, V_g / X_S)\, Sin\, \delta} \qquad \mathbf{(3.3)}$$

From the phasor diagram shown above (Fig 3.13)

$$\mathbf{V_g = E_g\, Cos\, \delta} \qquad \mathbf{(3.4)}$$

Using Eqn (3.4) in equation (3.3), the power equation can be expressed as

$$\mathbf{P_g = (3\, E_g^2 / 2X_s)\, Sin 2\delta}$$

Using Eqn (3.106) in Eqn (3.110), the equation representing torque can be expressed as

$$\mathbf{T_g = T_{max}\, Sin 2\delta}$$

Where $\mathbf{T_{max} = (3K_E^2 p / 4L_s)}$

**Operation of a Permanent Magnet Synchronous Generator in a variable-speed wind energy conversion scheme:**

The basic wind energy conversion requirements of a variable-speed permanent magnet generator are almost the same as those of a wound-field synchronous generator. The power circuit topology is basically the same as that shown in Fig. 3.7.(Scheme pertaining to Synchronous Generator)The permanent magnet generator dispenses with the need for external excitation. Therefore, the output voltage, under variable-speed operation, varies both in frequency and in magnitude. As a result, the dc-link voltage changes in an uncontrolled manner. The control, therefore, is realized via a dc/ac converter, i.e., an inverter, on the grid side as shown in the figure below.

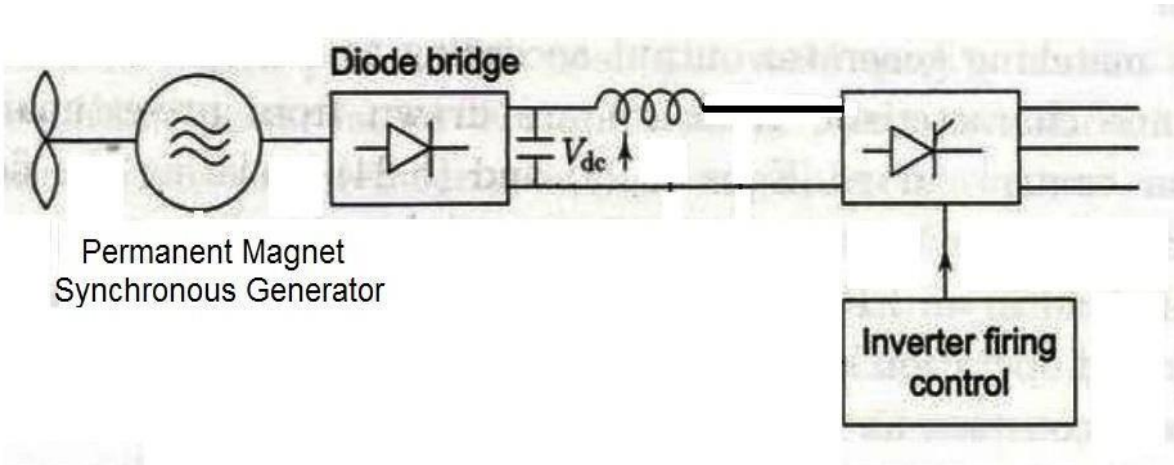


**Figure - 10: Operation of a Permanent Magnet Synchronous Generator with aGrid side Inverter.**

## 3. Grid connected Wind Turbine systems

**Basic Features and Configuration:**

Most of the Grid-connected Wind Turbine Systems are large utility-scale power plants. A typical electrical system layout in such plants is shown in the figure below (Figure 5.7). Typical technical features of such a wind power plant (wind farm) are:

- The wind generator output which is typically 440 volts AC is raised to an intermediate level of 11 kV by a pad-mounted transformer.
- An overhead transmission line provides the link to the site substation, where the voltage is raised again to the grid level say 33kV or 132 kV. (These values of voltages given are only typical. Actual values in a given wind farm depend on the total number of wind turbines in a farm, their total power levels etc and may vary from site to site.)

- A centralized site computer located in the substation, sometimes using multiplexer and remote radio links or fiber optical links, controls the wind turbines in response to the wind conditions and the load demand.

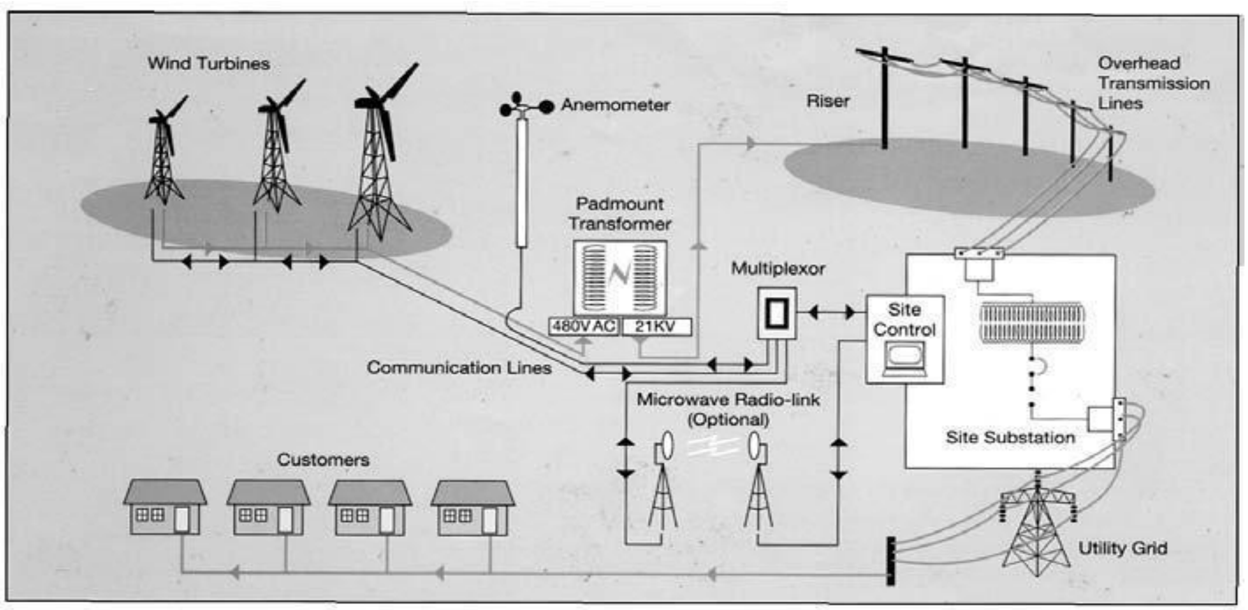


**Figure - 11: Electrical system layout of a Typical Grid-connected wind powersystem.**

- Large wind systems being installed now tend to have a variable-speed design
- The power schematic of such a system is shown in the figure below (Figure 5.12).The variable-frequency generator output is first rectified into DC, and then inverted into a fixed-frequency AC. Before the inversion, the rectifier harmonics are filtered out from the DC by inductors and capacitors.
- The frequency reference for the inverter firing and the voltage reference for the rectifier phase-angle control are taken from the grid lines.
- The optimum reference value of the tip-speed ratio is stored and continuously compared with the value computed from the measured speeds of the wind and the rotor. The turbine speed is accordingly changed to assure maximum power production at all times.

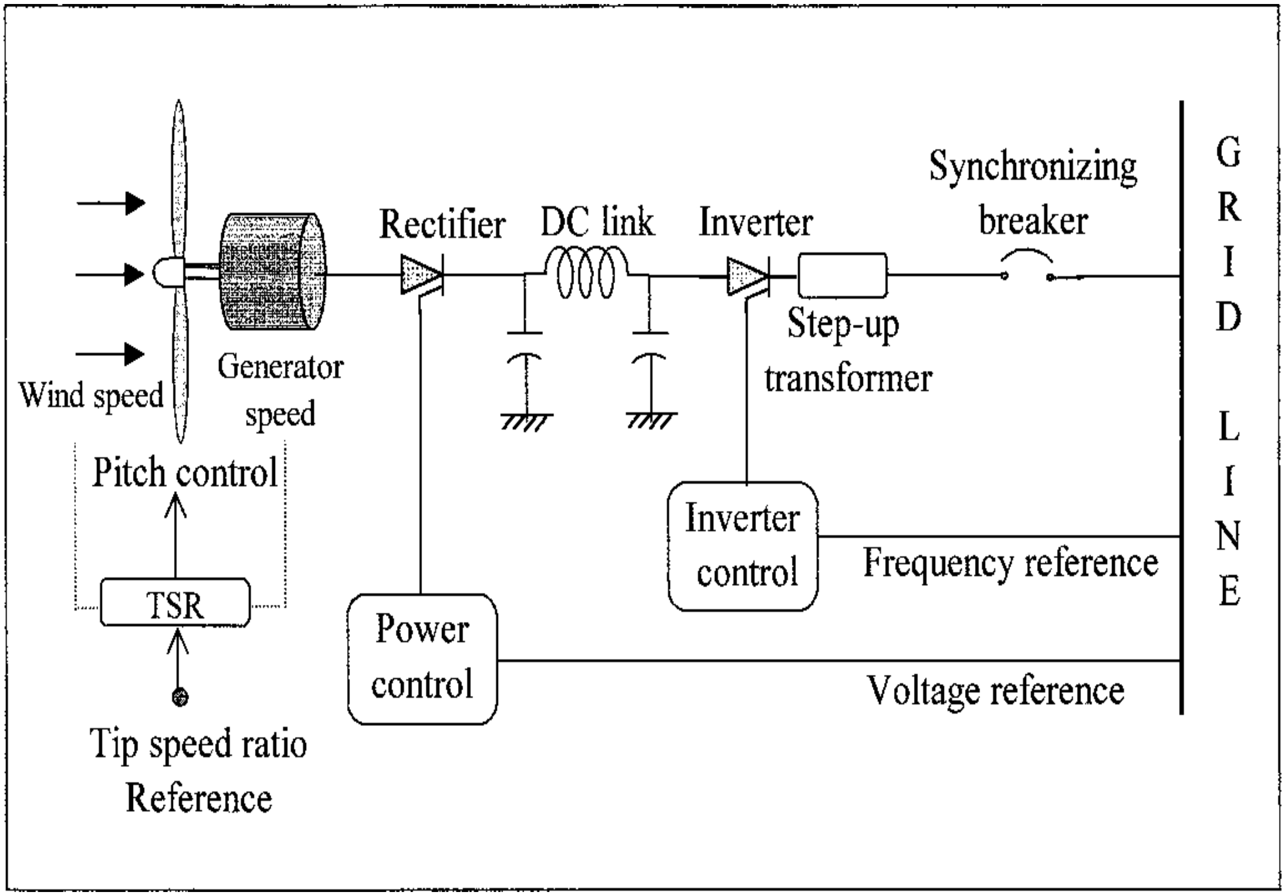


**Figure - 12: Electrical schematic diagram of a Grid-connected variable speedwind power system.**

## Interface Requirements:

Both the wind and the PV systems interface the grid at the output terminals of the synchronizing breaker at the output end of the inverter as shown in the figure above. The power flows in either direction depending on the site voltage at the breaker terminals.

The fundamental requirements on the site voltage for interfacing with the grid are as follows:

- The voltage magnitude and phase must equal to that required for the desired magnitude and direction of the power flow. The voltage is controlled by the transformer turn ratio and/or the rectifier/ inverter firing angle in a closed- loop control system.

- The frequency must be exactly equal to that of the grid, or else the system will not work. To meet the exacting frequency requirement, the only effective means is to use the utility frequency as a reference for the inverter switching frequency.
- In the wind system, the synchronous generators of the grid system supply magnetizing current for the Induction Generator.

The interface and control issues are similar in many ways between both the **PV** and the **Wind Systems**. The wind system, however, is more involved since the electrical generator and the turbine with large inertia introduce certain dynamic issues not applicable in the static **PV** system. Moreover, wind plants generally have much greater power capacity than the **PV** plants. For example, many wind plants that have been already installed around the world have capacity in tens of MW each. The newer wind plants in the hundreds of MW capacity are coming up .

**Synchronizing with Grid:**

The synchronizing breaker shown in the figure above has internal voltage and phase angle sensors to monitor the site and grid voltages and signal the correct instant for closing the breaker. As a part of the automatic protection circuit, any attempt to close the breaker at an incorrect instant is rejected by the breaker. Four conditions which must be satisfied before the synchronizing switch will permit the closure are as follows:

- The frequency must be as close as possible with the grid frequency.
- The terminal voltage magnitude must match with that of the grid, preferably a few percent higher.
- The phase sequence of both the three-phase voltages must be same.
- The phase angle between the two voltages must be within 5 degrees.

## 4. Power Flow between Two Synchronous Sources (Active and Reactive power control)

In the power converters that are used in wind electrical systems to convert the Generator output to a suitable voltage and frequency level, a pulse width modulated (PWM) voltage source inverter is used to exchange power between the Generator and a fixed- frequency AC system through a DC link. The inverter produces an output voltage **'$V_I$'** at the fundamental frequency with the required phase angle and magnitude and synchronized with the ac system voltage **'$V_S$'**, through an inductor. Under the assumption of balanced sinusoidal voltages, the per-phase steady-state equivalent circuit for the Synchronized Inverter-AC system and its phasor diagram can be drawn as shown in the figure below (5.13).

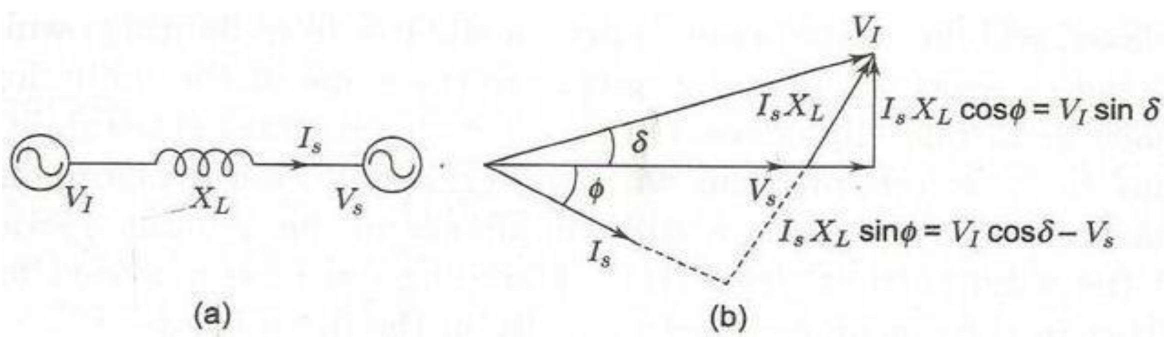


**Figure - 13: (a) Schematic diagram of an Inverter /AC system interface (b) Phasordiagram**

From the phasor diagram (see Fig. 3.24(b), the following relations are obtained. Active power flow into the system is given by:

$$P_s = 3 V_s I_s cos\emptyset$$

$$= 3 \frac{V_s}{X_L} I_s X_L \cos\emptyset$$

$$= 3 \frac{V_S}{X_L} V_I \sin \delta$$

Reactive power flow into the system is given by:

$$Q_S = 3V_s I_s \sin \emptyset$$

$$= 3 \frac{VS}{X_L} I_S X_L \sin \emptyset$$

$$= 3 \frac{VS}{X_L} V_I \cos \delta - 3 \frac{V_S^2}{X_L}$$

Thus, the real power and the reactive power flow can be regulated by controlling the inverter output voltage and its phase angle relative to the AC system.

## 5. Effect of a Wind Generator on the network:

Many wind farms are connected to the local network at low, medium, or high voltage. The injection of wind power into the network has an impact on the voltage magnitude, its flicker, and its waveform at the point of common coupling (PCC).

The effect on the voltage magnitude depends on the 'strength' of the utility distribution network at the point of coupling as well as on the active and reactive power of the wind generator(s).The strength of the system at the point of coupling under consideration is decided by the short-circuit power, called the fault level, at that point. The short-circuit power is the product of the short-circuit current, following a three-phase fault at that point, and the voltage of the system. In fact, a power system comprises many interconnected power sources. The loads are fed through extended transmission and distribution networks. At the point of connection, as illustrated in the figure below [Fig. 5.14(a)], an equivalent ideal voltage source in series with impedance **'$Z_S$'**, may be assumed to replace the power system.

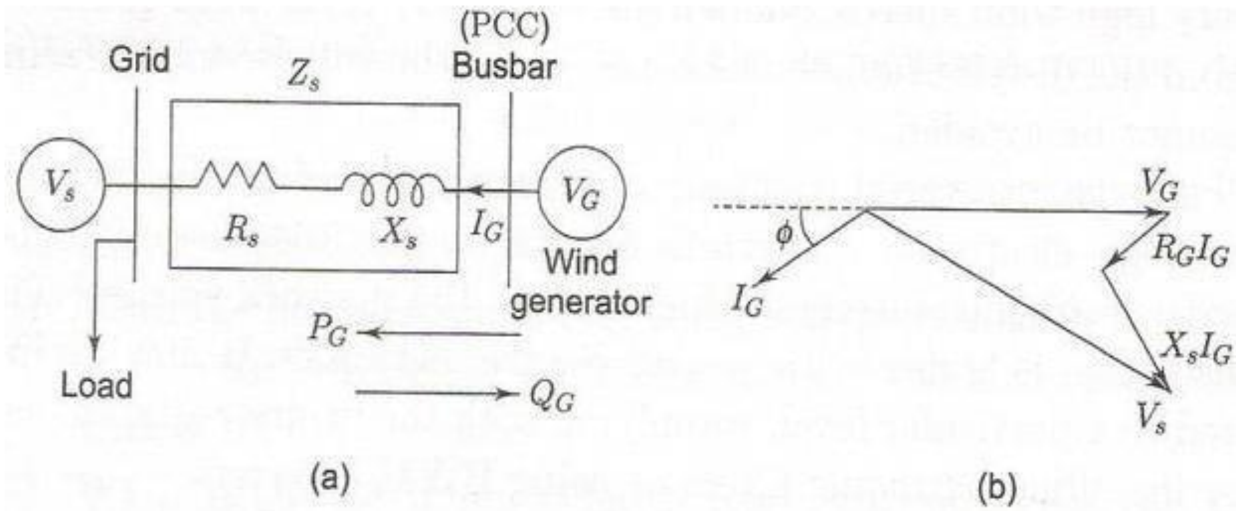


**Figure - 14: (a) Schematic diagram of a Generator connection to DistributionNetwork (b) Phasor diagram**

Thus, the higher the fault current, the lower the source impedance. The wind farm with induction generators receives reactive power from the network and delivers real power to it. Without contribution from the wind generator, the fault level at the point of connection near the wind farm is

$$\mathbf{M = I_f V_s}$$

Where

$$\mathbf{I_f = V_s / Z_s}$$

Thus the fault level and hence the network strength are indicative of the source impedance. Areas of high wind velocity are suitable locations for wind farms. These areas are usually sparsely populated. Long transmission and distribution lines are normally required for connecting wind farms with the power system network. As a result, fault levels at the wind farms are generally low, making them weak electrical systems.

With reference to figure 5.14 (b), if the phase difference between **'$V_S$'** and **'$V_G$'** is not large, the voltage at the PCC will be close to:

$$\mathbf{V_G = V_s + R_s I_G \cos \varphi - X_s I_G \sin \varphi}$$

$$= V_s + P_G R_s / V_G - Q_G X_s / V_G$$

Thus, at low power delivery, the voltage at the PCC reduces if the induction generator absorbs reactive power from the grid, while, at increased power flow, the voltage rises. ‘Flicker’ is defined as the unsteadiness of the distribution network voltage. It may be caused by the continuous operation of a wind turbine or the switching operations of turbines. While operating, the rotor of a wind turbine experiences a cyclic torque variation at the frequency with which the blades move past the tower. This cyclic power variation may lead to flicker, and depends on the wind speed distribution at the site. While being connected to the network, the induction generator draws excessive current. Soft-start systems are usually employed to minimize the transient inrush current. However, at very high wind speeds, sudden disconnection of the wind generator from the distribution network may cause the voltage to dip, which cannot be avoided.

Interfacing variable-speed wind turbines with the network through electronic converters results in the injection of higher order harmonic currents, which distort the network voltage. This distortion is higher with weaker electric networks. It may be limited to a particular level, complying with the utility requirements, by installing harmonic filters or using PWM inverters

## 6. Summary - Important Concepts/Relations

- This chapter deals with Grid-connected Induction Generator operational details.
- The detailed schemes with both Squirrel Cage and Wound Rotor Induction Machines, whose stator windings are directly connected to the grid have been presented and explained.
- The near-synchronous-speed squirrel cage induction generator, driven by a wind turbine via a gear box, prevails dominantly (more than 80%) over the other types of generators in the wind power market. Their manufacturing range extends up to 1.5 MW. Both classical stall and active stall are used with these fixed-speed turbines to limit the power generation at high wind speeds.

This system is cheap and simple, but it draws the least amount of energy from wind compared to other technologies for the same wind speed statistics at a given site. This is so because with a fixed speed of Wind Turbine **'$C_p$'** is not optimized for capturing maximum power from wind.

- For variable-speed operation, the wound rotor induction machine is used. The stator is directly connected to the grid. The rotor also feeds power to the grid via a converter. This system, known as a Double Output Induction Generator, is the favored choice for variable-speed, high-capacity turbines in the range 1-4.5 MW.
- In order to extract the maximum amount of power from wind, the tip speed ratio must be kept fixed at the optimal value while the wind speed fluctuates continuously. This requires corresponding change of Turbine speed according to wind speed variation. Consequently, the electrical generator should be able to operate at variable speed. Since variable-speed generation is most energy efficient this chapter deals with the variable-speed-based generation schemes with Synchronous Generators both with wound field and Permanent Magnets also.
- Even though constant-speed wind turbines with grid-connected Squirrel Cage Induction Generators have dominated the wind market, there is a clear trend over the past few decades towards use of variable-speed wind turbines with DFIG and Synchronous Generators (both wound field and Permanent Magnet).
- For direct drive applications permanent magnet synchronous machines are attractive.

## 7. Important Questions:

1. Explain the operation of a fixed Speed Wind Turbine system with a single output Squirrel Cage Induction Generator with the help of a block diagram highlighting all the technical aspects, advantages and limitations.

2. (a) Explain the principle of operation of a Doubly Fed Induction Generator with the help of Power flow diagram and Block diagram .
(b) Explain clearly how a DFIG works satisfactorily in a variable speed Wind Turbine system over a wide speed range with the help of Torque speed

Characteristics with both positive and negative slip regions showing the equivalent Rotor resistance variation.

3. Explain the Operation of a wound field Synchronous Generator in a variable-speed wind energy conversion scheme with control strategy based on 'speed cube law' to obtain optimal power output from the wind turbine.

4. (a) Explain the limitation of a Synchronous generator to get output at utility frequency by direct connection to the Turbine Rotor. Elaborate how this limitation is overcome with a Permanent Magnet Synchronous generator.
(b) Explain with simple sketches the constructional features of PMSGs.

5. (a) With the help of a simple phasor diagram of a PMSG derive the equations for steady state Power and Torque generated in such a Machine.
(b) Explain the operation of a PMSG in a variable-speed wind energy conversion scheme with the help of a suitable Block diagram.

6. (a) What are the important technical features and subsystems of a typical wind farm with several wind Power Generators colocated.
(b) Explain briefly the salient features of such a Wind Turbine with the help of a detailed block diagram.
(c) What are the interfacing requirements and the conditions for synchronizing of such a wind generator with the Grid?

7. Explain how active power & reactive power flow into a grid system from a wind energy system employing a PWM Inverter as final power output stage can be controlled with the help of a single phase equivalent circuit and the corresponding Phasor diagram.

8. Explain the effects of Wind Generator on the Grid with the help of a simple equivalent circuit and a Phasor diagram

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