PPT ON
WIND AND SOLAR ENERGY SYSTEMS
V SEM (IARE-R18)

B.Tech V Semester (R18)
(2020-2021)

Prepared
By

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MODULE-I
DESIGN AND OPERATION OF WIND POWER SYSTEM

MODULE I - SYLLABUS

Wind Power System: Components, turbine rating, electrical load matching, variable-speed operation, system design features, maximum power operation, system control requirements, speed control, rate control and environmental aspects, wind energy conversion systems and their classification.

COURSE OUTCOMES MAPPED WITH MODULE I

CO	Course Outcomes	Blooms Taxonomy
CO 1	**Recall** the power conversions involved in windmills/ PV Systems for production of electricity.	Remember
CO 2	**Outline** various components involved and their functionality in production of electricity from wind and solar power plants.	Understand
CO 3	**Summarize** the control schemes, environmental aspects and classification of wind energy conversion systems for reliable operation.	Understand

PROGRAM OUTCOMES MAPPED WITH MODULE I

PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
PO 3	**Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

MAPPING OF COs AND POS FOR MODULE I

COs	PROGRAM OUTCOMES											
	1	2	3	4	5	6	7	8	9	10	11	12
CO1	√											
CO2	√	√	√									
CO3	√	√										

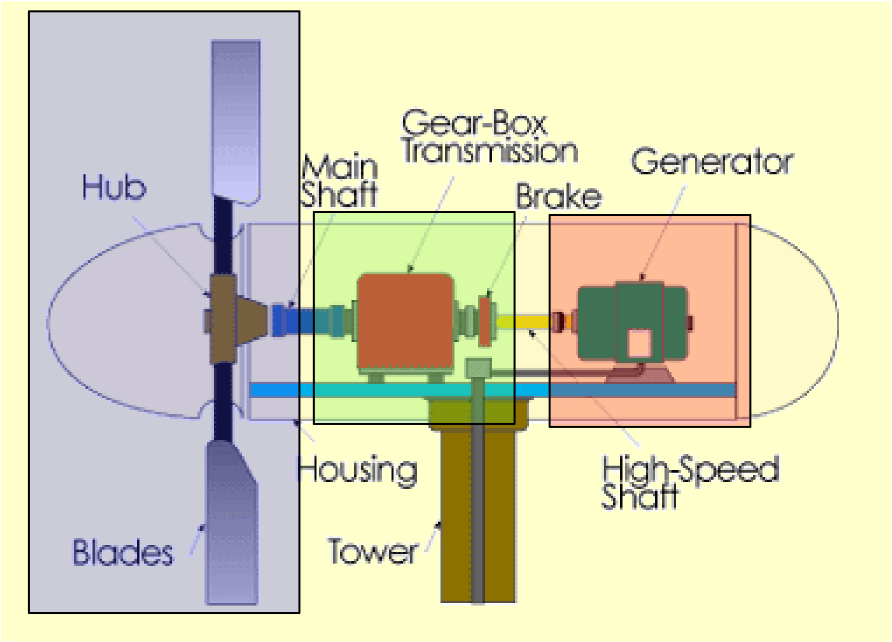
Wind Turbine Design

Two types of turbine design are possible – Horizontal axis and Vertical axis. In horizontal axis turbine, it is possible to catch more wind and so the power output can be higher than that of vertical axis. But in horizontal axis design, the tower is higher and more blade design parameters have to be defined. In vertical axis turbine, no yaw system is required and there is no cyclic load on the blade, thus it is easier to design. Maintenance is easier in vertical axis turbine whereas horizontal axis turbine offers better performance.

Vertical axis Turbine

Horizontal axis Turbine

Main components of a Horizontal Axis Wind Turbine

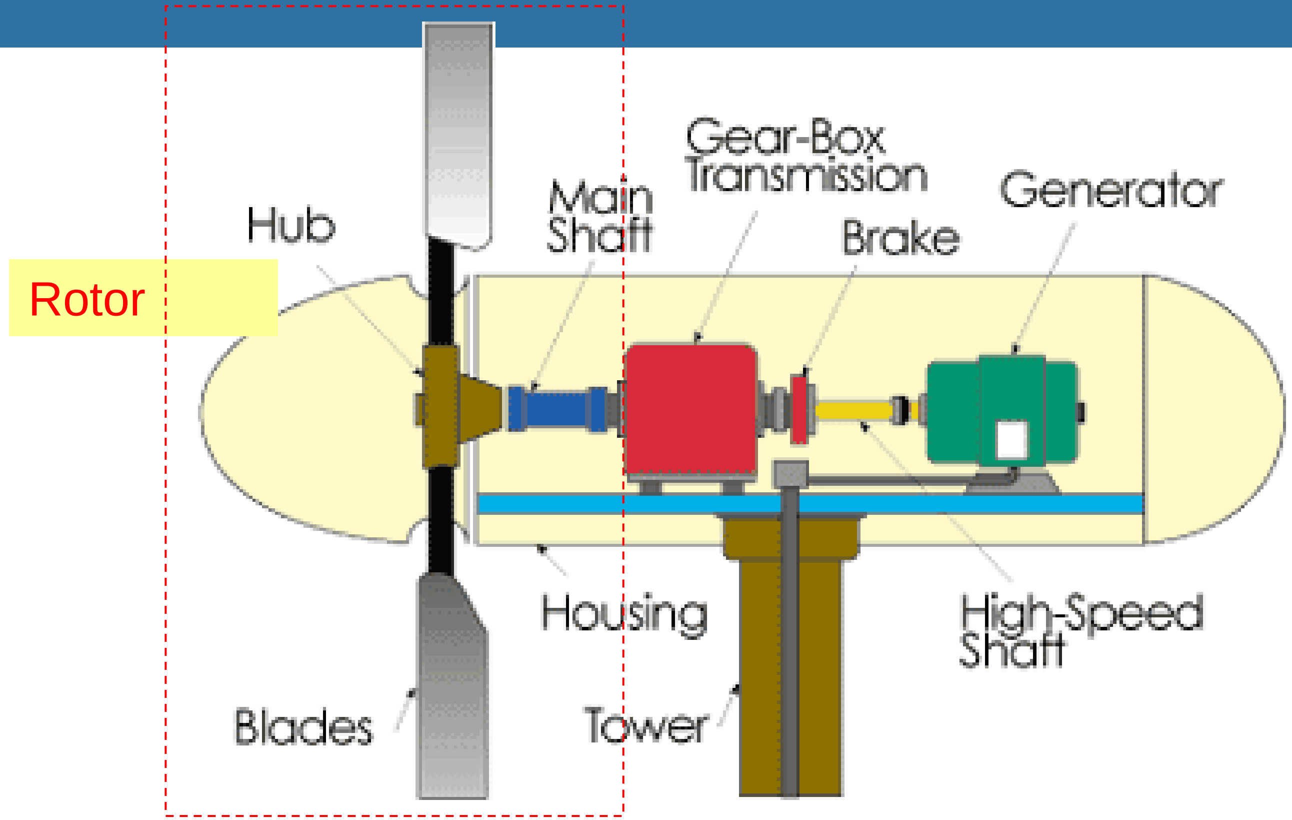


<u>Blades and rotor</u>: Converts the wind power to a rotational mechanical power.

<u>Generator</u>: Converts the rotational mechanical power to electrical power.

<u>Gear box</u>: Wind turbines rotate typically between 40 rpm and 400 rpm. Generators typically rotates at 1,200 to 1,800 rpm. Most wind turbines require a step-up gear-box for efficient generator operation (electricity production).

Main components of a Wind Turbine



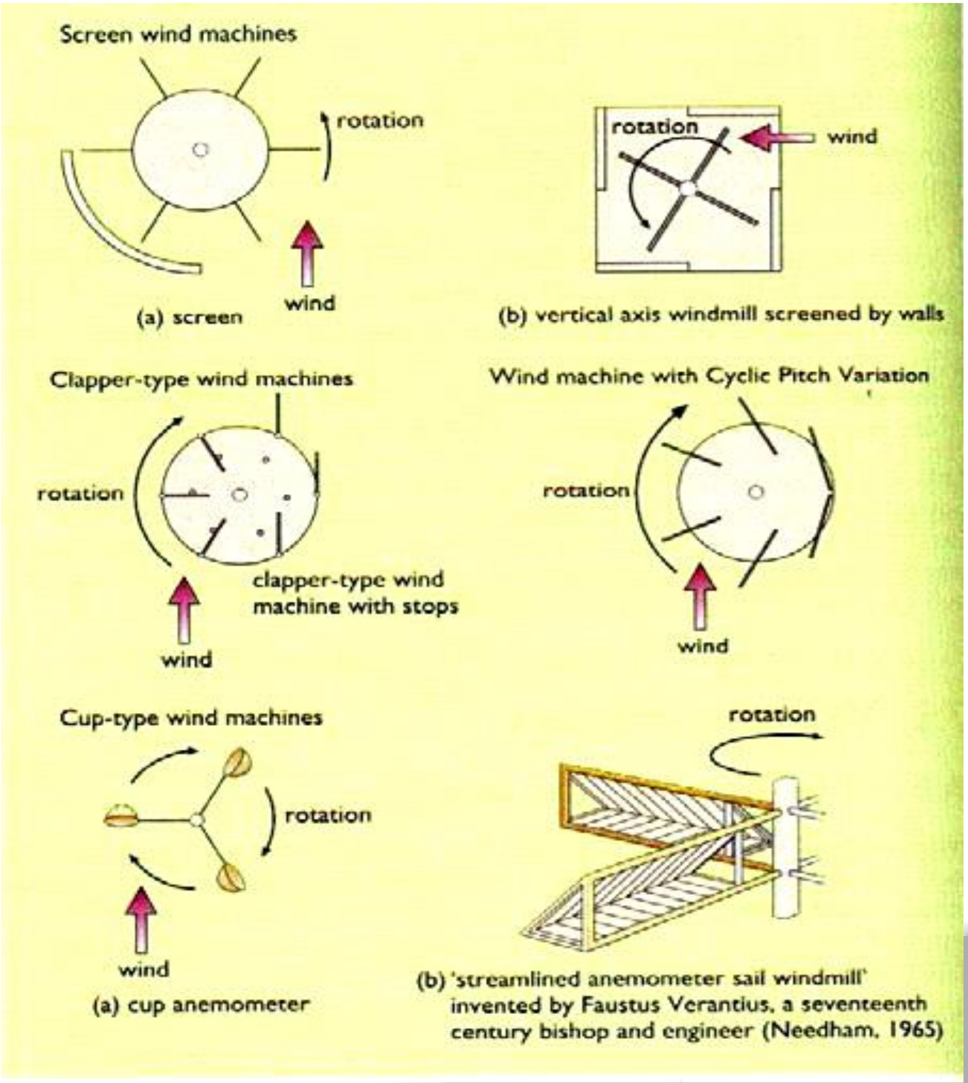
Rotor

The portion of the wind turbine that collects energy from the wind is called the rotor. The rotor usually consists of two or more wooden, fiberglass or metal blades (new design) which rotate about an axis (horizontal or vertical) at a rate determined by the wind speed and the shape of the blades. The blades are attached to the hub, which in turn is attached to the main shaft.

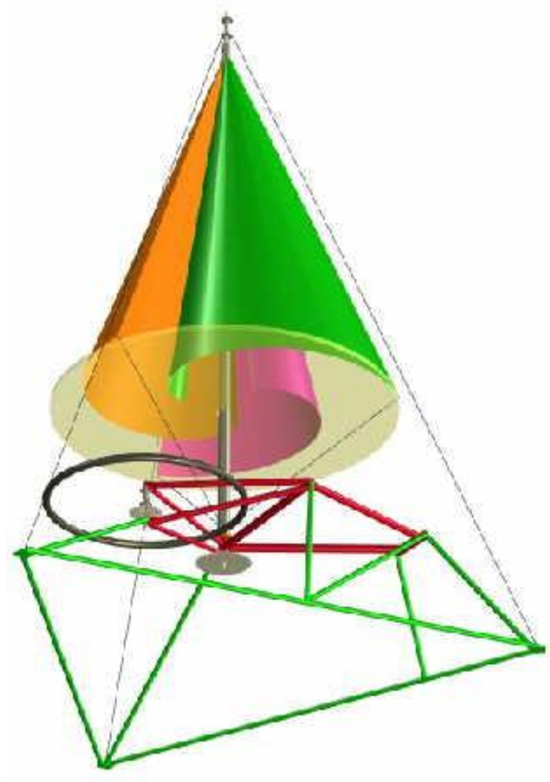
Blade designs operate on either the principle of drag or lift.

Drag Design

For the drag design, the wind literally pushes the blades out of the way. Drag powered wind turbines are characterized by slower rotational speeds and high torque capabilities. They are useful for the pumping, sawing or grinding work that Dutch, farm and similar "work-horse" windmills perform. For example, a farm-type windmill must develop high torque at start-up in order to pump, or lift, water from a deep well.



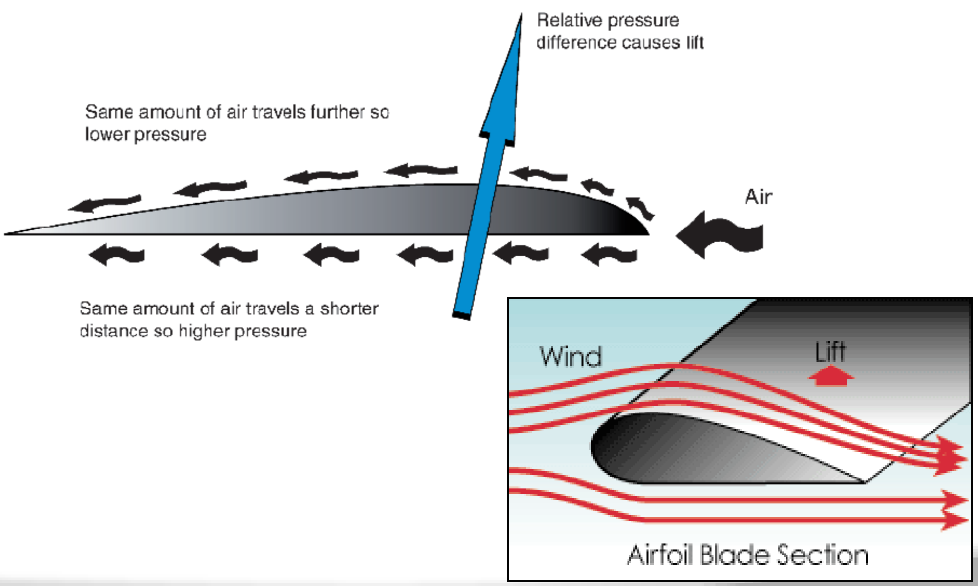
Wind Turbine Design using Drag Principle

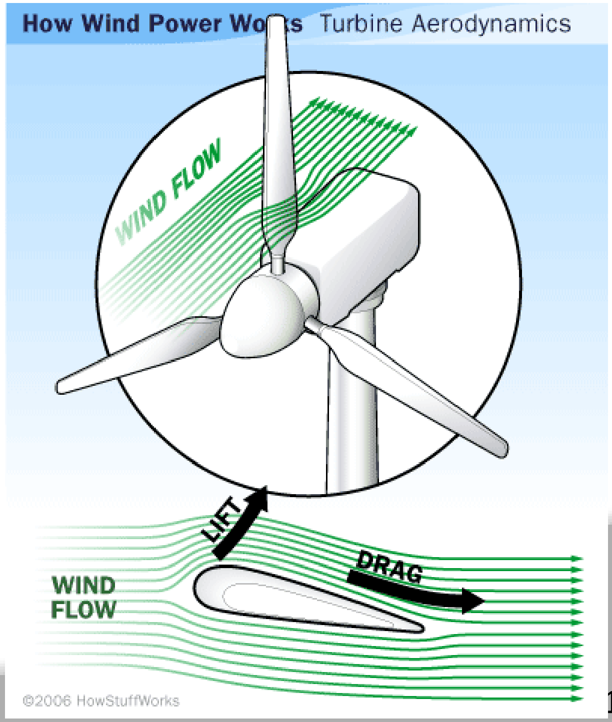


Wind Turbine

Lift Design

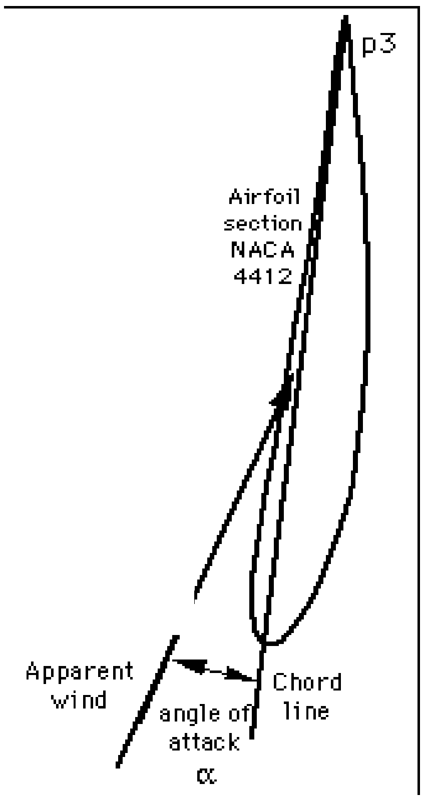
The lift blade design employs the same principle that enables airplanes, kites and birds to fly. The blade is essentially an airfoil, or wing. When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces. The pressure at the lower surface is greater and thus acts to "lift" the blade. When blades are attached to a central axis, like a wind turbine rotor, the lift is translated into rotational motion. Lift-powered wind turbines have much higher rotational speeds than drag types and therefore are well suited for electricity generation.

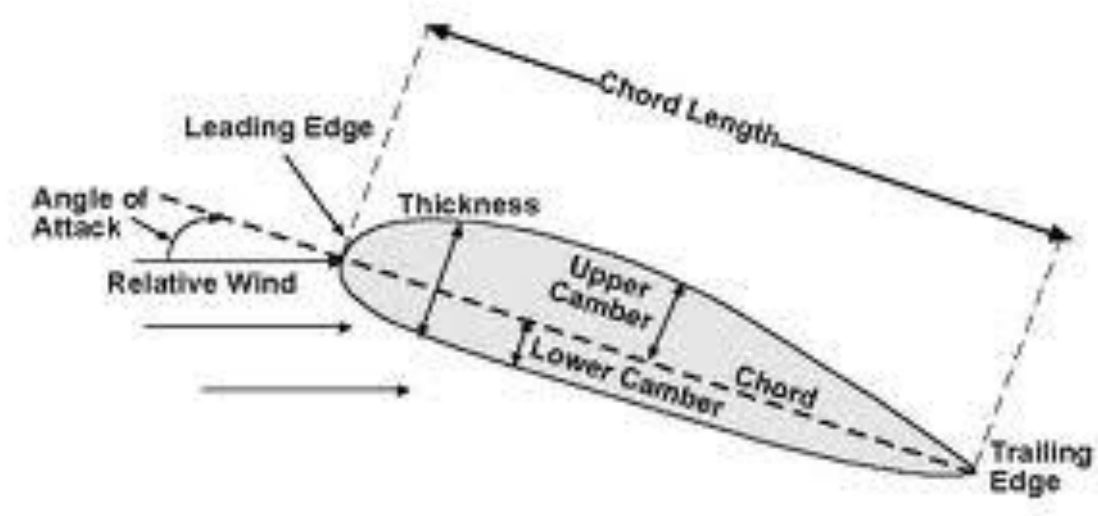




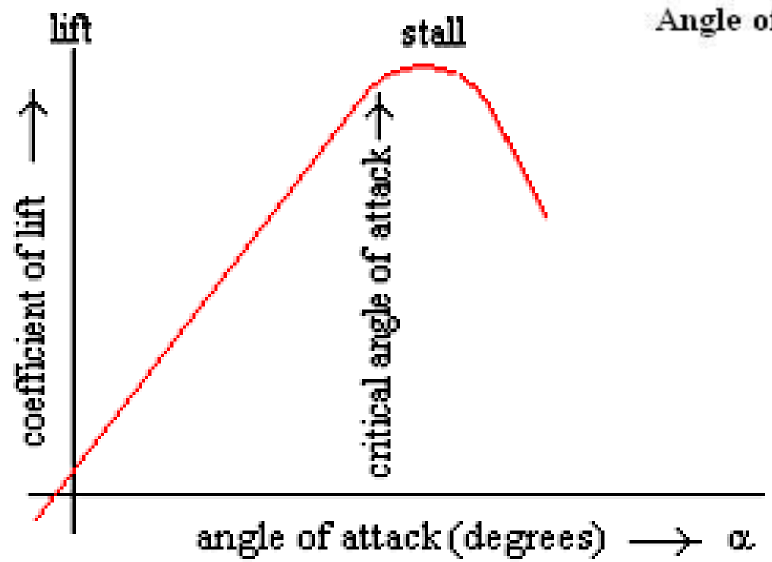
Angle of attack (blade angle)

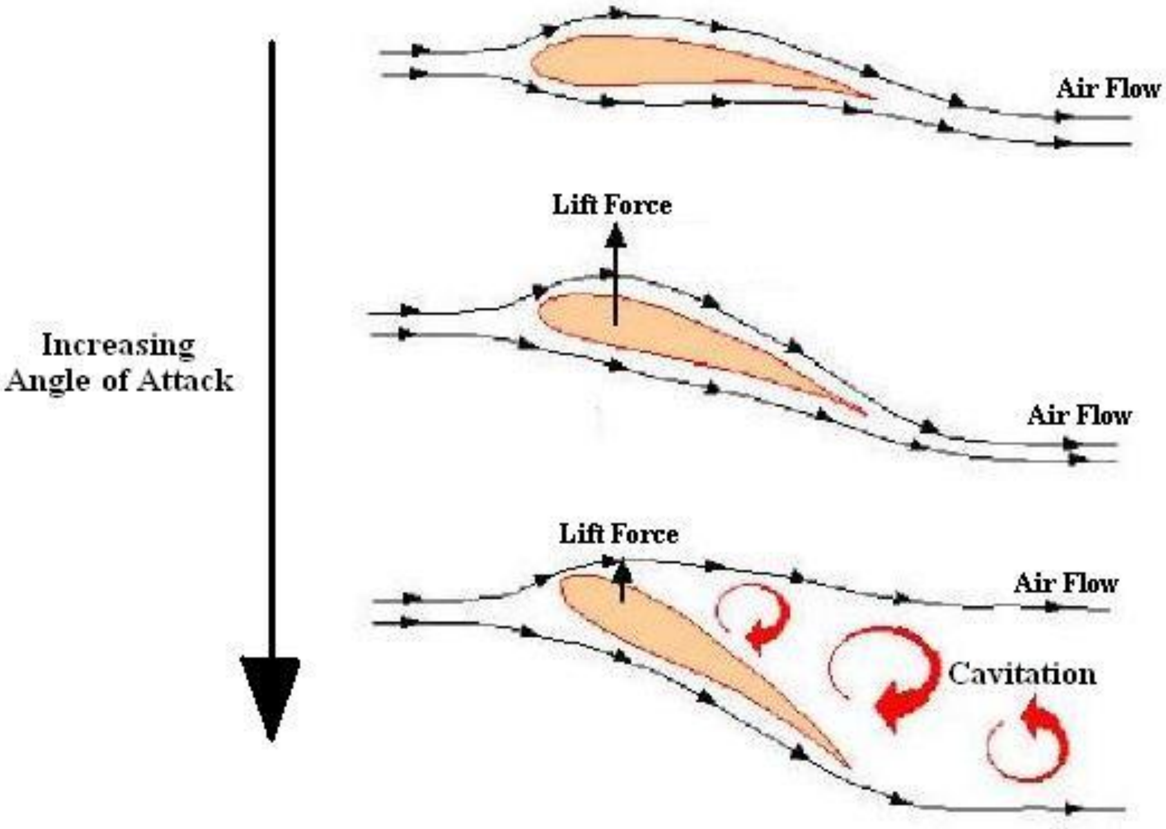
The angle between the chord line of the airfoil and the flight direction is called the angle of attack. Angle of attack has a large effect on the lift generated by an airfoil. This is the propeller efficiency. Typically, numbers here can range from 1.0 to 15.0 degrees.





Angle of attack





Wind Turbine – Blade Design

Blade Number

The determination of the number of blades involves design considerations of aerodynamic efficiency, component costs, system reliability, and aesthetics..

Aerodynamic efficiency increases with the number of blades but with diminishing return.

Increasing the number of blades from ***one to two*** yields a **6% increase in efficiency**, whereas increasing the blade count from ***two to three*** yields only an additional **3% in efficiency**. Further increasing the blade count yields minimal improvements in aerodynamic efficiency and sacrifices too much in blade stiffness as the blades become thinner.

One blade rotor

Generally, the fewer the number of blades, the lower the material and manufacturing costs will be. Higher rotational speed reduces the torques in the drive train, resulting in lower gearbox and generator costs.

Wind Turbine – Blade Design

The ideal wind turbine design is not dictated by technology alone, but by a combination of technology and economics: Wind turbine manufacturers wish to optimize their machines, so that they deliver electricity at the lowest possible cost per kilowatt hour (kWh) of energy.

Wind turbines are built to catch the wind's kinetic (motion) energy. You may therefore wonder why modern wind turbines are not built with a lot of rotor blades, like the old "American" windmills you have seen in the Western movies and still being used in many farms.

The ideal wind turbine rotor has an infinite number of infinitely thin blades. In the real world, more blades give more torque, but slower speed, and most alternators need fairly good speed to cut in.

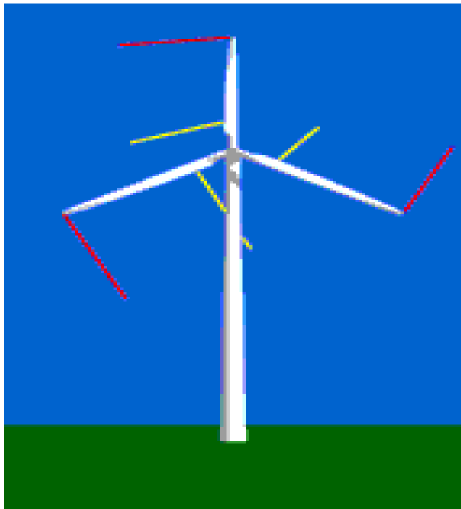
Turbines with many blades or very wide blades will be subject to very large forces, when the wind blows at a hurricane speed.

Wind Turbine – Blade Design

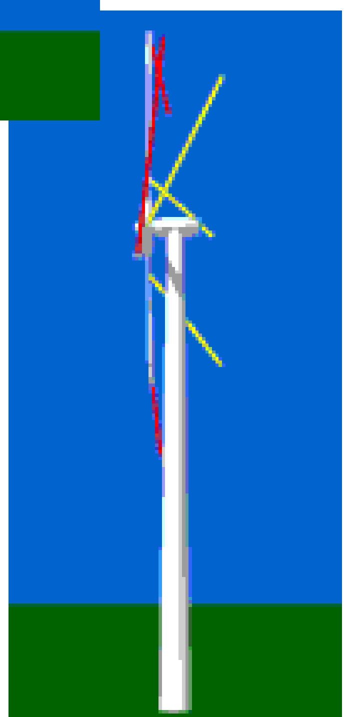
Even or Odd Number of Blades

A rotor with an even number of blades will cause stability problems for a wind turbine. The reason is that at the very moment when the uppermost blade bends backwards, because it gets the maximum power from the wind, the lower most blade passes into the wind shade in front of the tower. This produces uneven forces on the rotor shaft and rotor blade.

Wind Turbine – Blade Design (Shape)



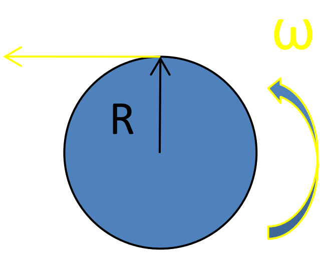
To study how the wind moves relative to the rotor blades of a wind turbine, attach red ribbons to the tip of the rotor blades and yellow ribbons about 1/4 of the way out from the hub.



Since most wind turbines have constant rotational speed, the speed with which the tip of the rotor blade moves through the air (the tip speed) is typically some 64 m/s, while at the centre of the hub it is zero. 1/4 out from the hub, the speed will then be some 16 m/s.

The yellow ribbons close to the hub of the rotor will be blown more towards the back of the turbine than the red ribbons at the tips of the blades. This is because, at the tip of the blades, the speed is some 8 times higher than the speed of the wind hitting the front of the turbine.

$$V = R\omega$$



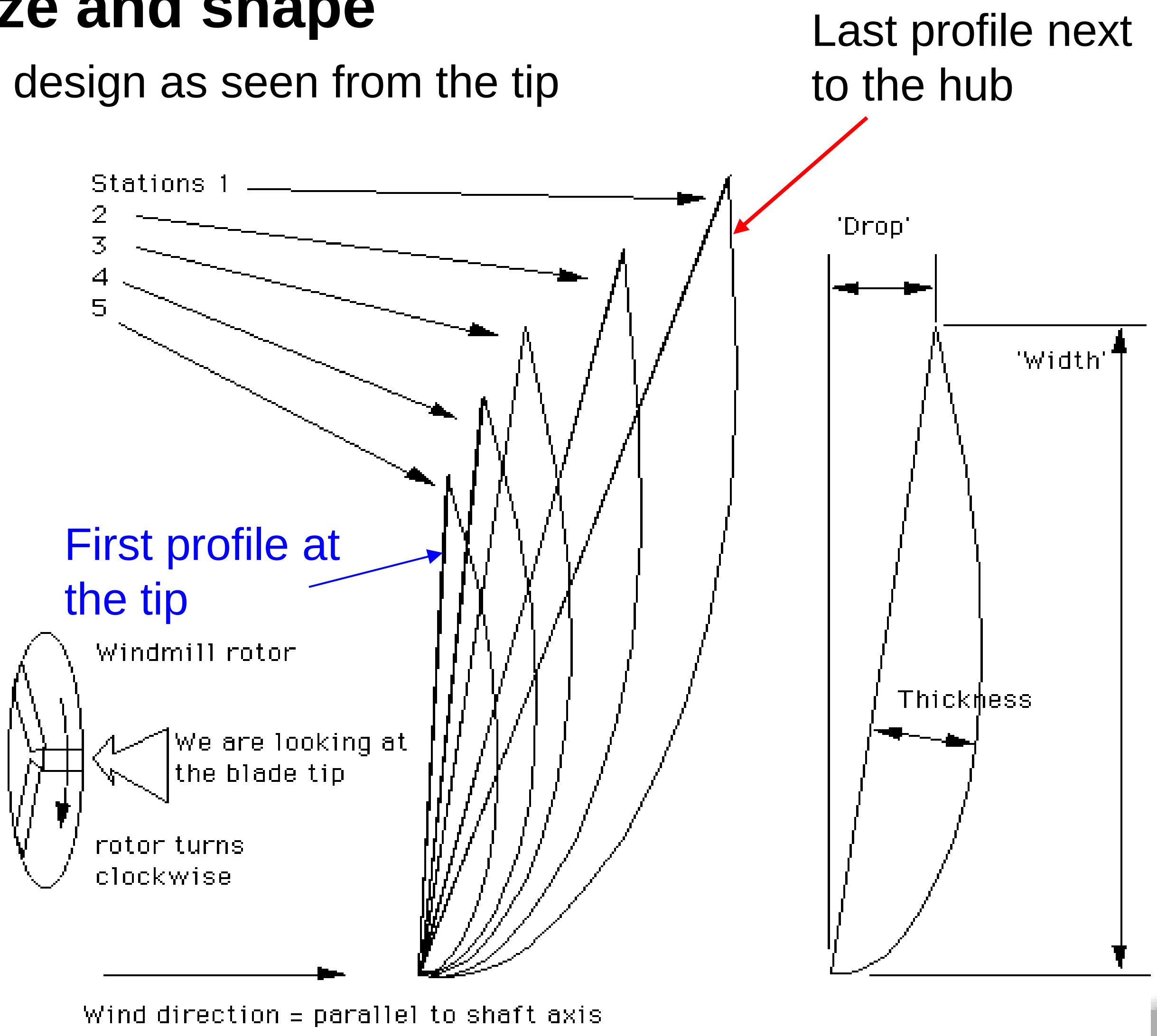
Wind Turbine – Blade Design (Shape)

Rotor blades for wind turbines are always twisted. Seen from the rotor blade, the wind will be coming from a much steeper angle (more from the general wind direction in the landscape), as you move towards the root of the blade, and the center of the rotor. A rotor blade will stop giving lift (stall), if the blade is hit at an angle of attack which is too steep.

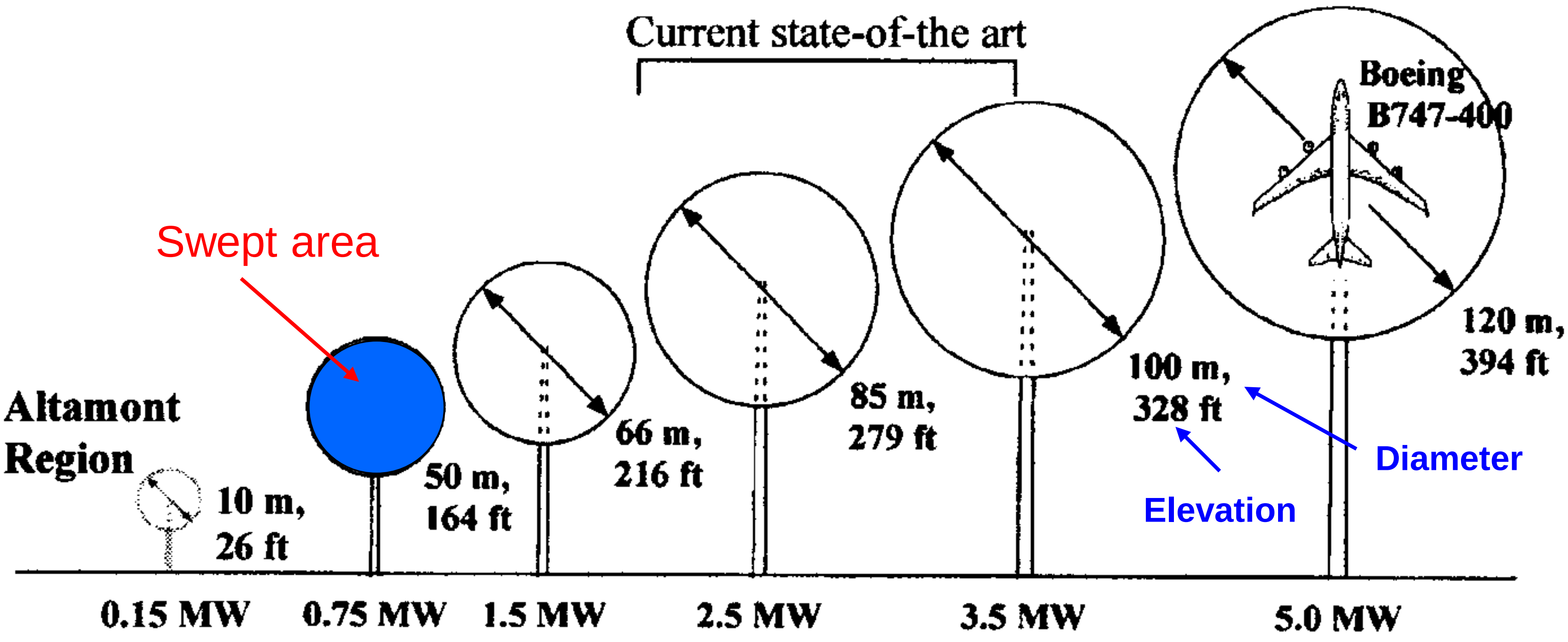
Therefore, the rotor blade has to be twisted, so as to achieve an optimal angle of attack throughout the length of the blade.

Blade size and shape

5-station design as seen from the tip



Power Generated by Wind Turbine



There are about 4,800 wind turbines in California at Altamont Pass (between Tracy and Livermore). The capacity is 580 MW, enough to serve 180,000 homes. In the past, Altamont generated 822x10^6 kW hours, enough to provide power for 126,000 homes (6500 Kwh per house)

Typical Wind Turbine Operation

0 ~ 10 mph --- Wind speed is too low for generating power. Turbine is not operational. Rotor is locked.

10 ~ 25 mph --- 10 mph is the minimum operational speed. It is called "Cut-in speed". In 10 ~ 25 mph wind, generated power increases with the wind speed.

25 ~ 50 mph --- Typical wind turbines reach the rated power (maximum operating power) at wind speed of 25mph (called Rated wind speed). Further increase in wind speed will not result in substantially higher generated power by design. This is accomplished by, for example, pitching the blade angle to reduce the turbine efficiency.

> 50 mph --- Turbine is shut down when wind speed is higher than 50mph (called "Cut-out" speed) to prevent structure failure.

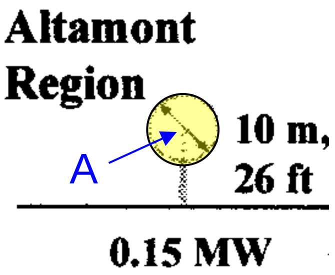
Theoretical Power Generated by Wind Turbine

$$\text{Power} = \tfrac{1}{2}(\rho)(A)(V)^3$$

ρ = Density of air = 1.2 kg/m^3 (.0745 lb/ft^3), at sea level, 20 ^{o}C and dry air

A = swept area = π(radius)^2, m^2

V = Wind Velocity, m/sec.



ρ = 1.16 kg/m^3, at 1000 feet elevation

ρ = 1.00 kg/m^3, at 5000 feet elevation

ρ = 1.203 kg/m^3 at San Jose, at 85 feet elevation. The average wind velocity is 5 mph at 50m tower height

ρ = 1.16 kg/m^3 at Altamont pass, at 1010 feet elevation and average wind velocity of 7m/s (15.6 mph) at 50m tower height (turbines need a minimum of 14 mph, 6.25 m/s, wind velocity to generate power).

Wind Turbine Efficiency, η

Betz Limit

It is the flow of air over the blades and through the rotor area that makes a wind turbine function. The wind turbine extracts energy by slowing the wind down. The theoretical maximum amount of energy in the wind that can be collected by a wind turbine's rotor is approximately 59.3%. This value is known as the Betz limit.

If the blades were 100% efficient, a wind turbine would not work because the air, having given up all its energy, would entirely stop. In practice, the collection efficiency of a rotor is not as high as 59%. A more typical efficiency is 35% to 45%. A complete wind energy system, including rotor, transmission, generator, storage and other devices, which all have less than perfect efficiencies, will deliver between 10% and 30% of the original energy available in the wind.

Power Generated by HWind Turbine

How much power a wind turbine with 50 meters long blade can generate with a wind speed of 12 m/s? The site of the installation is about 1000 feet above sea level. Assume 40% efficiency (η).

Air density is lower at higher elevation. For 1000 feet above sea level, ρ is about 1.16 kg/m^3

$$\text{Power} = \tfrac{1}{2}(\rho)(A)(V)^3(\eta)$$

$$= 0.5(1.16)(\pi 50^2)(12)^3(0.4)$$

$$= 3.15 \times 10^6 \text{ Watt}$$

$$= 3.15 \text{ MW}$$

where we assumed the turbine efficiency is 40%.

Site selection considerations

- High annual average wind speed
- Availability of anemometry data
- Availability of wind curve at the proposed site
- Wind structure at the proposed site
- Altitude of the proposed site
- Terrain and its aerodynamic
- Local Ecology
- Distance to roads and railways
- Nearness of site to load centres
- Nature of ground
- Favourable land cost
- Other conditions such as icing problem

Tip Speed Ratio

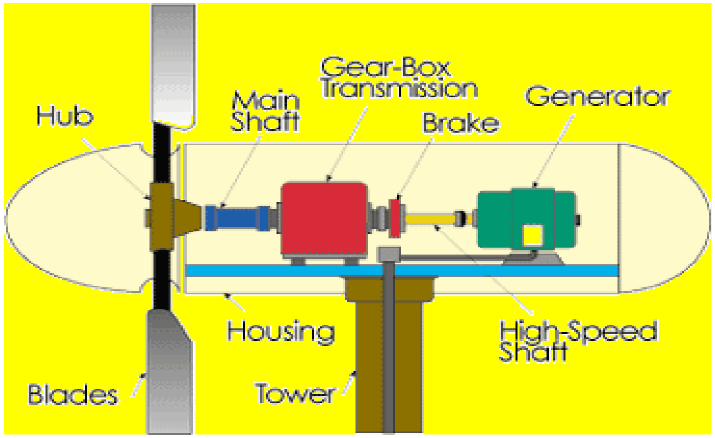
The tip-speed ratio is the ratio of the ***rotational speed of the blade to the wind speed.*** The larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed. Electricity generation requires high rotational speeds. Lift-type wind turbines have maximum tip-speed ratios of around 10, while drag-type ratios are approximately 1.

Given the high rotational speed requirements of electrical generators, ***it is clear that the lift-type wind turbine is the most practical for this application.***

The number of blades and the total area they cover affect wind turbine performance. For a lift-type rotor to function effectively, the wind must flow smoothly over the blades. To avoid turbulence, spacing between blades should be great enough so that one blade will not encounter the disturbed, weaker air flow caused by the blade which passed before it.

The Generator

The generator converts the mechanical energy of the turbine to electrical energy (electricity).



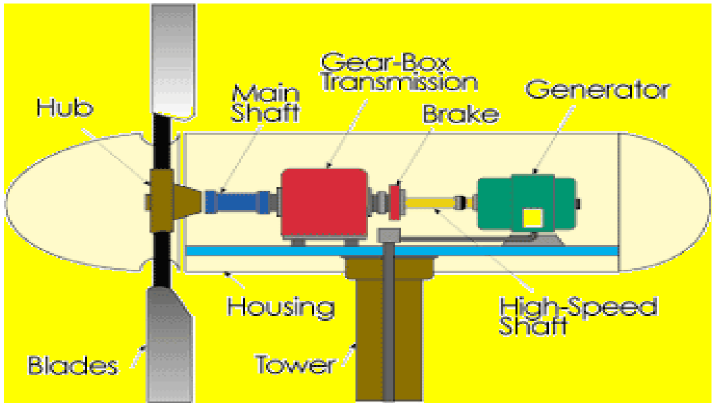
Inside this component, coils of wire are rotated in a magnetic field to produce electricity. Different generator designs produce either alternating current (AC) or direct current (DC), available in a large range of output power ratings.

Most home and office appliances operate on 120 volt (or 240 volt), 60 cycle AC. Some appliances can operate on either AC or DC, such as light bulbs and resistance heaters, and many others can be adapted to run on DC. Storage systems using batteries store DC and usually are configured at voltages of between 12 volts and 120 volts.

Generators that produce AC are generally equipped with features to produce the correct voltage (120 or 240 V) and constant frequency (60 cycles) of electricity, even when the wind speed is fluctuating.

Transmission

Most wind turbines require a gear-box transmission to increase the rotation of the generator to the speeds necessary for efficient electricity production.



The number of revolutions per minute (rpm) of a wind turbine rotor can range between 40 rpm and 400 rpm, depending on the model and the wind speed. Generators typically require rpm's of 1,200 to 1,800. As a result, Some DC-type wind turbines do not use transmissions. Instead, they have a direct link between the rotor and generator. These are known as direct drive systems. Without a transmission, wind turbine complexity and maintenance requirements are reduced, but a much larger generator is required to deliver the same power output as the AC-type wind turbines.

Cut-in Speed

Cut-in speed is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 7 and 15 mph.

Rated Speed

The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. For example, a "10 kilowatt" wind turbine may not generate 10 kilowatts until wind speeds reach 25 mph. Rated speed for most machines is in the range of 25 to 35 mph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases. The output of most machines levels off above the rated speed. Most manufacturers provide graphs, called "power curves," showing how their wind turbine output varies with wind speed.

Wind Turbine

Cut-out Speed

At very high wind speeds, typically between 45 and 80 mph, most wind turbines cease power generation and shut down. The wind speed at which shut down occurs is called the cut-out speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage. Shut down may occur in one of several ways.

In some machines an automatic brake is activated by a wind speed sensor.

Some machines twist or "pitch" the blades to spill the wind.

Still others use "spoilers," drag flaps mounted on the blades or the hub which are automatically activated by high rotor rpm's, or mechanically activated by a spring loaded device which turns the machine sideways to the wind stream. Normal wind turbine operation usually resumes when the wind drops back to a safe level.

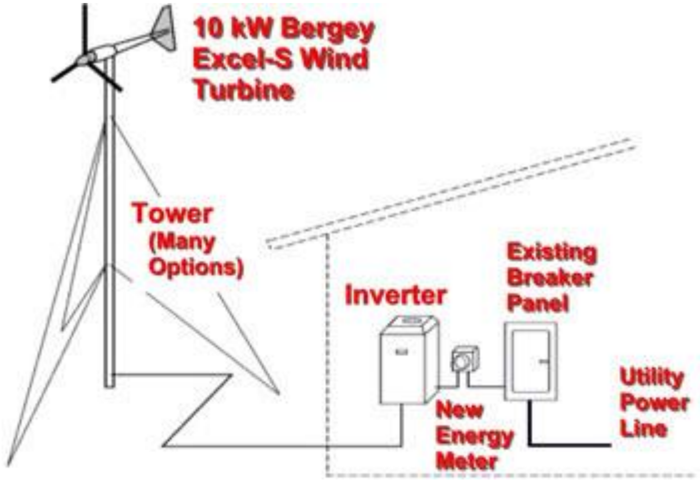
Power Generated by Wind Turbine

Wind turbines with rotors (turbine blades and hub) that are about 8 feet in diameter (50 square feet of swept area) may peak at about 1,000 watts (1 kilowatt; kW), and generate about 75 kilowatt-hours (kWh) per month with a 10 mph average wind speed. Turbines smaller than this may be appropriate for sailboats, cabins, or other applications that require only a small amount of electricity. [Small Wind]

For wind turbine farms, it's reasonable to use turbines with rotors up to 56 feet in diameter (2,500 square feet of swept area). These turbines may peak at about 90,000 watts (90 kW), and generate 3,000 to 5,000 kWh per month at a 10 mph average wind speed, enough to supply 200 homes with electricity.

Homes typically use 500-1,500 kilowatt-hours of electricity per month. Depending upon the average wind speed in the area this will require a wind turbine rated in the range 5-15 kilowatts, which translates into a rotor diameter of 14 to 26 feet.

Example Residential Wind Turbine



Bergey wind turbines operate at variable speed to optimize performance and reduce structural loads. Power is generated in a direct drive, low speed, permanent magnet alternator. The output is a 3-phase power that varies in both voltage and frequency with wind speed. This variable power (wild AC) is not compatible with the utility grid. To make it compatible, the wind power is converted into grid-quality 240 VAC, single phase, 60 hertz power in an IGBT-type synchronous inverter, the GridTek Power Processor. The output from the GridTek can be directly connected to the home or business circuit breaker panel. Operation of the system is fully automatic. It has a rotor diameter of 23 feet and is typically installed on 80 or 100 foot towers.

10kW Turbine	$27,900
100 ft.Tower Kit	$9,200
Tower Wiring Kit	$1,000
Total Cost:	**$38,100**

Wind Turbine

Doubling the tower height increases the expected wind speeds by 10% and the expected power by 34%. Doubling the tower height generally requires doubling the diameter as well, increasing the amount of material by a factor of eight.

At night time, or when the atmosphere becomes stable, wind speed close to the ground usually subsides whereas at turbine altitude, it does not decrease that much or may even increase. As a result, the wind speed is higher and a turbine will produce more power than expected - doubling the altitude may increase wind speed by 20% to 60%.

Tower heights approximately two to three times the blade length have been found to balance material costs of the tower against better utilization of the more expensive active components.

COMPONENTS OF WIND POWER SYSTEM

1. Tower
2. Wind turbine with two or three blades
3. Yaw mechanism
4. Mechanical gear
5. Electrical generator
6. Speed sensors and control

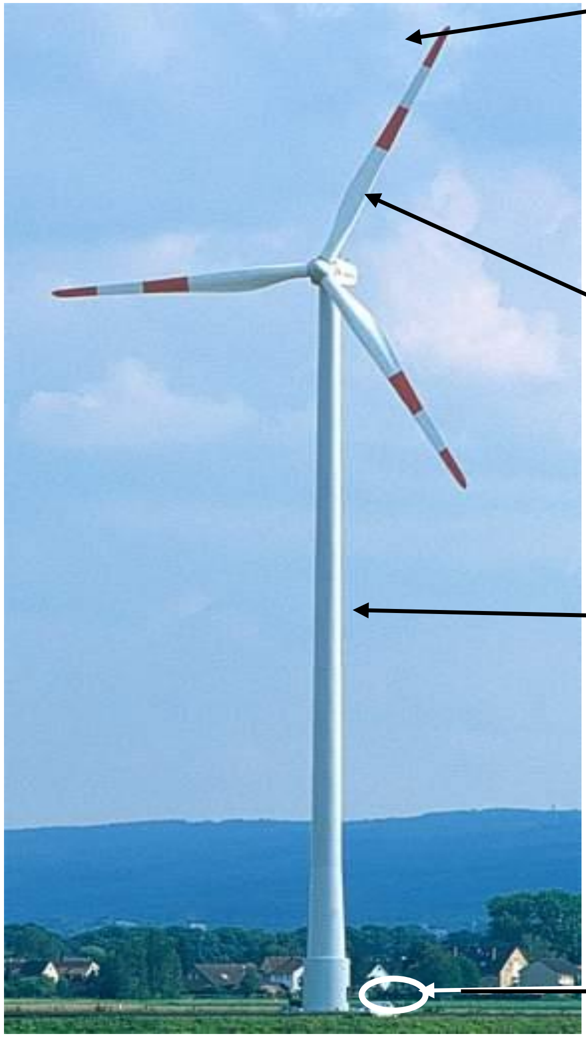
The modern system has the following additional components

1. Power electronics
2. Control electronics
3. Battery for improving the load availability in stand alone mode
4. The transmission link connecting to the area grid

Tower

Wind Turbine Components

GE 1.5 MW
1200-1700 Households



Rotor
35 metric tons
77 meters diameter

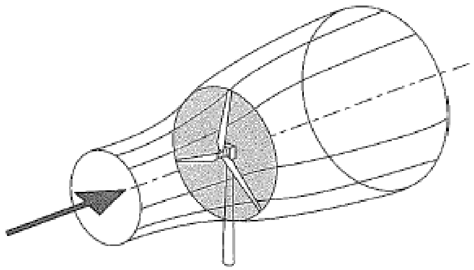
Nacelle
52 metric tons

Tower
120+ metric tons
60 to 100 meters

Car (for scale)

Wind Turbine Principles

Converting one form of energy to another

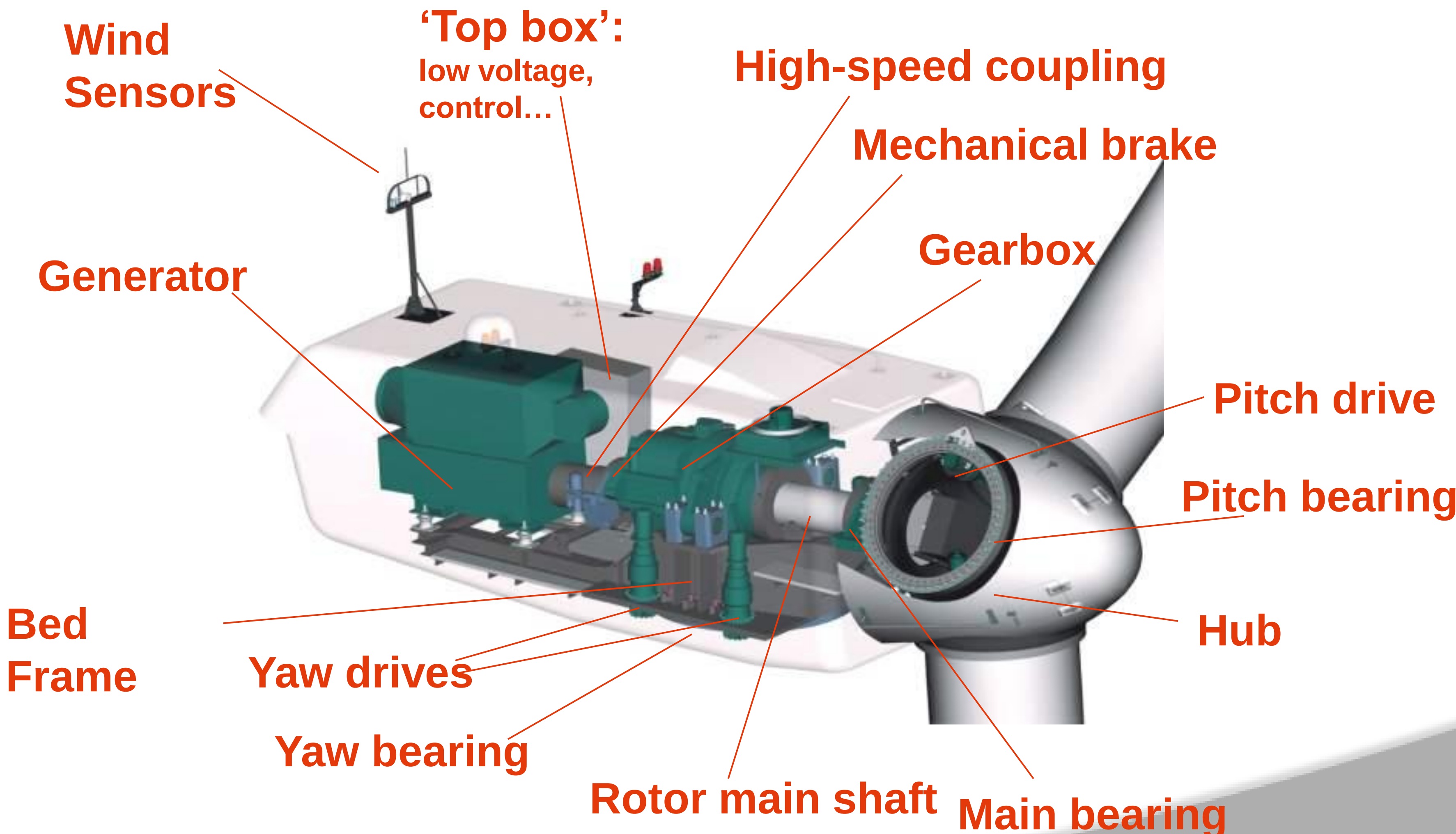


Kinetic Energy → Mechanical Energy → Electrical Energy

Component	Rotor	Gearbox	Generator	Converter
Efficiency	45-52%	95-97%	97-98%	96-99%

Overall: 42 – 50% Efficient Today… Theoritical Maximum is 59.3% (no losses)

Nacelle & Hub components



Each rotor blade can be turned using the pitch drive.

The drive train of the WTGS consists of the hub, the rotor shaft, the gearbox, the coupling, and the generator.

This is mounted on the ground frame. The rotor shaft is mounted in the main bearing.

The gearbox and the generator are noise decoupled to minimized the transmission of noise into the tower.

The gear oil is cooled using the oil cooler above a particular temperature. The generator is cool with the chiller above it. In the so-called "top box" there is a small portion of the control system.

The yaw drives are used to turn the WTGS into the direction of the wind.

Types of turbines

1. Vertical axis wind turbine (VAWT)
2. Horizontal axis wind turbine (HAWT)

Turbine Evolution

Used for

- Pumping water
- Grinding grain

Mainly used for

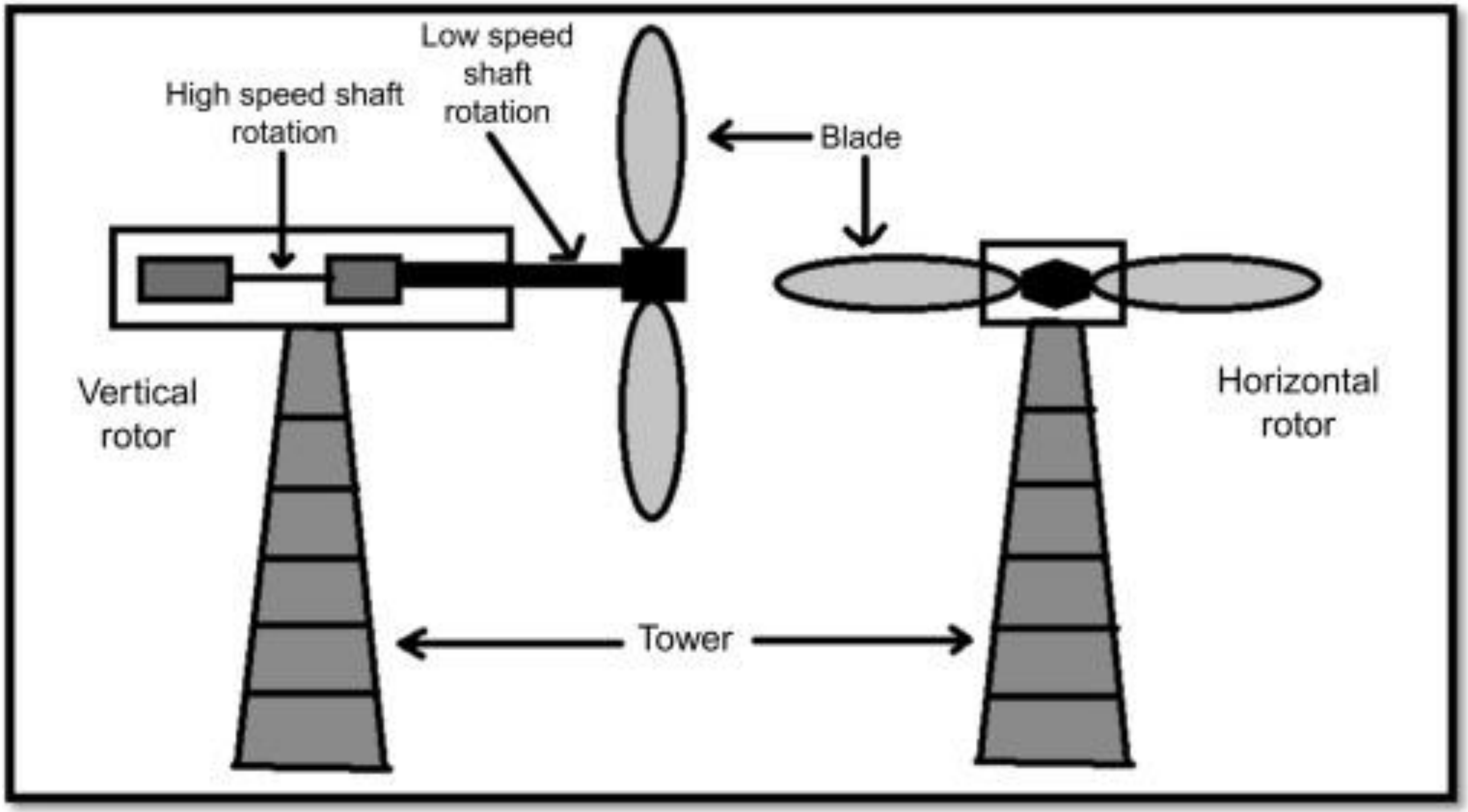
- Generating Electricity

Wind energy collectors

Horizontal Axial Machines

1. Horizontal axis using two aerodynamic blades
2. Horizontal axis propeller type using single blade
3. Horizontal axis multi bladed type
4. Horizontal axis dutch type wind mill
5. Sail type

Horizontal axis using two aerodynamic blades



Horizontal axis propeller type using single blade

- Advantages of 0ne bladed rotor:

(i) Simple blade controls

- lower blade weight and cost
- lower gear box cost

(ii) Counter weight costs less than a second blade

(iii) Counter weight can be inclined to reduce blade coning

(iv) Pitch bearings do not carry centrifugal force

(v) Blade root spar can be large diameter ie.. More rugged

- Disadvantages:

(i) Vibration produced, due to aerodynamic torque.

(ii) Unconventional appearance.

(iii) Large blade root bending moment.

(iv) Starting torque reduced by ground boundary layer

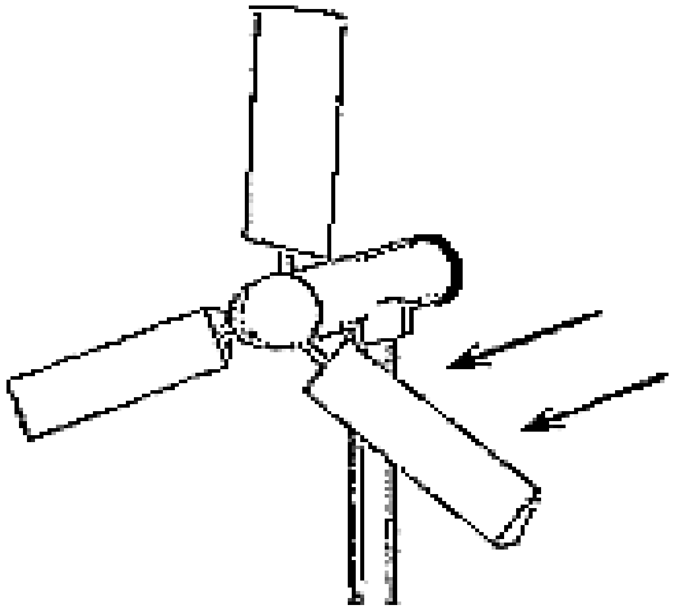
Horizontal axis multi bladed type propeller

Horizontal axis, Dutch type wind mill

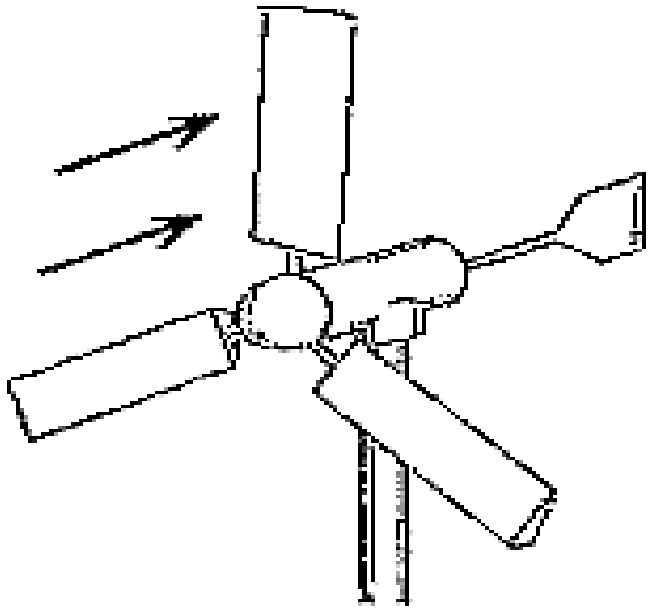
Sail type wind mill

Two types of HAWT

DOWNWIND TURBINE



UPWIND TURBINE

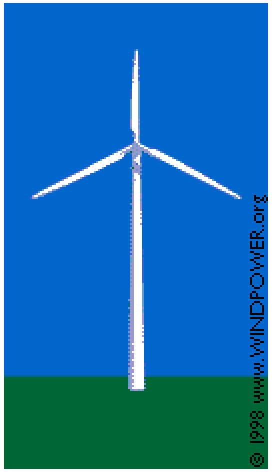


Counter Rotating HAWT

- Increase the rotation speed
- Rear one is smaller and stalls at high wind speeds
- Operates for wider range of wind speeds

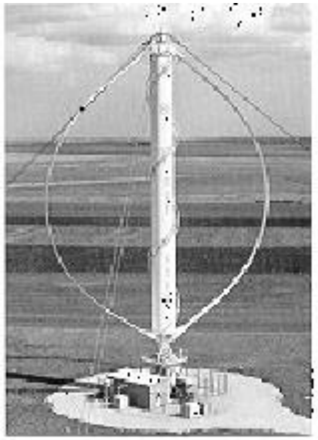
- Number of blades
  - Three blade HAWT are most efficient
  - Two blade turbines don’t require a hub
  - As the number increases; noise, wear and cost increase and efficiency decreases
  - Multiple blade turbines are generally used for water pumping purposes

- Yaw Mechanism
  - To turn the turbine against the wind
  - Yaw error and fatigue loads
  - Uses electric motors and gear boxes
- Wind turbine safety
  - Sensors – controlling vibrations
  - Over speed protection
    - Aero dynamic braking
    - Mechanical braking



Types of turbines

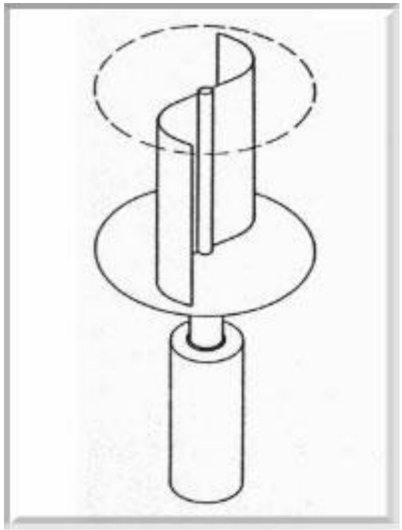
VAWT

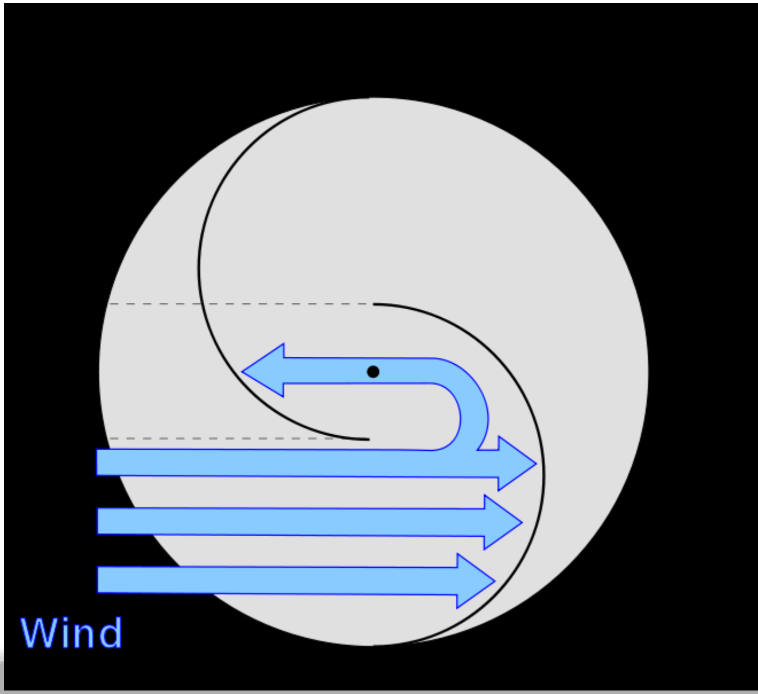


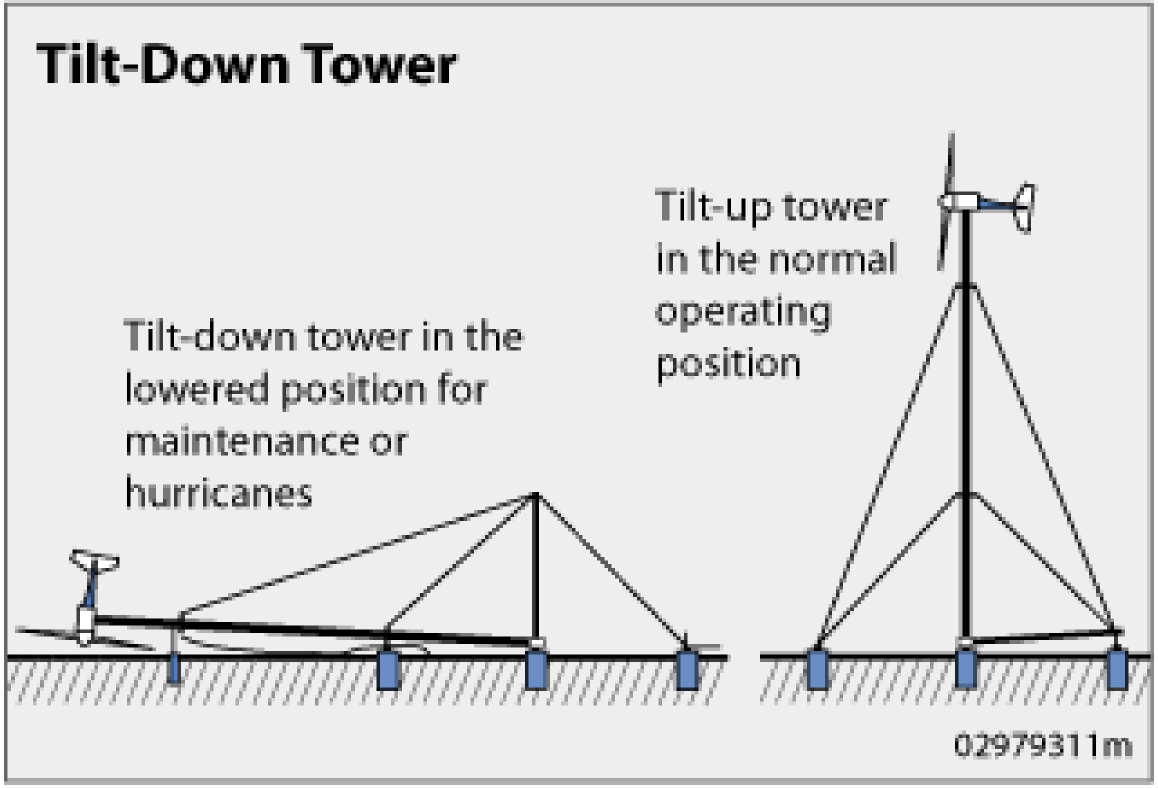
- Drag is the main force
- Nacelle is placed at the bottom
- Yaw mechanism is not required
- Lower starting torque
- Difficulty in mounting the turbine
- Unwanted fluctuations in the power output

The Darrieus turbine has long, thin blades in the shape of loops connected to the top and bottom of the axle; it is often called an "eggbeater windmill." It is named after the French engineer Georges Darrieus who patented the design in 1931. The Darrieus turbine is characterised by its C-shaped rotor blades which give it its eggbeater appearance. It is normally built with two or three blades.

Invented in Finland in the 1922 by Sigurd J. Savonius, the Savonius turbine is S-shaped if viewed from above, and has two, three, or more scoops to catch the wind. Although, unlike the Darrieus turbine (which uses airfoils and aerodynamic lift to turn the blades), the Savonius turbine can't rotate faster than the speed of the wind, it does yield a high torque.






Tilt-Down Tower
Tilt-down tower in the lowered position for maintenance or hurricanes
Tilt-up tower in the normal operating position
02979311m

Disc type wind turbine

- Much more efficient than HAWT

- Requires less height
- Low noise
- Works in any wind direction

Forces on the blade and thrust on turbines

- $P = \rho A V^3$
- $T = P/(\pi D N)$
- Where T = torque kgf or Newton(N)
- W = angular velocity of turbine wheel, m/s
- D = diameter of turbine wheel = $\sqrt{4/\pi} * A$ m
- N = wheel revolutions per unit time 1/s
- The real efficiency = P/Ptotal
- P = efficiency*Ptotal
- $P = \eta * (\rho A V^3)/2g_c$
- $T = \eta * (\rho A V^3)/(2g_c * \pi D N)$
- $T = \eta * (\rho D V^3)/(8g_c * N)$

- The maximum efficiency is 59.3 = 16/27
- Tmax = $2*(\rho DV^3)/(27gc*N)$

1. Wind at 1 standard atmospheric pressure and 15 degrees has velocity of 15m/s calculate

i. The total power density in the wind turbine
ii. Maximum obtainable power density
iii. A reasonably obtainable power density
iv. The total power
v. The torque

Given turbine diameter = 120m, and turbine operating speed is 40rpm at maximum efficiency

For air the value of gas constant

$R = 0.287$ kJ/Kg K

1 atm = 1.01325*10^5 Pa

Air density $\rho = P/RT$

$= 1.226$ kg/m^3

Total power Ptotal = $(\rho AV^3)/2gc$

Power density = Ptotal/A = $(\rho V^3)/2gc$ = 1.226*15^3/(2*1)= 2068.87

Maximum power density = Pmax/A = $8*(\rho AV^3)/(27gcA)$

= 8*1.226*15^3/(27*1)

= 1226 W/m^2

Assuming efficiency = 35%

P/A = η*Ptotal = 0.35*2068.87 = 724W/m^2

Total power = power density*area = 724* πD^2/4 = 8184KW

Tmax = 2*(ρDV^3)/(27gc*N) = 2*1.226*120*15^3/(27*1*(40/60))

= 55170 N

Typical cost statistics

- Size: 51 MW
- Wind Speed: 13-18 miles/hour
- Capital cost: $ 65 million ($1300/MW)
- Annual production: 150 million kW-hr
- Electricity costs: 3.6-4.5 cents
- Payback period: 20 years

- Visual impact
    - Off shore turbines
    - Arrangement
- Avian concerns
    - Suitable choice of site
    - Using tubular towers instead of lattice tower
    - Using radars

- Noise
  - Varies as 5^{th} power of relative wind speed
  - Streamlining of tower and nacelle
  - Acoustic insulation of nacelle
  - Specially designed gear box
  - Use of upwind turbines
  - Reducing angle of attack
  - Low tip speed ratios

- Changes in wind patterns
  - Reducing turbulence
- Intermittent
  - Coupling with hydro or solar energy
- TV, microwave, radar interference
  - Switching from conducting material to non-conducting and composite material

- A typical 600 kW wind turbine has a rotor diameter of 43-44 meters, i.e. a rotor area of some 1,500 square meters.

- The rotor area determines how much energy a wind turbine is able to harvest from the wind.

- Since the rotor area increases with the square of the rotor diameter, a turbine which is twice as large will receive $2^2 = 2 \times 2 =$ four times as much energy.

  - To be considered a good location for wind energy, an area needs to have average annual wind speeds of at least 12 miles per hour.

Turbine rating

- The wind turbines are manufactured in sizes ranging from a few kW for stand-alone remote applications to a couple of MW each for utility scale power generation.
- The method of assessing the nominal rating of the wind turbine has no globally acceptable standard. The difficulty arises because the power output of the turbine depends on the square of the rotor diameter and the cube of the wind speed.

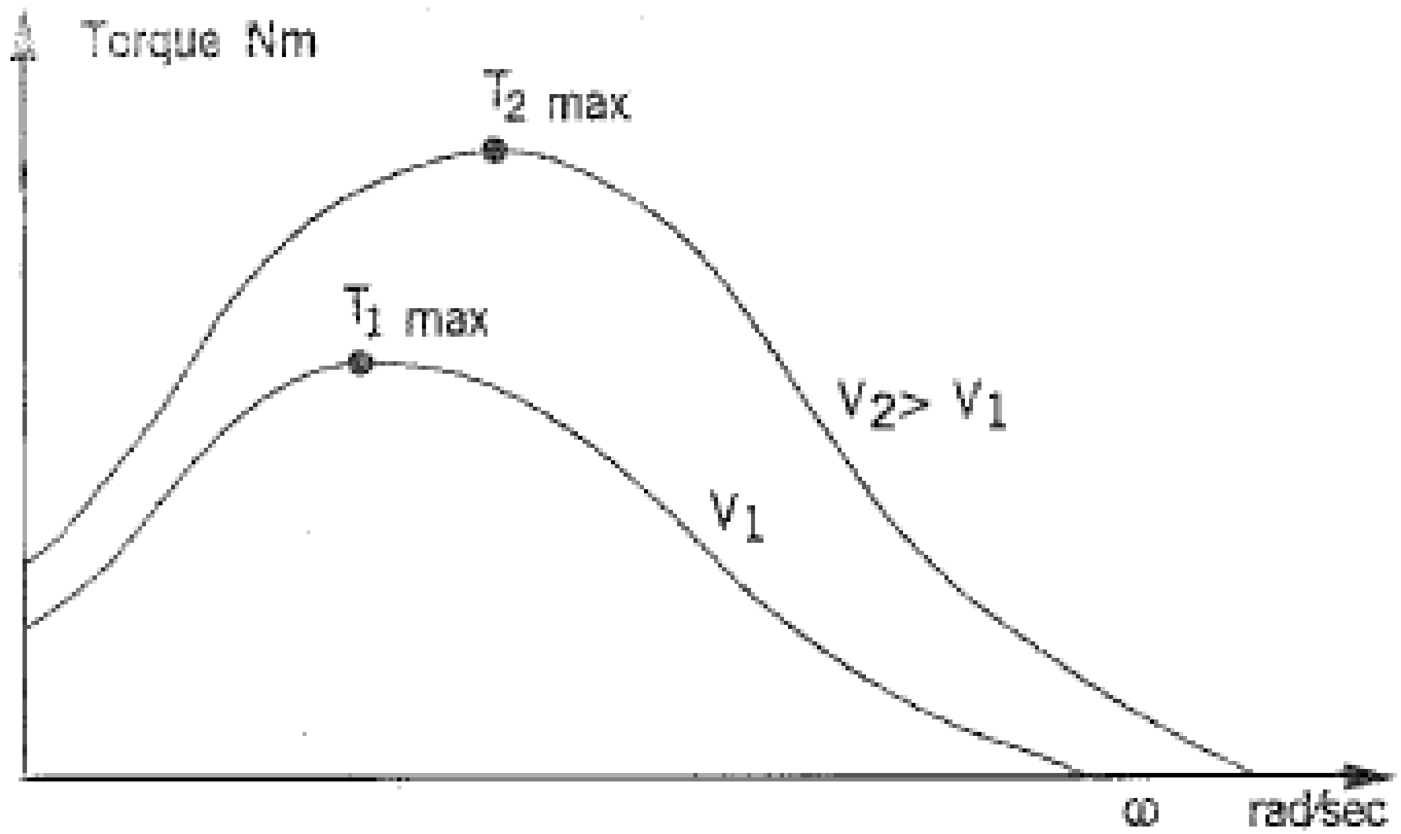
- The rotor of a given diameter will, therefore, generate different power at different wind speed. The turbine that can generate 300 kW at 7 m/s would produce 450 kW at 8 m/s wind.
- The specific rated capacity (SRC) is often used as a comparative index of the wind turbine designs. It is defined as follows:
- *SRC = Generator electrical capacity/Rotor swept area*
- For the 300/30 wind turbine, the specific rated capacity is

  300/(π*15^2) = 0.42 kW/m^2
- The specific rated capacity increases with the diameter, giving a favorable economy of scale to large machine.

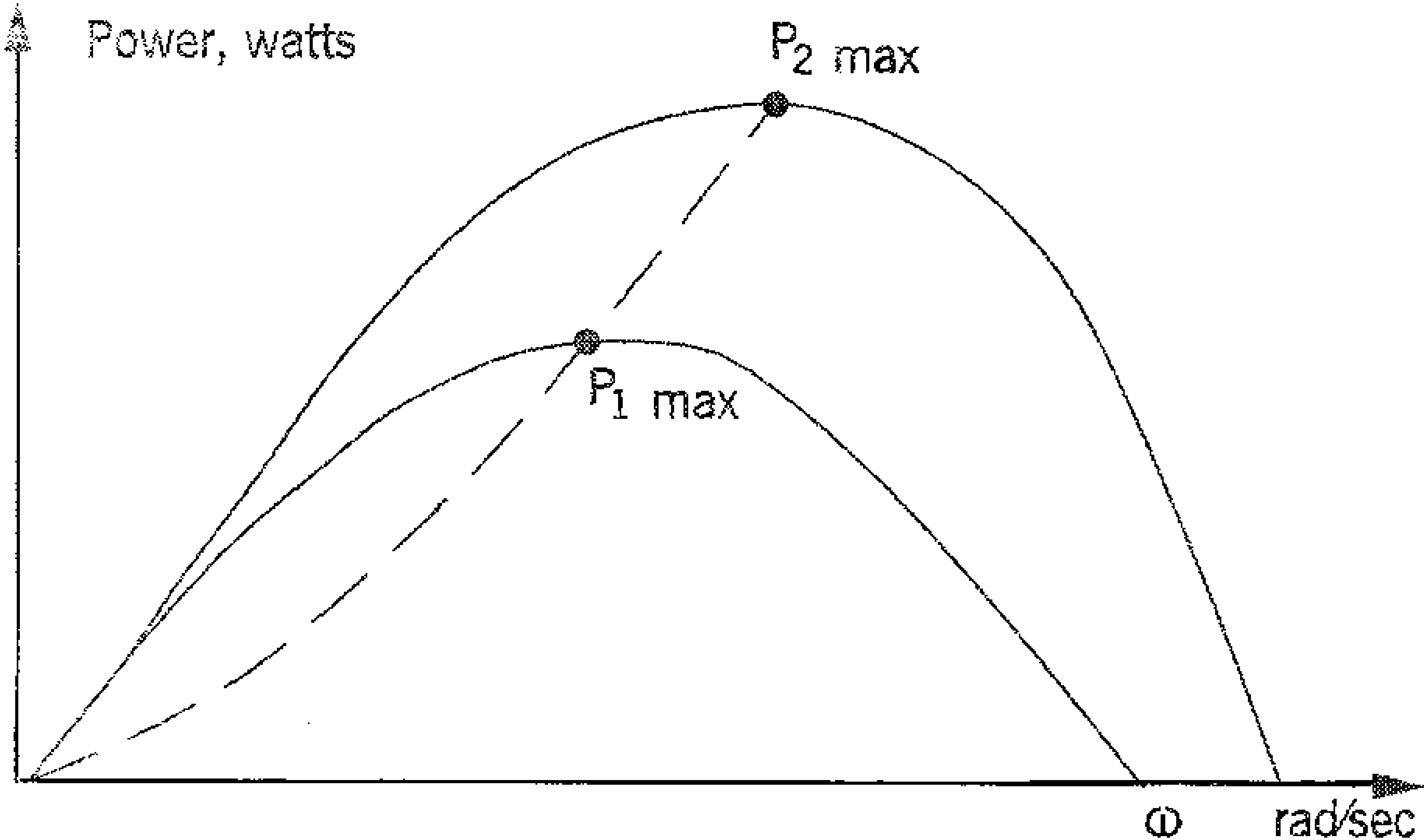
- The turbine rating is important as it indicates to the system designer how to size the induction generator, the plant’s transformer, connecting cables to the substation, and the transmission link interfacing the grid.
- The power system must be sized on the peak capacity of the generator, and the generator is rated in a different manner than the wind turbine. The turbine power depends on the cube of the wind speed.
- The system design engineer is, therefore, required to match the turbine and the generator performance characteristics.

Electrical load matching

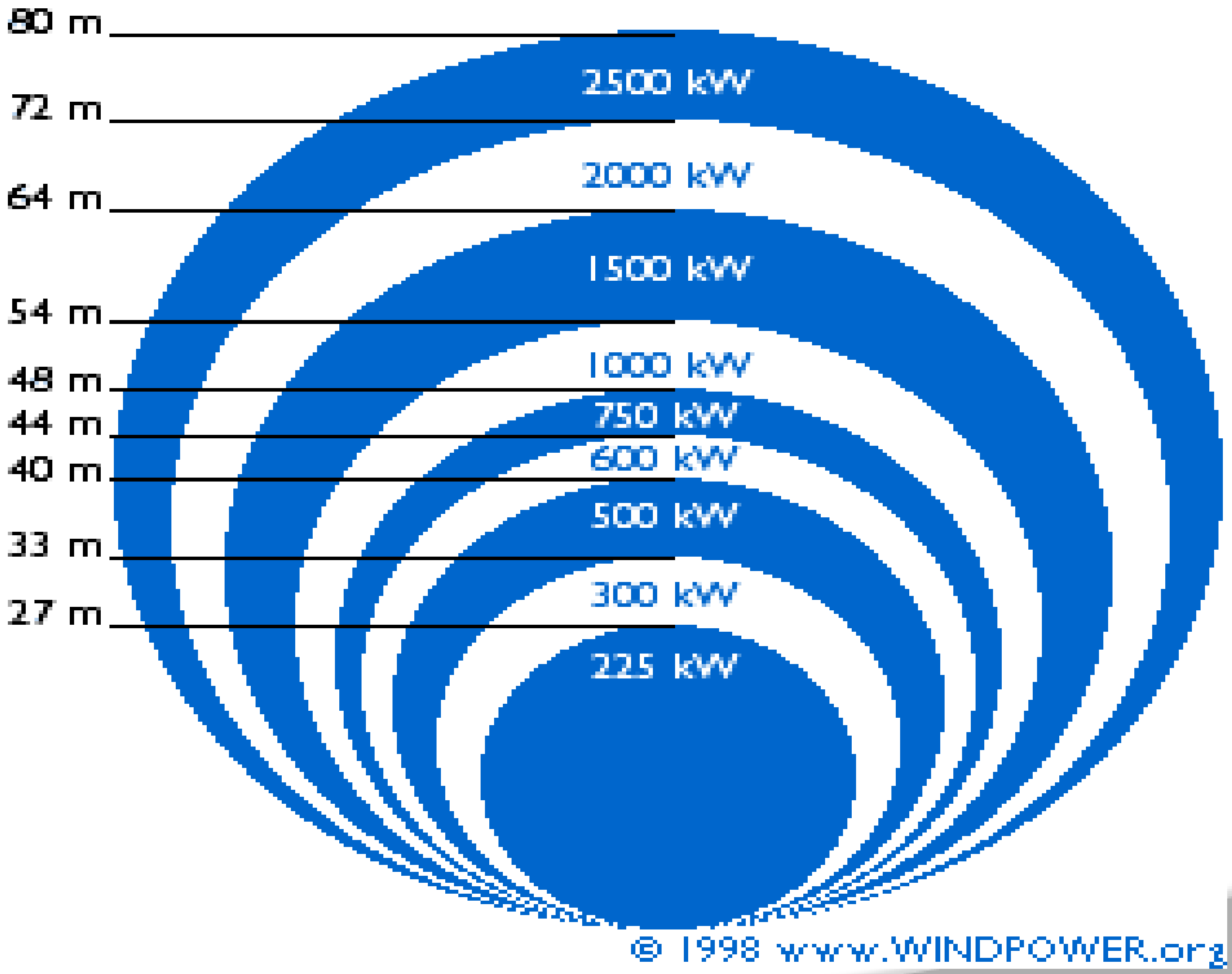
- The operating strategy of a well-designed wind power system is to match the load on the electrical generator so that the rotor operates continuously at speeds as close as possible to the Pmax points.
- Since the Pmax point changes with the wind speed, the rotor speed must therefore be adjusted in accordance with the wind speed to make the rotor work continuously at Pmax



Wind turbine torque versus rotor speed characteristic at two wind speeds V1 and V2



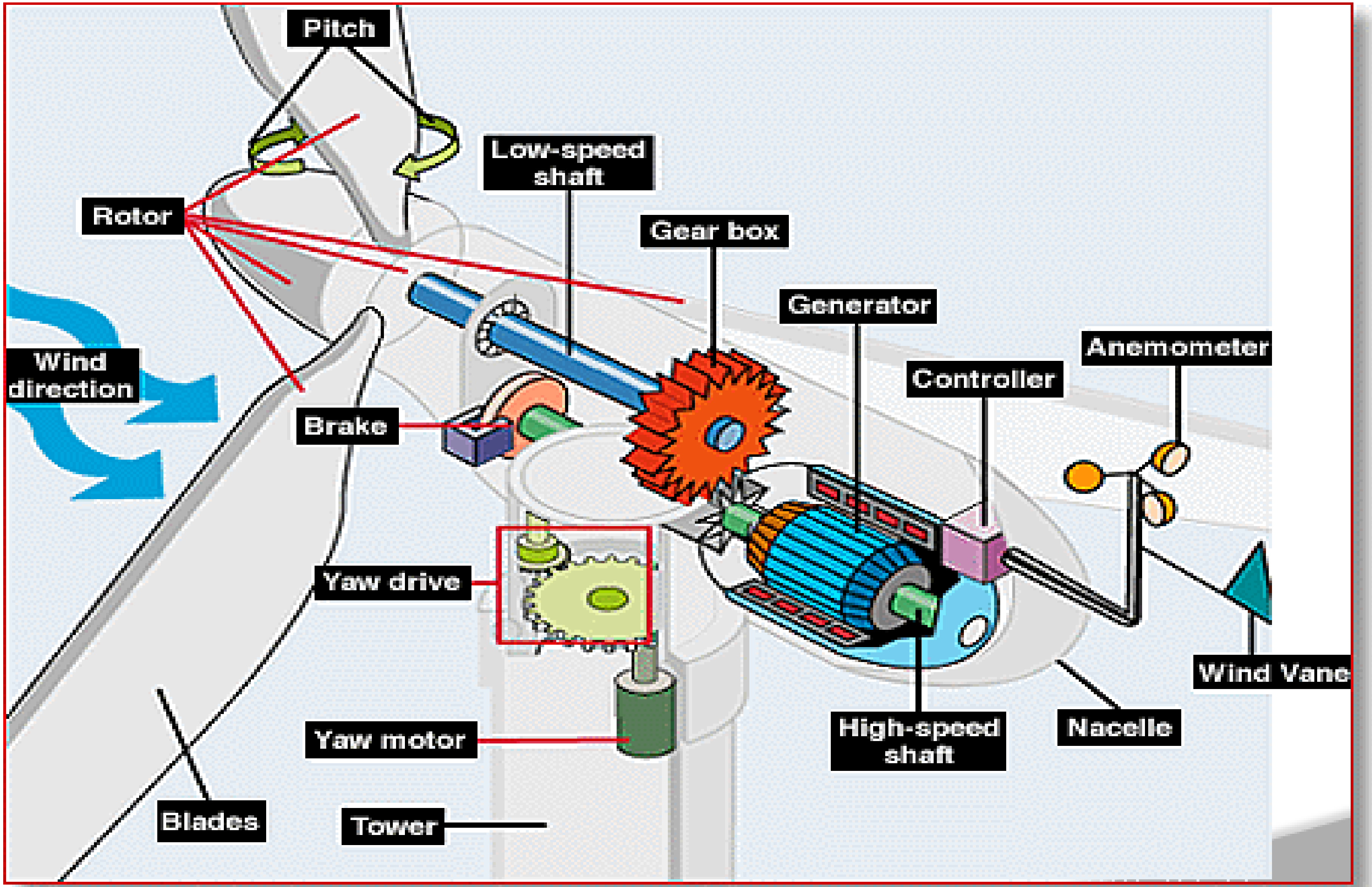
Wind turbine power versus rotor speed characteristic at two wind speeds V1and V2.



80 m
72 m
64 m
54 m
48 m
44 m
40 m
33 m
27 m
2500 kW
2000 kW
1500 kW
1000 kW
750 kW
600 kW
500 kW
300 kW
225 kW
© 1998 www.WINDPOWER.org

- Winds are influenced by the ground surface at altitudes up to 100 meters.
- Wind is slowed by the surface roughness and obstacles.
- When dealing with wind energy, we are concerned with surface winds.
- A wind turbine obtains its power input by converting the force of the wind into a torque (turning force) acting on the rotor blades.
- The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.
- The kinetic energy of a moving body is proportional to its mass (or weight). The kinetic energy in the wind thus depends on the density of the air, i.e. its mass per unit of volume.

  In other words, the "heavier" the air, the more energy is received by the turbine.
- at 15° Celsius air weighs about 1.225 kg per cubic meter, but the density decreases slightly with increasing humidity.


Pitch
Low-speed shaft
Rotor
Gear box
Generator
Anemometer
Controller
Wind direction
Brake
Yaw drive
Wind Vane
Yaw motor
High-speed shaft
Nacelle
Blades
Tower

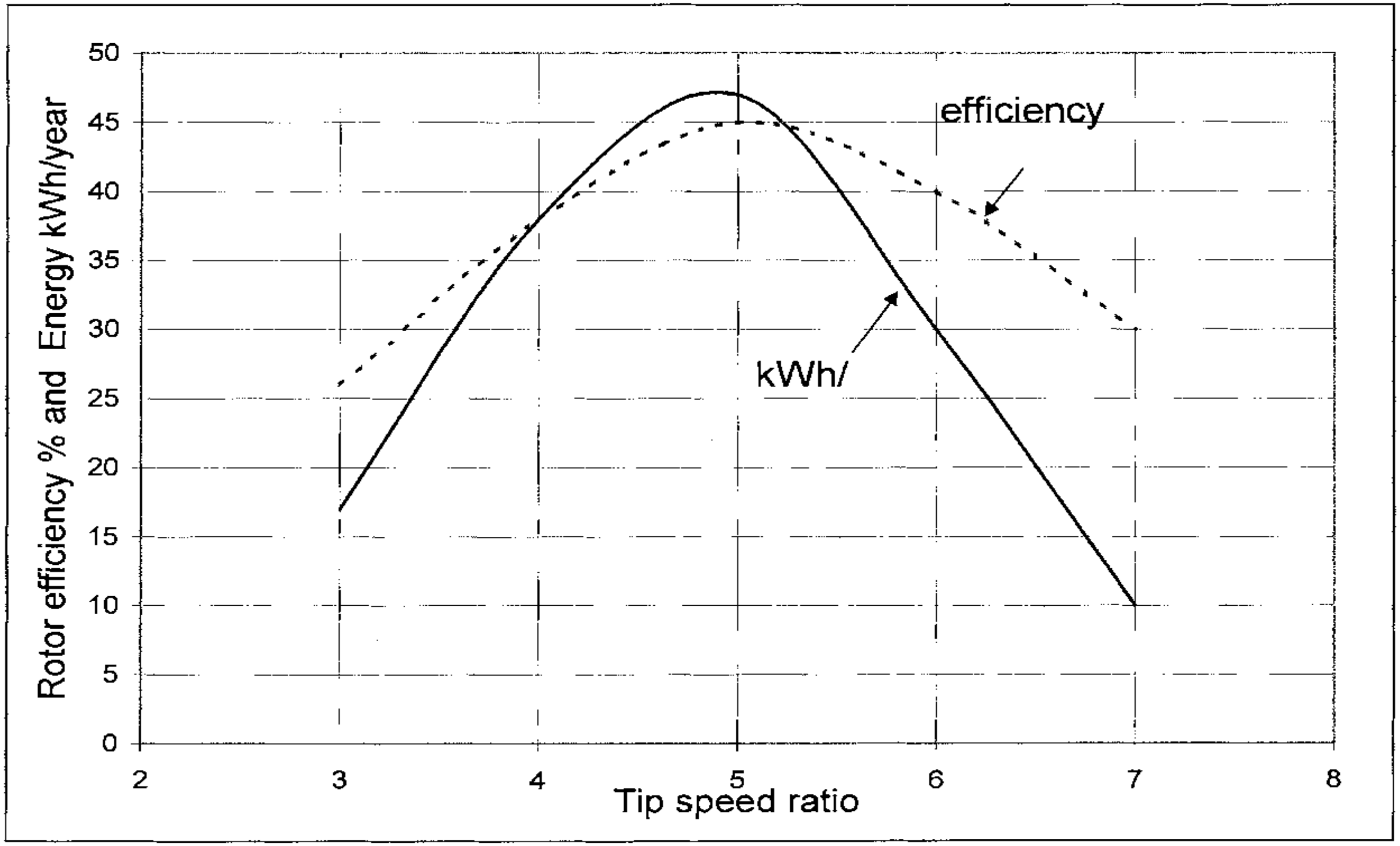
Variable speed operation

- TSR = Linear speed of the blade outer most tip/free upstream wind velocity= $\omega R/V$
- where R and ω are the rotor radius and the angular speed, respectively

Variable speed operation

- Three system performance attributes are related to the TSR:
- The centrifugal mechanical stress in the blade material is proportional to the TSR. The machine working at a higher TSR is stressed more. Therefore, if designed for the same power in the same wind speed, the machine operating at a higher TSR would have slimmer rotor blades.
- The ability of a wind turbine to start under load is inversely proportional to the design TSR. As this ratio increases, the starting torque produced by the blade decreases.
- As seen above, the TSR is also related to the operating point for extracting the maximum power. The maximum rotor efficiency Cp is achieved at a particular TSR, which is specific to the aerodynamic design of a given turbine. The TSR needed for the maximum power extraction ranges from nearly one for multiple-blade, slow-speed machines to nearly six for modern high-speed, two-blade machines.

Variable speed operation



Rotor efficiency and annual energy production versus rotor tip-speed ratio

Advantages of Fixed and Variable Speed Systems

Fixed-Speed System	Variable-Speed System
Simple and inexpensive electrical system	Higher rotor efficiency, hence, higher energy capture per year
Fewer parts, hence higher reliability	Low transient torque
Lower probability of excitation of mechanical resonance of the structure	Fewer gear steps, hence inexpensive gear box
No frequency conversion, hence, no current harmonics present in the electrical system	Mechanical damping system not needed, the electrical system could provide damping if required
Lower capital cost	No synchronization problems Stiff electrical controls can reduce system voltage sags

System Design Features

1. Number of Blades

- The major factors involved in deciding the number of blades are as follows:
- the effect on power coefficient.
- the design tip-speeds ratio.
- the cost.
- the nacelle weight.
- the structural dynamics.
- the means of limiting yaw rate to reduce gyroscopic fatigue

System Design Features

2. Rotor Upwind or Downwind

- 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.
- The downwind blades, on the other hand, allow the use of free yaw system. It also allows the blades to deflect away from the tower when loaded. Both types are used at present with no clear trend.

System Design Features

3. Horizontal Axis Versus Vertical Axis

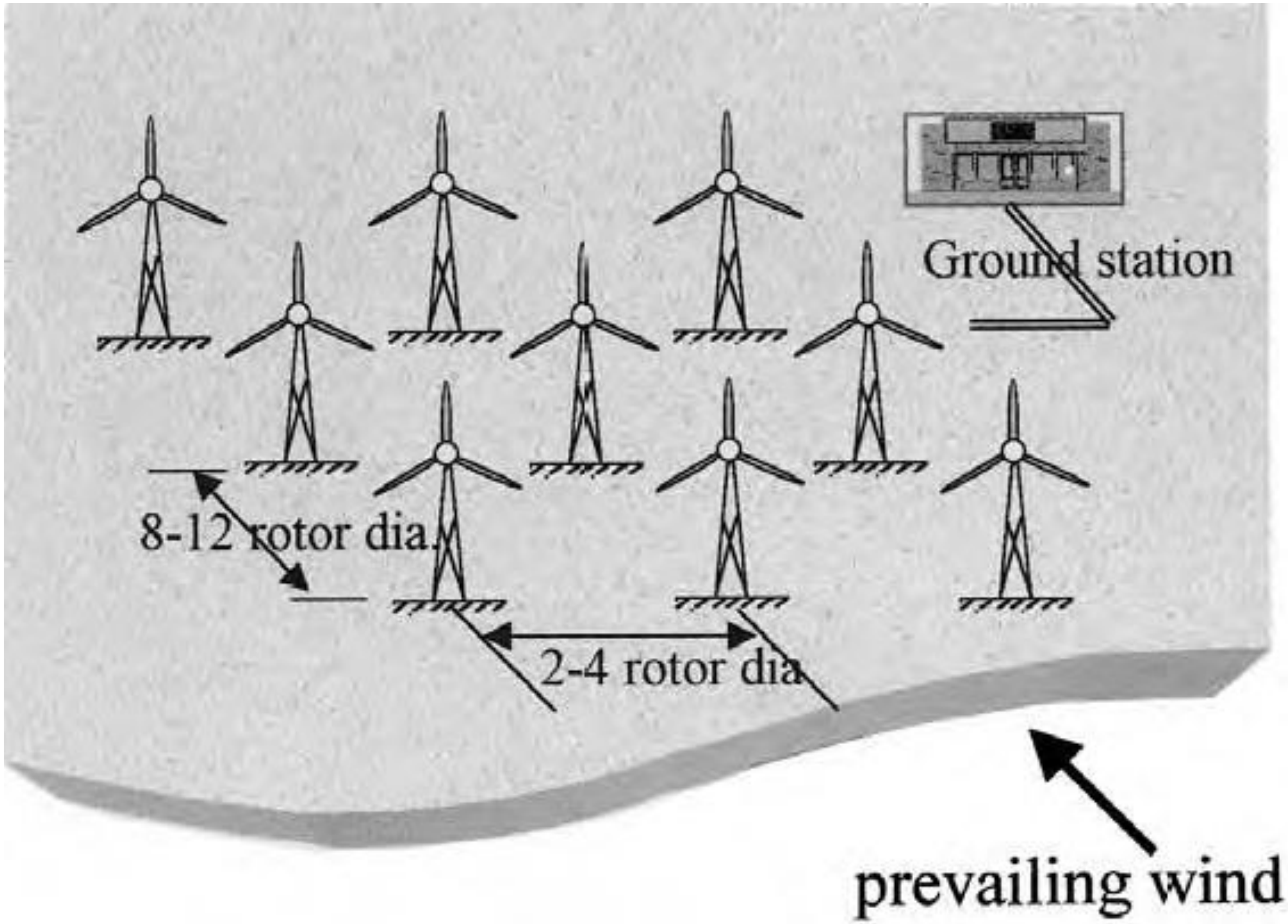
- Most wind turbines built at present have a horizontal axis.
- The vertical axis Darrieus machine has several advantages. First of all, it is omnidirectional and requires no yaw mechanism to continuously orient itself toward the wind direction.
- The vertical axis machine has not been widely used because its output power cannot be easily controlled in high winds simply by changing the blade pitch.

System Design Features

4. Spacing of the Towers

- The spacing depends on the terrain, the wind direction, the speed, and the turbine size.
- The optimum spacing is found in rows 8 to 12-rotor diameters apart in the wind direction, and 1.5 to 3-rotor diameters apart in the crosswind direction

System Design Features



Optimum tower spacing in wind farms in flat terrain.

System Design Features

When the land area is limited or is at a premium price, one optimization study that must be conducted in an early stage of the wind farm design is to determine the number of turbines, their size, and the spacing for extracting the maximum energy from the farm. The trades in such a study are as follows:

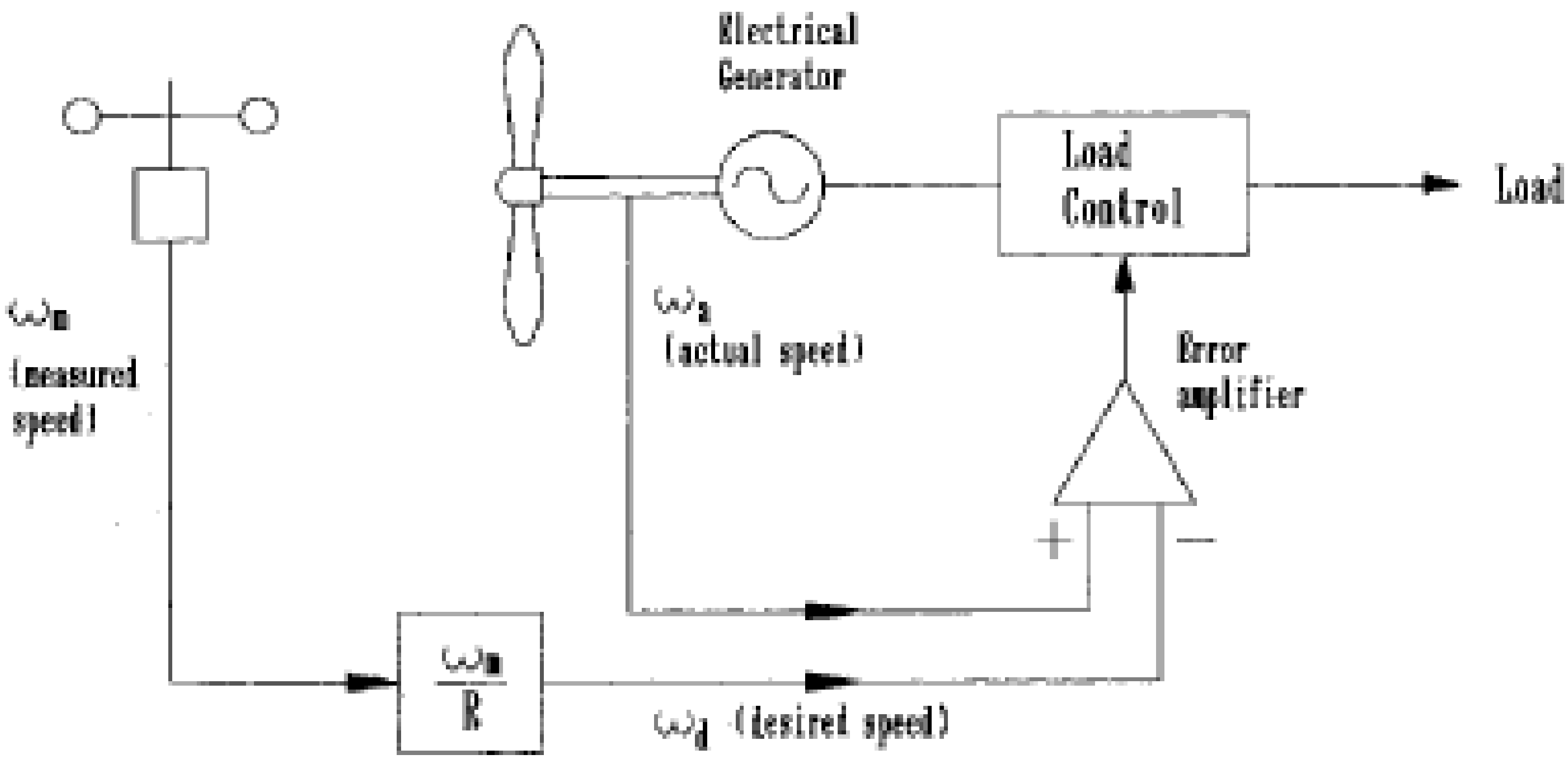
- larger turbines cost less per MW capacity and occupy less land area.
- fewer large machines can reduce the MWh energy crop per year, as downtime of one machine would have larger impact on the energy output.
- the wind power fluctuations and electrical transients on fewer large machines would cost more in electrical filtering of the power and voltage fluctuations, or would degrade the quality of power, inviting penalty from the grid.

Maximum Power Operation

Constant Tip-Speed Ratio Scheme

- This scheme is based on the fact that the maximum energy is extracted when the optimum tip-speed ratio is maintained constantly at all wind speeds.
- The optimum TSR is a characteristic of the given wind turbine. This optimum value is stored as the reference TSR in the control computer.
- The wind speed is continuously measured and compared with the blade tip speed. The error signal is then fed to the control system, which changes the turbine speed to minimize the error

Maximum Power Operation



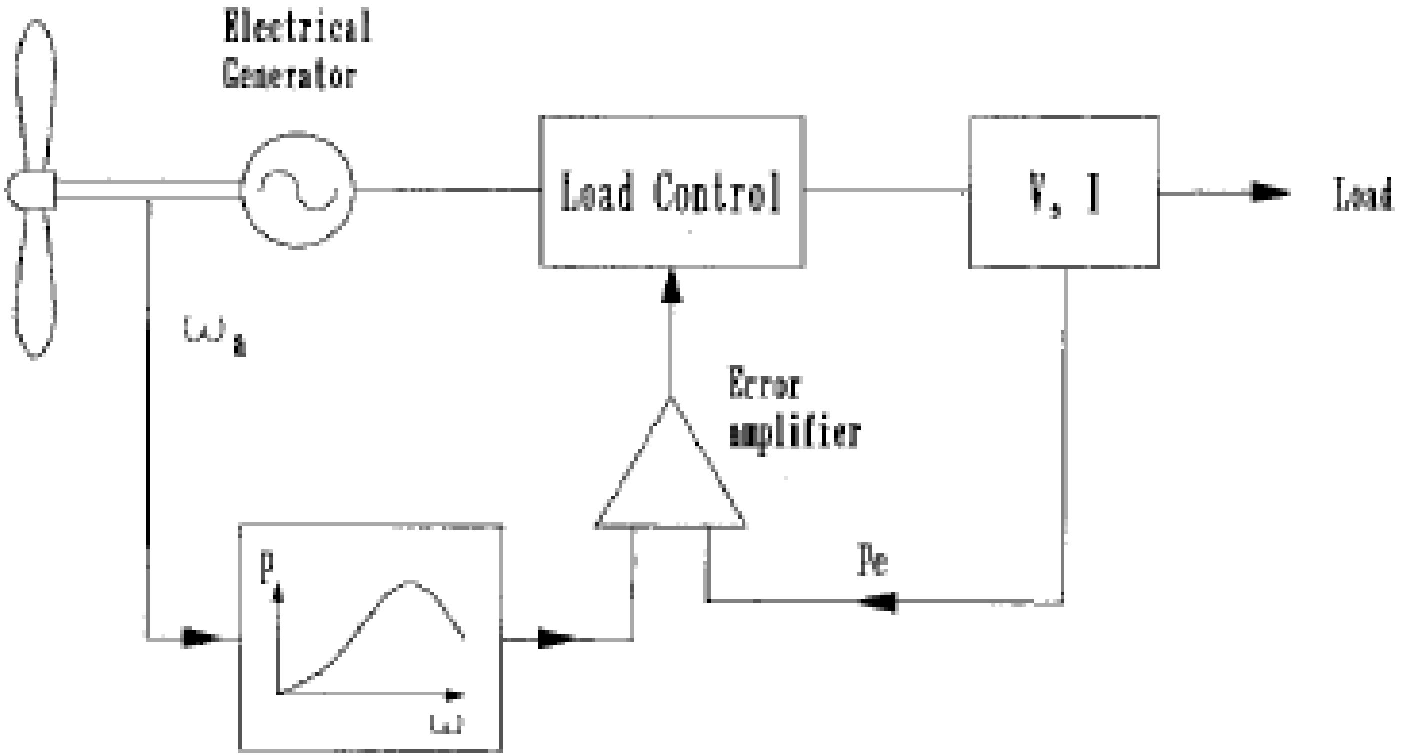
Maximum power operation using rotor tip-speed control scheme

Maximum Power Operation

Peak Power Tracking Scheme

- The power versus speed curve has a single well-defined peak. If we operate at the peak point, a small increase or decrease in the turbine speed would result in no change in the power output, as the peak point locally lies in a flat neighborhood. Therefore, a necessary condition for the speed to be at the maximum power point is as follows:
- $dp/dw=0$
- This method is insensitive to the errors in local wind speed measurement, and also to the wind turbine design. It is, therefore, the preferred method. In a multiple machine wind farm, each turbine must be controlled by its own control loop with operational safety functions incorporated.

Maximum Power Operation



Maximum power operation using power control scheme

System Control Requirements

- **Speed Control**

The rotor speed must be controlled for three reasons:

- to capture more energy, as seen above.
- 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.

System Control Requirements

The speed control requirement of the rotor has five separate regions

1. The cut-in speed at which the turbine starts producing power. Below this speed, it is not efficient to turn on the turbine.

2. The constant maximum Cp region where the rotor speed varies with the wind-speed variation to operate at the constant TSR corresponding to the maximum Cp value.

3. During high winds, the rotor speed is limited to an upper constant limit based on the design limit of the system components. In the constant speed region, the Cp is lower than the maximum Cp, and the power increases at a lower rate than that in the first region.

System Control Requirements

4. At still higher wind speeds, such as during a gust, the machine is operated at constant power to protect the generator and the power electronics from overloading. This can be achieved by lowering the rotor speed. If the speed is decreased by increasing electrical load, the generator will be overloaded, defeating the purpose. To avoid the generator overloading, some sort of brake, eddy current, or other type, must be installed on the rotor.

5. The cutout speed. Beyond certain wind speed, the rotor is shut off producing power in order to protect the blades, the electrical generator and other components of the systems.

System Control Requirements

- The large rotor inertia of the blades must be taken into account in controlling the speed.
- The acceleration and deceleration must be controlled to limit the dynamic mechanical stress on the rotor blades and the hub, and electrical load on the generator and the power electronics.
- The strategy for controlling the speed of the wind turbine varies with the type of the electrical machine used, i.e., the induction machine, the synchronous machine or the DC machine.

$$J\frac{d\omega}{dt} = \frac{P_m - P_e}{\omega}$$

where J = polar moment of inertia of the rotor

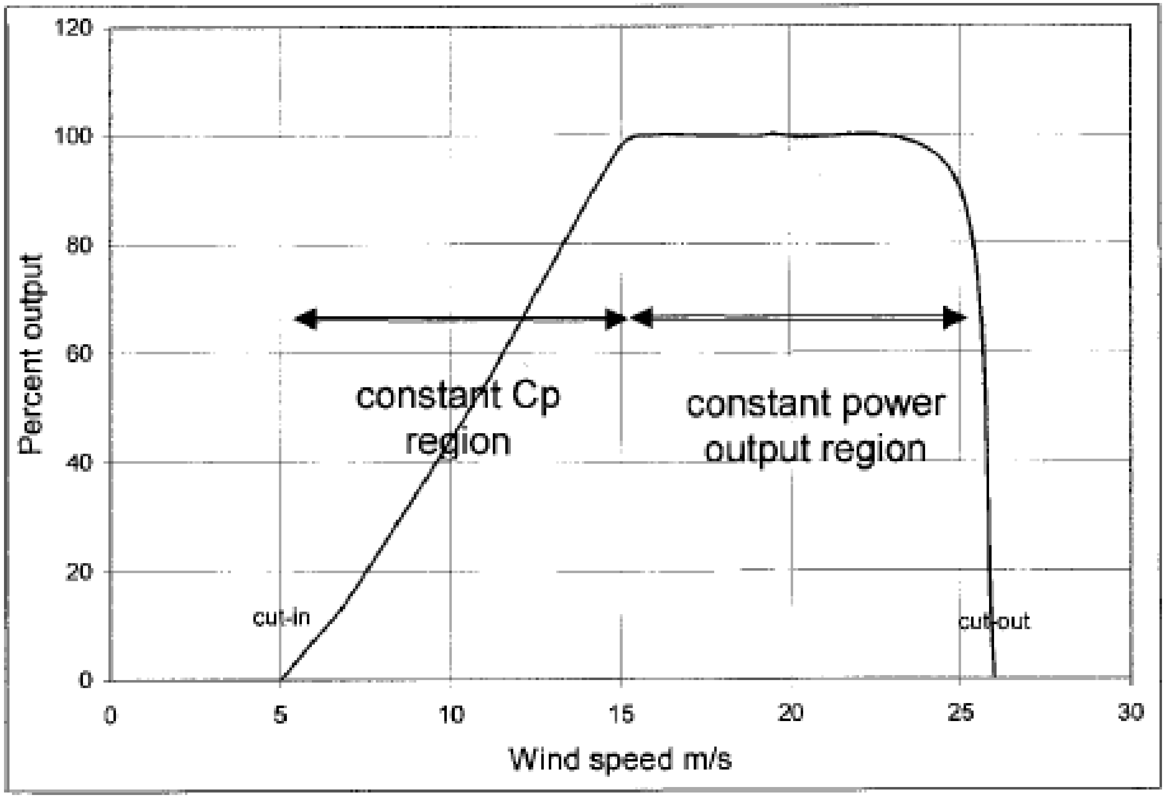
ω = angular speed of the rotor

P_m = mechanical power produced by the blades

P_e = electrical power delivered by the generator.

Integrating above equation gives

$$\frac{1}{2}J \cdot \left(w_2^2 - \omega_1^2\right) = \int_{t_1}^{t_2} \left(P_m - P_e\right) \cdot dt$$



Five regions of the turbine speed control.

Environmental Aspects

Audible Noise

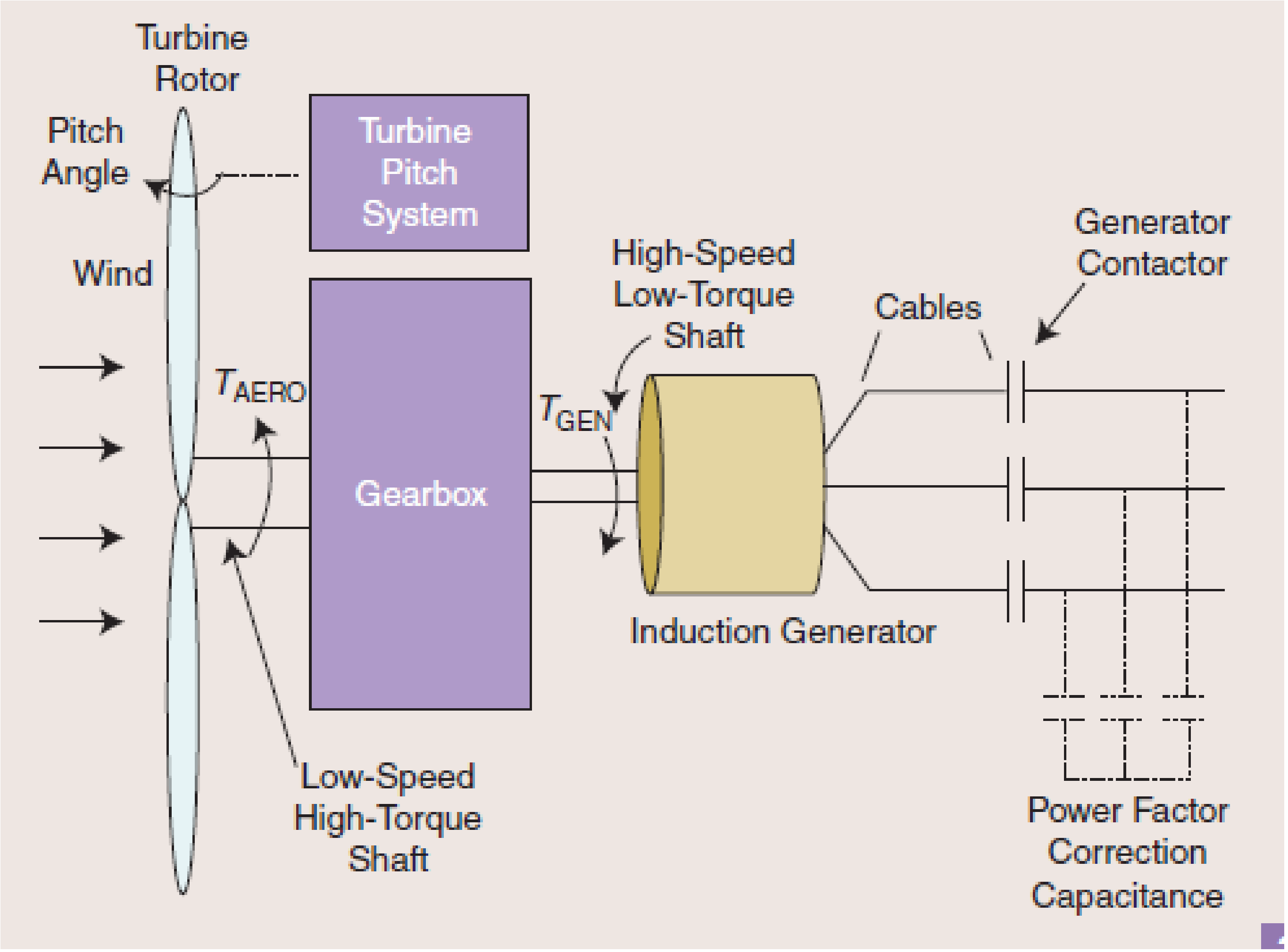
- The wind turbine is generally quiet. It poses no objectionable noise disturbance in the surrounding area. The wind turbine manufacturer generally supply the machine noise level data in dB versus the distance from the tower.

Noise Level of Some Commonly Known Sources Compared with Wind Turbine

Source	Noise level
Elevated train	100 dB
Noisy factory	90 dB
Average street	70 dB
Average factory	60 dB
Average office	50 dB
Quiet conversation	30 dB

- The turbine makes loud noise while yawing under the changing wind direction. The local noise ordinance must be complied with.
- There have been cases of noise complaints reported by the nearby communities.

- **Electromagnetic Interference (EMI)**
- Any stationary or moving structure in the proximity of a radio or TV tower interferes with the signals. The wind turbine towers, being large structures, can cause objectionable electromagnetic interference on the performance of the nearby transmitters or receivers.
- Additionally, rotor blades of an operating wind turbine may reflect impinging signals so that the electromagnetic signals in the neighborhood may experience interference at the blade passage frequency.
- The exact nature and magnitude of such EMI depend on a numberof parameters.



Turbine
Rotor
Pitch
Angle
Turbine
Pitch
System
Wind
T_{AERO}
Gearbox
T_{GEN}
High-Speed
Low-Torque
Shaft
Cables
Generator
Contactor
Induction Generator
Low-Speed
High-Torque
Shaft
Power Factor
Correction
Capacitance

SMALL TURBINES:

- Local electrical grids may not be able to handle the large electrical output from a large turbine, so smaller turbines may be more suitable.
- High costs for foundations for large turbines may not be economical in some areas.
- Landscape considerations

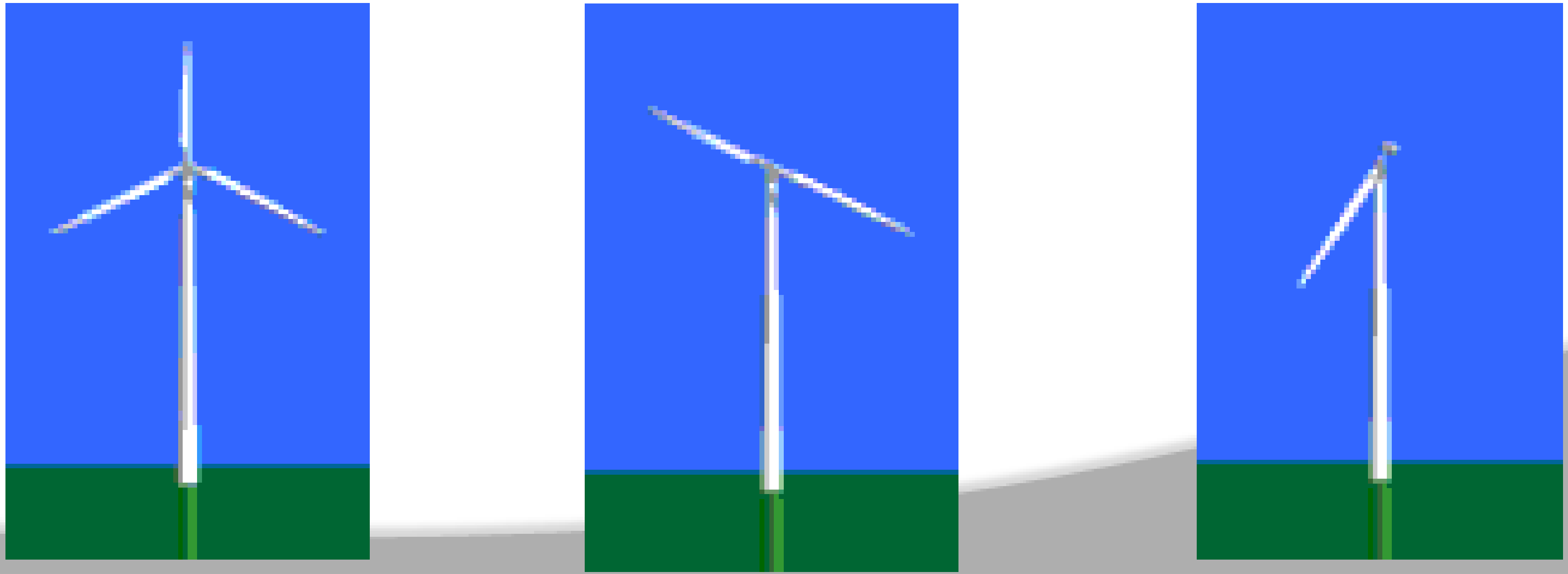
Wind Turbines

LARGE TURBINES:

- Able to deliver electricity at lower cost than smaller turbines, because foundation costs, planning costs, etc. are independent of size.
- Well-suited for offshore wind plants.
- In areas where it is difficult to find sites, one large turbine on a tall tower uses the wind extremely efficiently.

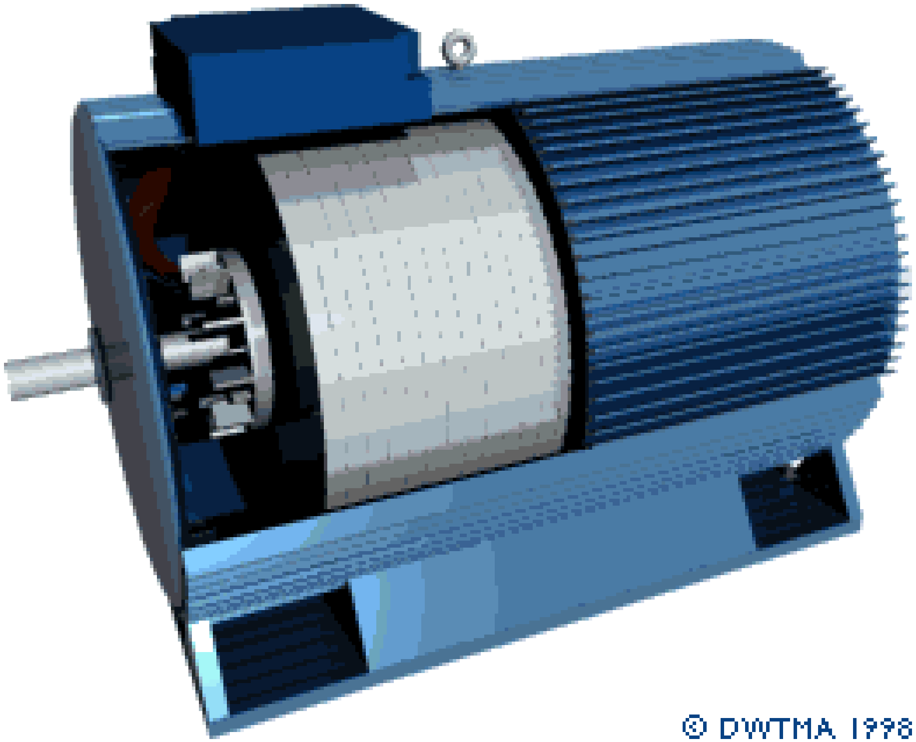
Wind Turbines: Number of Blades

- Most common design is the three-bladed turbine. The most important reason is the stability of the turbine. A rotor with an odd number of rotor blades (and at least three blades) can be considered to be similar to a disc when calculating the dynamic properties of the machine.
- A rotor with an even number of blades will give stability problems for a machine with a stiff structure. The reason is that at the very moment when the uppermost blade bends backwards, because it gets the maximum power from the wind, the lowermost blade passes into the wind shade in front of the tower.




IEEE INDUSTRY

Wind Turbine Generators



- Wind power generators convert wind energy (mechanical energy) to electrical energy.
- The generator is attached at one end to the wind turbine, which provides the mechanical energy.
- At the other end, the generator is connected to the electrical grid.
- The generator needs to have a cooling system to make sure there is no overheating.

Sizes and Applications

Small (≤10 kW)

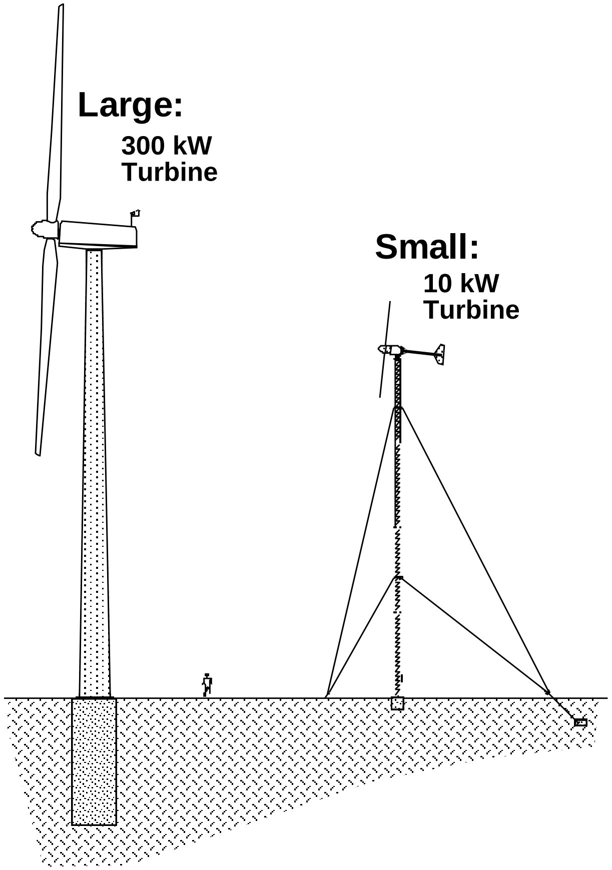
- Homes
- Farms
- Remote Application

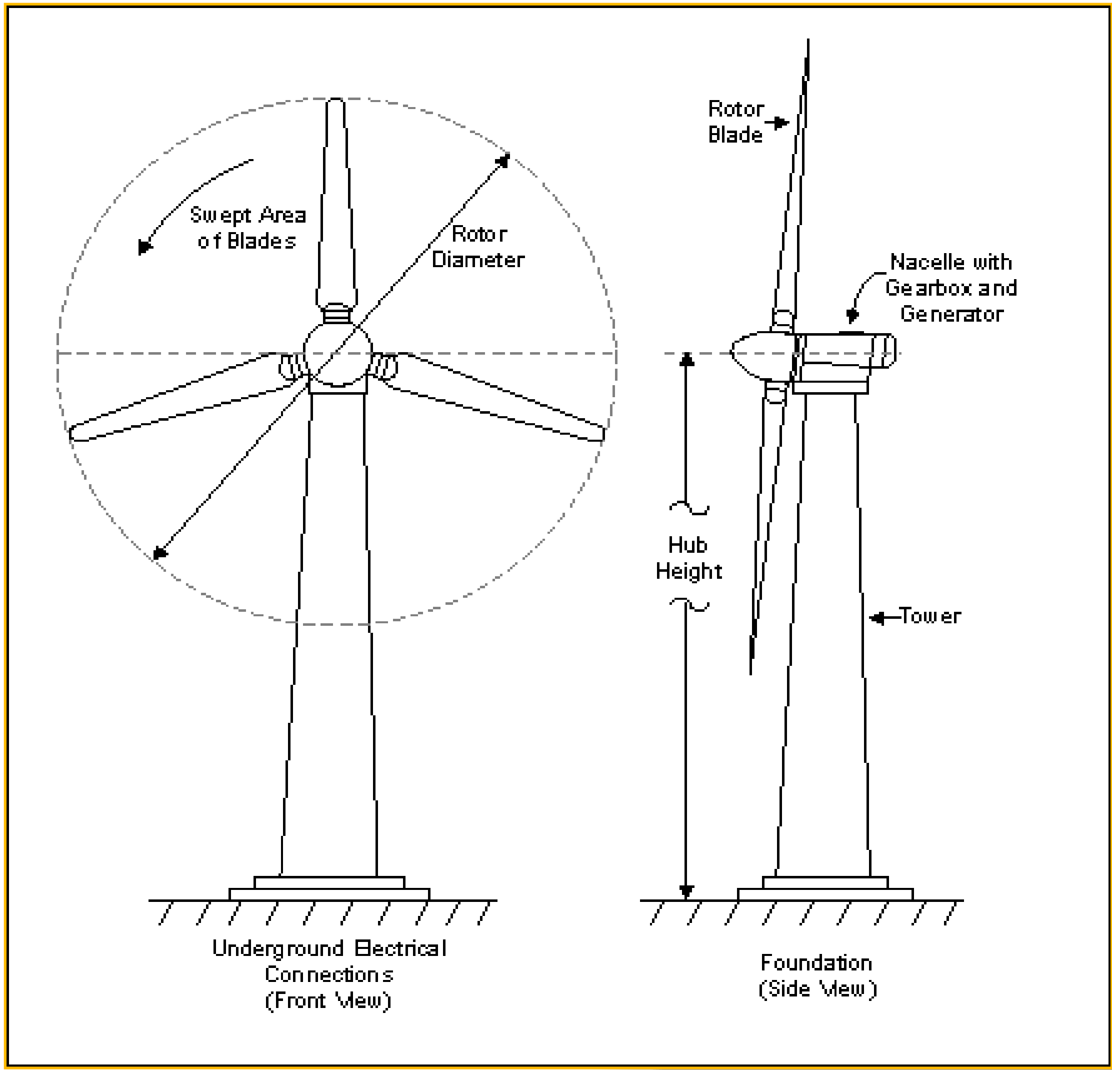
Intermediate
(10-250 kW)

- Village Power
- Hybrid Systems
- Distributed Power

Large (660 kW - 2+MW)

- Central Station Wind Farms
- Distributed Power
- Community Wind


Large:
300 kW
Turbine
Small:
10 kW
Turbine

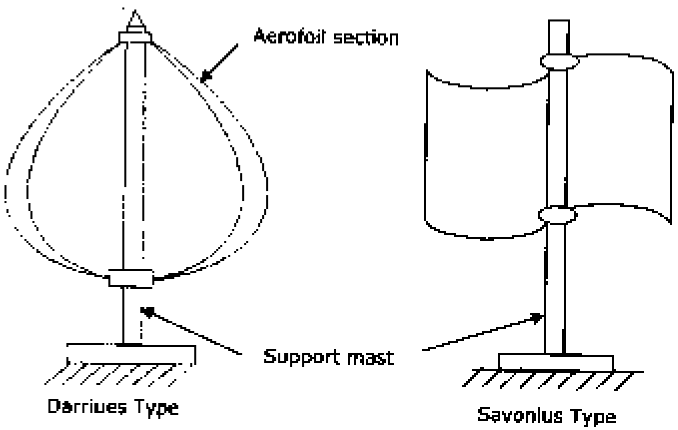

Rotor Blade
Swept Area of Blades
Rotor Diameter
Nacelle with Gearbox and Generator
Hub Height
Tower
Underground Electrical Connections (Front View)
Foundation (Side View)

VERTICAL AXIS WIND TURBINE

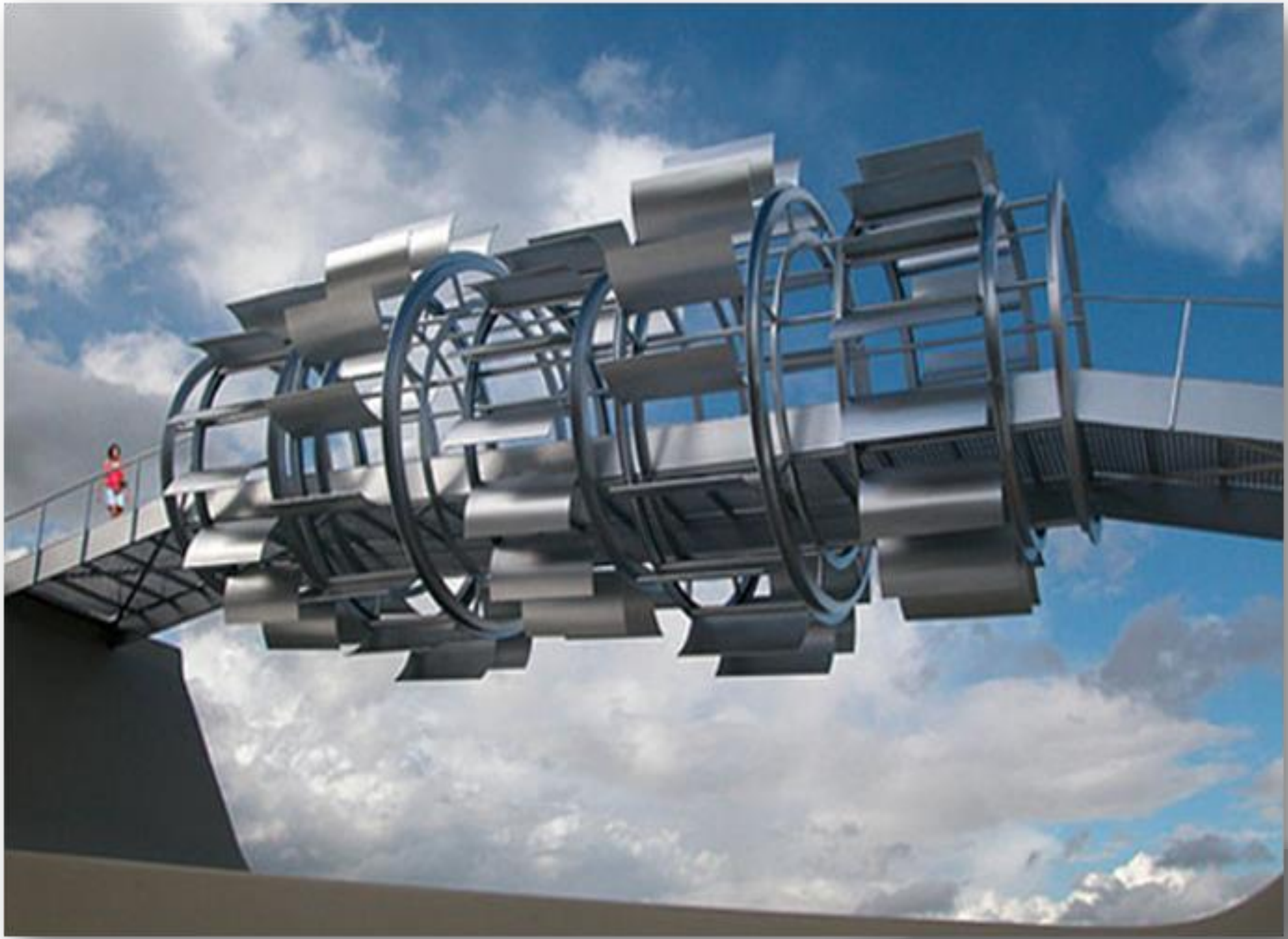
- Vertical axis wind turbine can be classified into two types

  Darrieus type

  Savonius type



- Turbine Size: 1.5MW
- Manufacturer: GE Wind
- Developer/Owner: GE Wind/Shell, PPM
- Capacity: 162 MW
- Commissioned: 2003



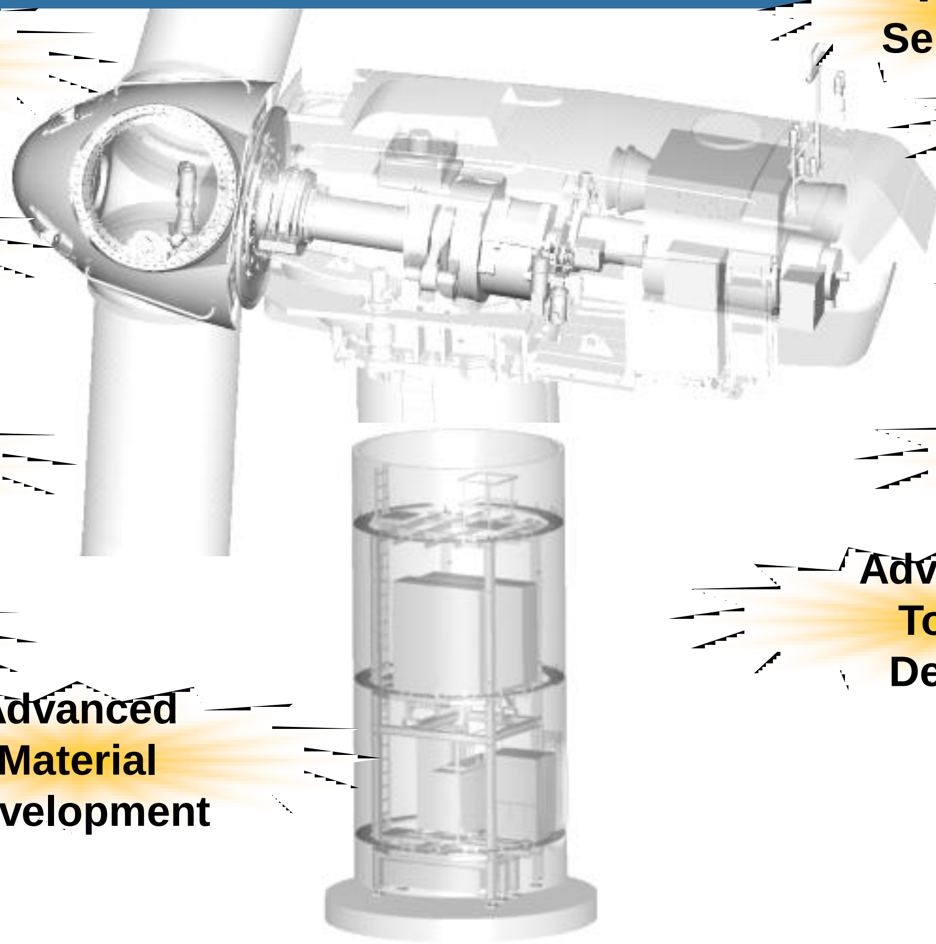
Environmental effects

- Wind power consumes no fuel, and emits no air pollution, unlike fossil fuel power sources. The energy consumed to manufacture and transport the materials used to build a wind power plant is equal to the new energy produced by the plant within a few months of operation.

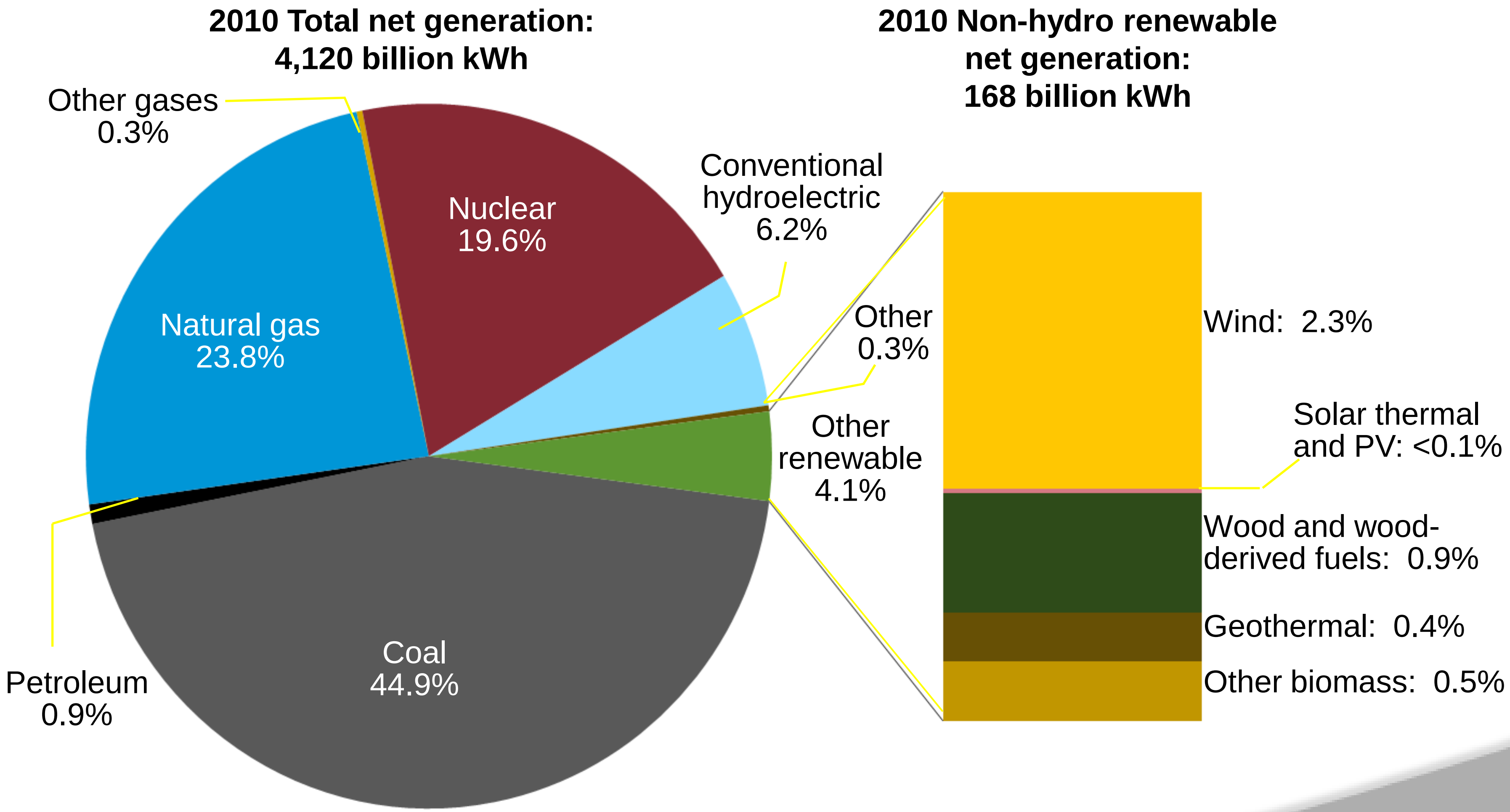
- Danger to birds and bats has been a concern in some locations. However, studies show that the number of birds killed by wind turbines is very low.

- wind energy help to prevent global warming.

Advanced technology development



In 2010, U.S. electricity generation was 70% fossil fuels, 20% nuclear, and 10% renewable



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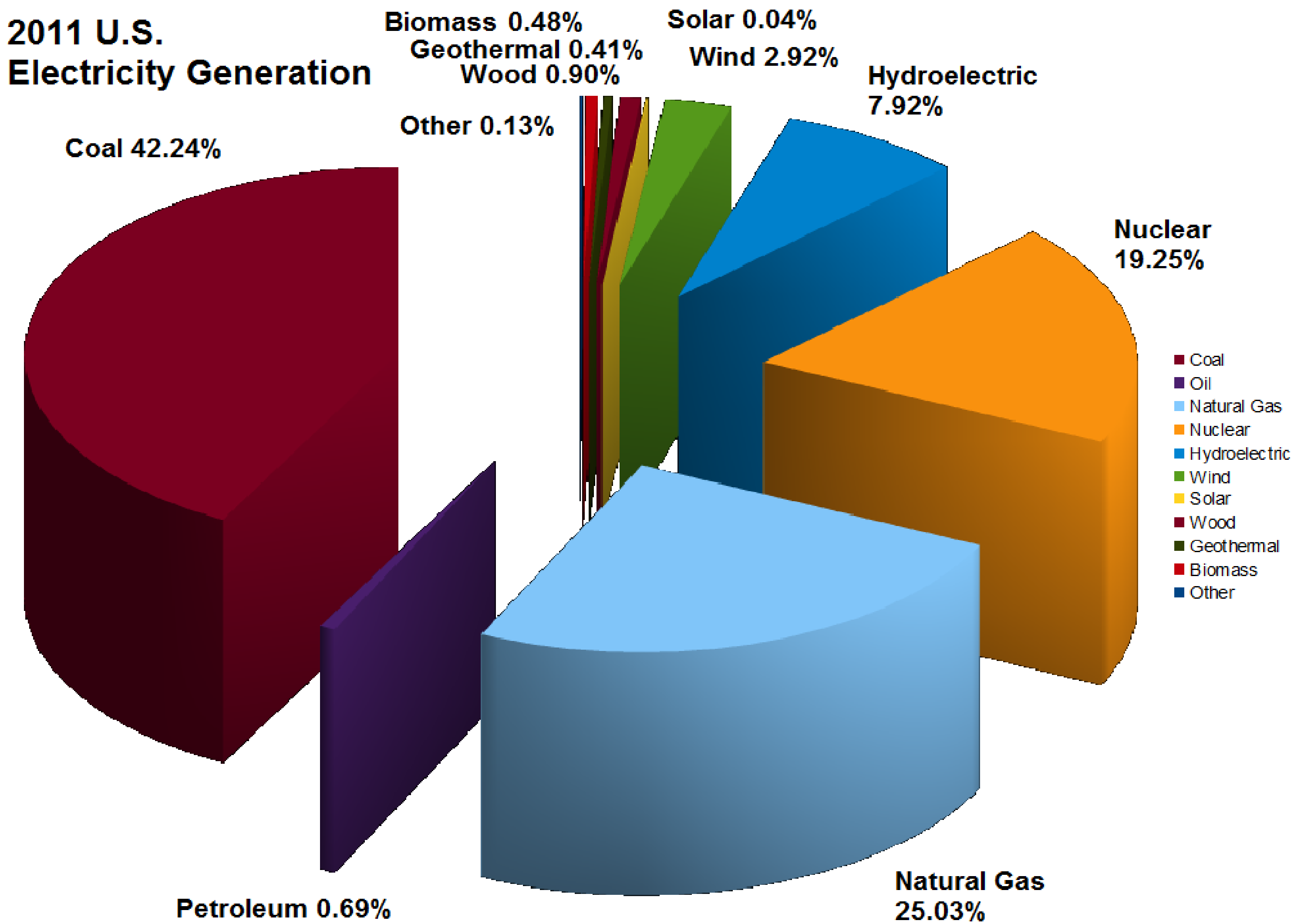
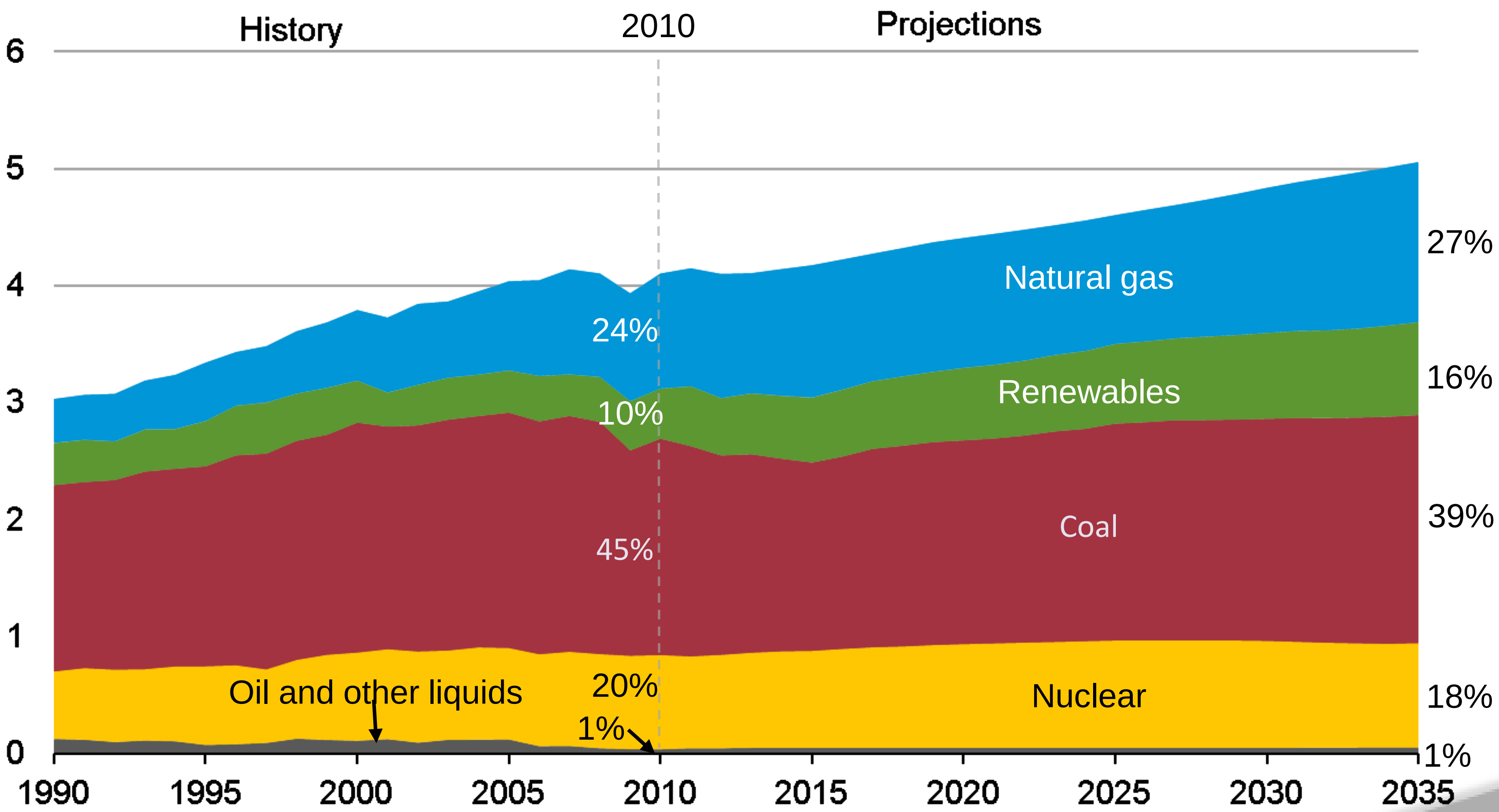


2011 U.S.
Electricity Generation
Biomass 0.48%
Geothermal 0.41%
Wood 0.90%
Solar 0.04%
Wind 2.92%
Hydroelectric 7.92%
Other 0.13%
Coal 42.24%
Nuclear 19.25%
Coal
Oil
Natural Gas
Nuclear
Hydroelectric
Wind
Solar
Wood
Geothermal
Biomass
Other
Petroleum 0.69%
Natural Gas 25.03%

Source: EIA, Annual Energy Outlook 2012 Early Release



MODULE-II
DESIGN AND OPERATION OF PV SYSTEM

MODULE II - SYLLABUS

Solar Photovoltaic Power System: The PV Cell, module and array, equivalent electrical circuit, open circuit voltage and short circuit current, I-V and P-V curves, array design, peak power point operation, PV system components; Solar Thermal System: Energy collection, synchronous generator, equivalent electrical circuit, excitation methods, electrical power output, transient stability limit, commercial power plants.

COURSE OUTCOMES MAPPED WITH MODULE II

CO	Course Outcomes	Blooms Taxonomy
CO 4	**Outline** the characteristics of solar PV modules for design of solar arrays.	Understand
CO 5	**Demonstrate** the functioning of various components involved in solar thermal systems for designing commercial solar power plants.	Understand
CO 6	**Develop** the suitable scheme for extracting maximum power from solar PV module using MPPT algorithms.	Apply

PROGRAM OUTCOMES MAPPED WITH MODULE II

PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
PO 3	**Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

MAPPING OF COs AND POS FOR MODULE II

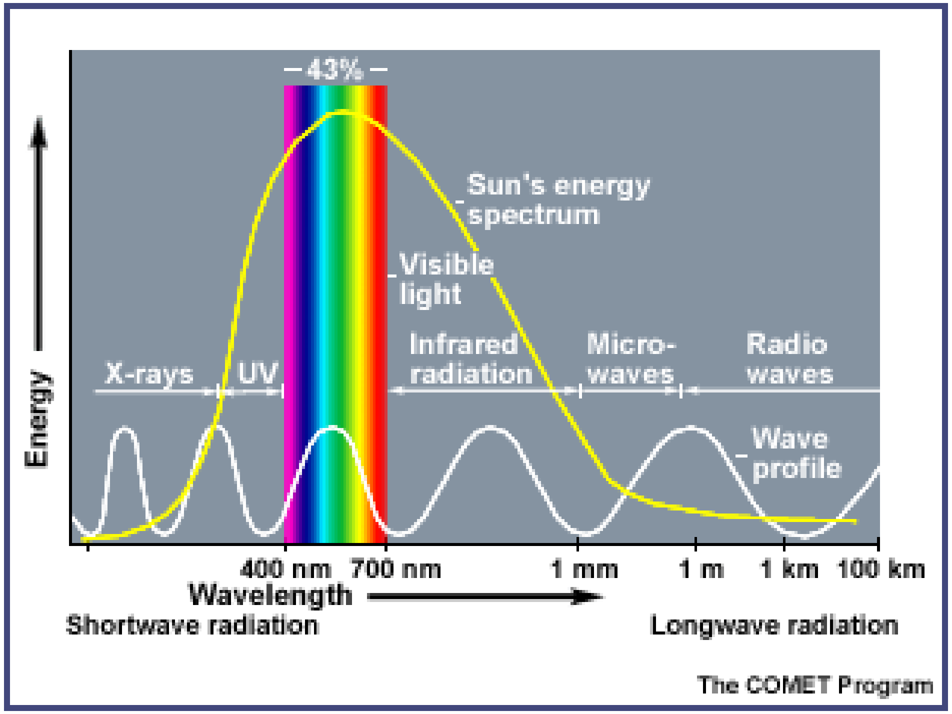
COs	PROGRAM OUTCOMES										
	1	2	3	4	5	6	7	8	9	10	11	12
CO4	√	√	√									
CO5	√	√										
CO6	√	√										

Introduction to solar energy

Solar energy received in the form of radiation can be converted directly or indirectly into other forms of energy such as heat and electricity. Since the sun is expected to radiate at an essentially constant rate for a few billion years, it may be recorded as inexhaustible source of useful energy

What is Solar Energy

- Originates with the thermonuclear fusion reactions occurring in the sun.
- Represents the entire electromagnetic radiation (visible light, infrared, ultraviolet, x-rays, and radio waves).

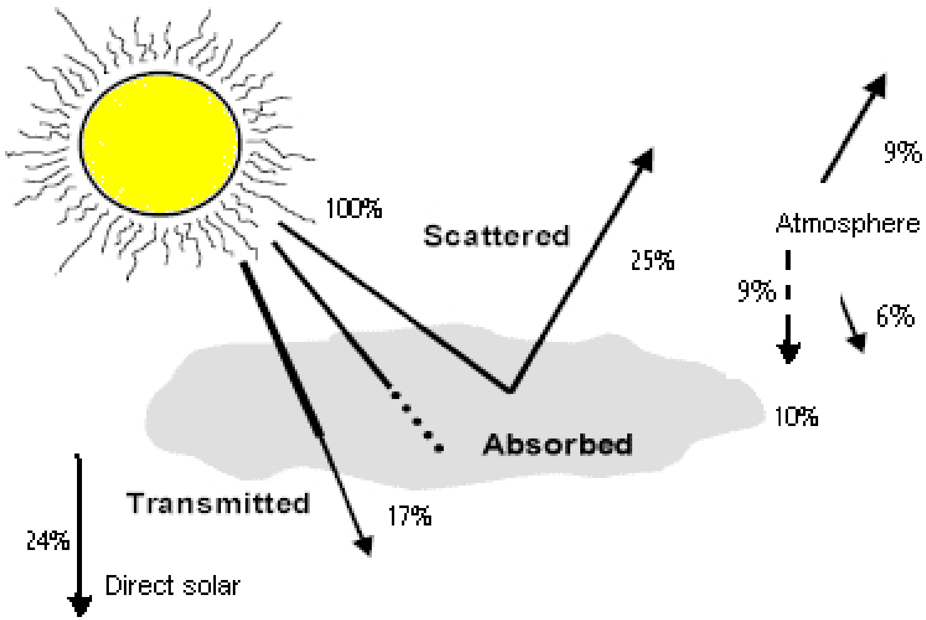


Advantages and Disadvantages

- Advantages
  - All chemical and radioactive polluting byproducts of the thermonuclear reactions remain behind on the sun, while only pure radiant energy reaches the Earth.
  - Energy reaching the earth is incredible. By one calculation, 30 days of sunshine striking the Earth have the energy equivalent of the total of all the planet's fossil fuels, both used and unused!
- Disadvantages
  - Sun does not shine consistently.
  - Solar energy is a diffuse source. To harness it, we must concentrate it into an amount and form that we can use, such as heat and electricity.
  - Addressed by approaching the problem through:

    1) collection, 2) conversion, 3) storage.

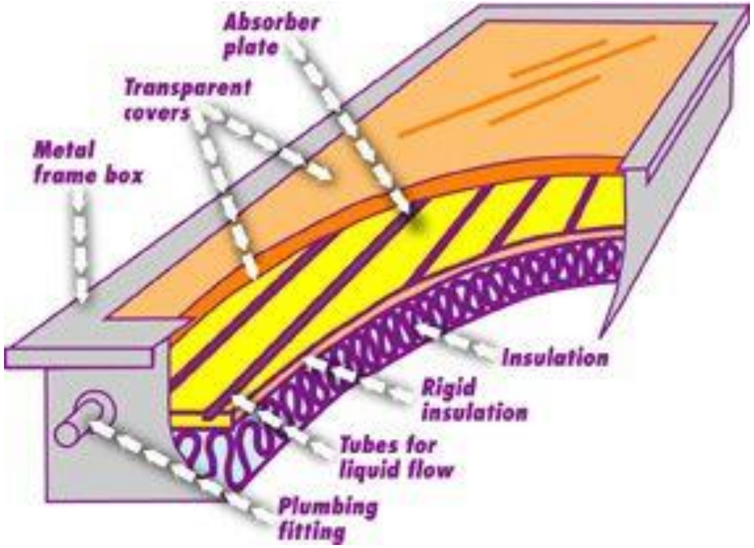
How much solar energy



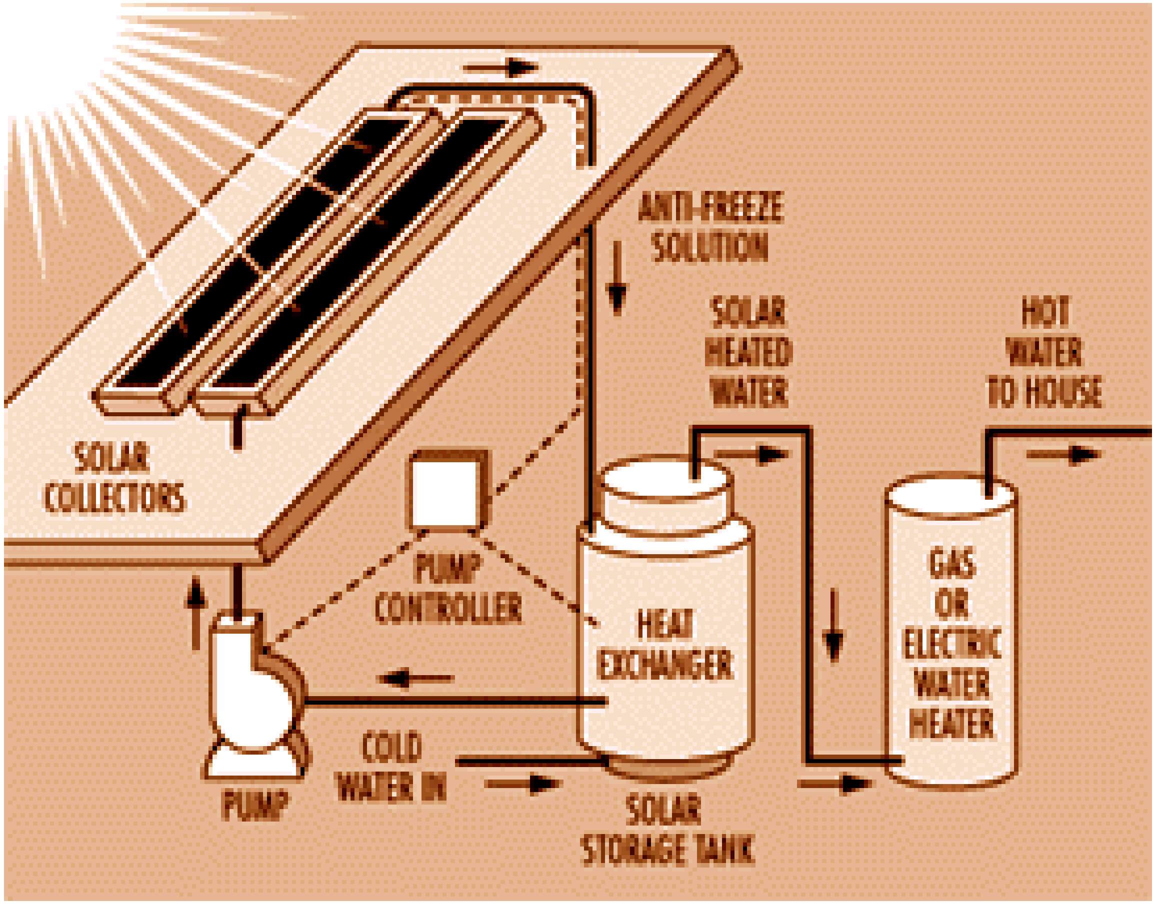
The surface receives about 47% of the total solar energy that reaches the Earth. Only this amount is usable.

Putting Solar Energy to Use: Heating Water

- Two methods of heating water: passive (no moving parts) and active (pumps).
- In both, a flat-plate collector is used to absorb the sun's energy to heat the water.
- The water circulates throughout the closed system due to convection currents.
- Tanks of hot water are used as storage.



Heating Water: Active System



Active System uses antifreeze so that the liquid does not freeze if outside temp. drops below freezing.

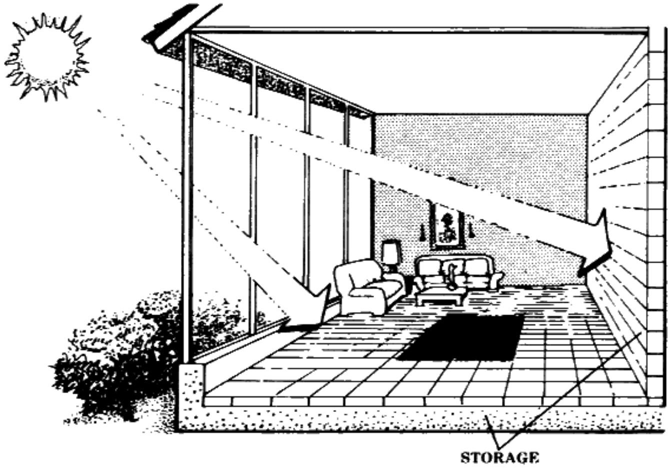
Heating Water

- Efficiency of solar heating system is always less than 100% because:
  - » % transmitted depends on angle of incidence,
  - » Number of glass sheets (single glass sheet transmits 90-95%), and
  - » Composition of the glass
- Solar water heating saves approx. 1000 megawatts of energy a yr, equivalent to eliminating the emissions from two medium sized coal burning power plants.
- By using solar water heating over gas water heater, a family will save 1200 pounds of pollution each year.
- Market for flat plate collectors grew in 1980s because of increasing fossil fuels prices and federal tax credits. But by 1985, when these credits were removed and fossil fuel prices were low, the demand for flat plate collectors shrunk quickly.
- While solar water heating is relatively low in the US, in other parts of the world such as Cyprus (90%) and Israel (65%), it proves to be the predominate form of water heating.

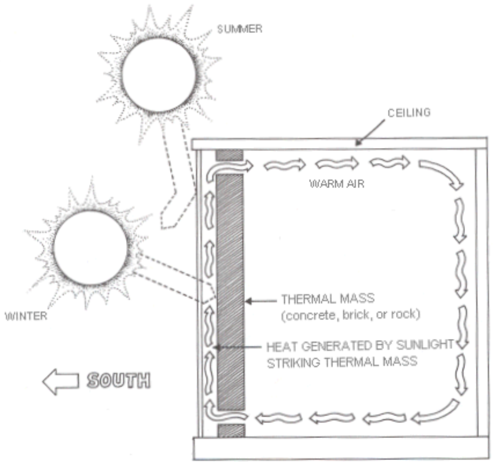
Heating Living Spaces

- Best design of a building is for it to act as a solar collector and storage unit. This is achieved through three elements: insulation, collection, and storage.
- Efficient heating starts with proper insulation on external walls, roof, and the floors. The doors, windows, and vents must be designed to minimize heat loss.
- Collection: south-facing windows and appropriate landscaping.
- Storage: Thermal mass—holds heat.
    - Water= 62 BTU per cubic foot per degree F.
    - Iron=54, Wood (oak) =29, Brick=25, concrete=22, and loose stone=20

Heating Living Spaces



Passive Solar



Trombe Wall

Passively heated home in Colorado

Heating Living Spaces

- A passively heated home uses about 60-75% of the solar energy that hits its walls and windows.
- The Center for Renewable Resources estimates that in almost any climate, a well-designed passive solar home can reduce energy bills by 75% with an added construction cost of only 5-10%.
- About 25% of energy is used for water and space heating.
- Major factor discouraging solar heating is low energy prices.

Solar-Thermal Electricity: Power Towers

- General idea is to collect the light from many reflectors spread over a large area at one central point to achieve high temperature.
- Example is the 10-MW solar power plant in Barstow, CA.
    - 1900 heliostats, each 20 ft by 20 ft
    - a central 295 ft tower
- An energy storage system allows it to generate 7 MW of electric power without sunlight.
- Capital cost is greater than coal fired power plant, despite the no cost for fuel, ash disposal, and stack emissions.
- Capital costs are expected to decline as more and more power towers are built with greater technological advances.
- One way to reduce cost is to use the waste steam from the turbine for space heating or other industrial processes.

Power Towers

Power tower

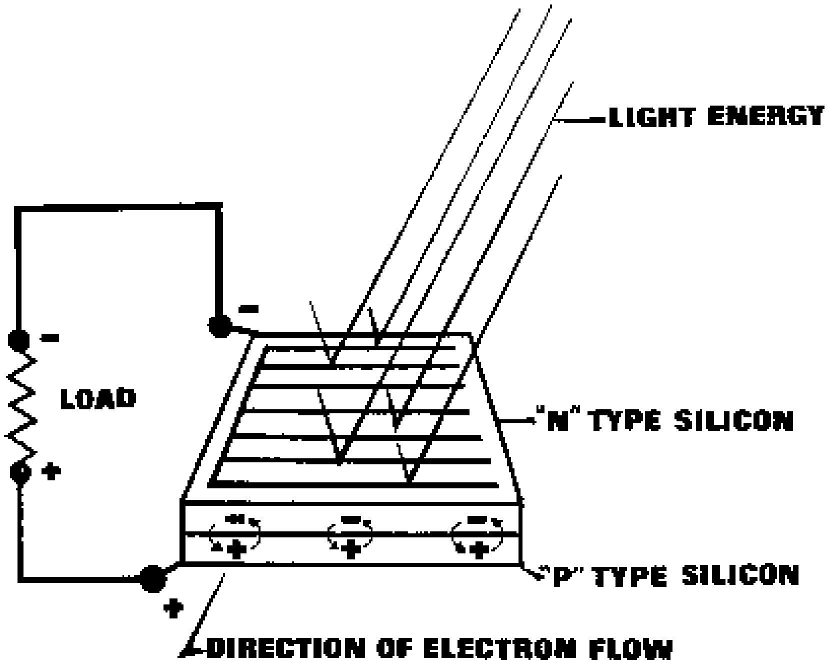
Solar-Thermal Electricity: Parabolic Dishes and Troughs

- Focus sunlight on a smaller receiver for each device; the heated liquid drives a steam engine to generate electricity.
- The first of these Solar Electric Generating Stations (SEGS) was installed in CA by an Israeli company, Luz International.
- Output was 13.8 MW; cost was $6,000/peak kW and overall efficiency was 25%.
- Through federal and state tax credits, Luz was able to build more SEGS, and improved reduced costs to $3,000/peak kW and the cost of electricity from 25 cents to 8 cents per kWh, barely more than the cost of nuclear or coal-fired facilities.
- The more recent facilities converted a remarkable 22% of sunlight into electricity.

Parabolic Dishes and Troughs

Because they work best under direct sunlight, parabolic dishes and troughs must be steered throughout the day in the direction of the sun.

Direct Conversion into Electricity



- Photovoltaic cells are capable of directly converting sunlight into electricity.
- A simple wafer of silicon with wires attached to the layers. Current is produced based on types of silicon (n- and p-types) used for the layers. Each cell=0.5 volts.
- Battery needed as storage
- No moving parts→do no wear out, but because they are exposed to the weather, their lifespan is about 20 years.

Solar Panels in Use

- Because of their current costs, only rural and other customers far away from power lines use solar panels because it is more cost effective than extending power lines.
- Note that utility companies are already purchasing, installing, and maintaining PV-home systems (Idaho Power Co.).
- Largest solar plant in US, sponsored by the DOE, served the Sacramento area, producing 2195 MWh of electric energy, making it cost competitive with fossil fuel plants.

Efficiency and Disadvantages

- Efficiency is far lass than the 77% of solar spectrum with usable wavelengths.
- 43% of photon energy is used to warm the crystal.
- Efficiency drops as temperature increases (from 24% at 0°C to 14% at 100°C.)
- Light is reflected off the front face and internal electrical resistance are other factors.
- Overall, the efficiency is about 10-14%.
- Cost of electricity from coal-burning plants is anywhere b/w 8-20 cents/kWh, while photovoltaic power generation is anywhere b/w $0.50-1/kWh.
- Does not reflect the true costs of burning coal and its emissions to the nonpolluting method of the latter.
- Underlying problem is weighing efficiency against cost.
  - Crystalline silicon-more efficient, more expensive to manufacture
  - Amorphous silicon-half as efficient, less expensive to produce.

Solar energy variation

- Argument that sun provides power only during the day is countered by the fact that 70% of energy demand is during daytime hours. At night, traditional methods can be used to generate the electricity.
- Goal is to decrease our dependence on fossil fuels.
- Currently, 75% of our electrical power is generated by coal-burning and nuclear power plants.
- Mitigates the effects of acid rain, carbon dioxide, and other impacts of burning coal and counters risks associated with nuclear energy.
- pollution free, indefinitely sustainable.

Solar Energy

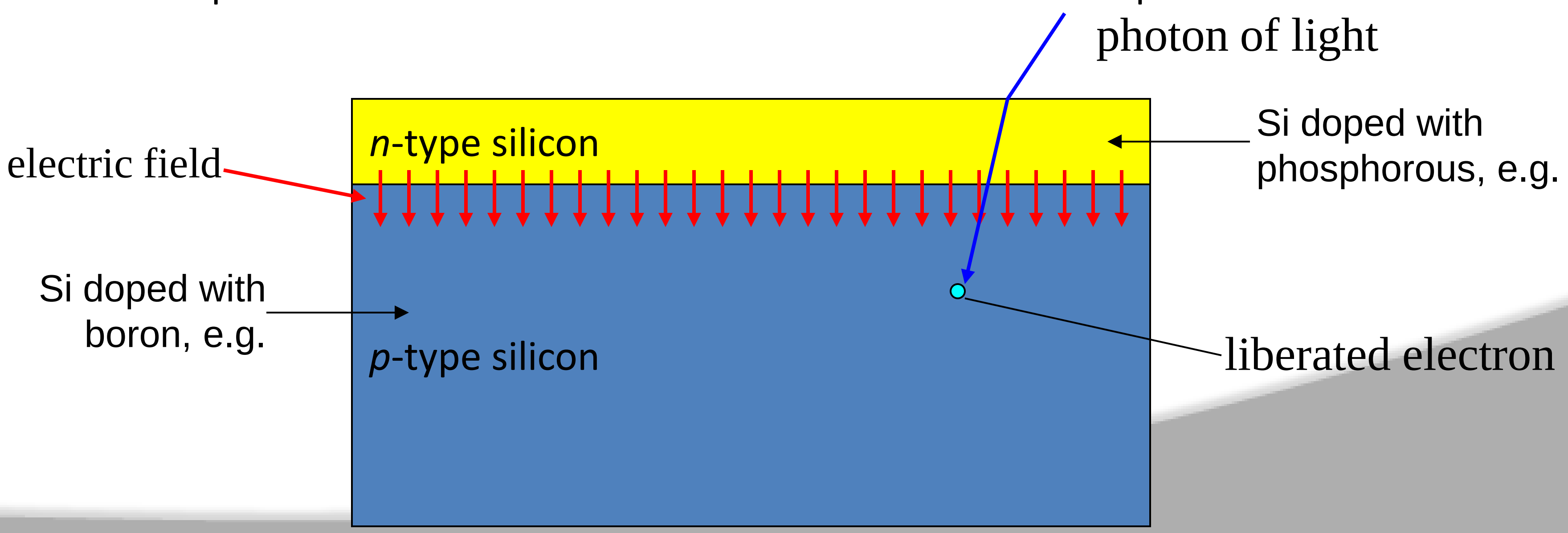
- Solar energy is an important, clean, cheap and abundantly available renewable energy.
- It is received on Earth in cyclic, intermittent and dilute form with very low power density 0 to 1 kW/m2. Solar energy received on the ground level is affected by atmospheric clarity, degree of latitude, etc.
- For design purpose, the variation of available solar power, the optimum tilt angle of solar flat plate collectors, the location and orientation of the
- heliostats should be calculated.

Units of solar power and solar energy:

- In SI units, energy is expressed in Joule. Other units are angley and Calorie where
- 1 angley = 1 Cal/cm2.day
- 1 Cal = 4.186 J
- For solar energy calculations, the energy is measured as an hourly or monthly or yearly average and is expressed in terms of kJ/m2/day or kJ/m2/hour. Solar power is expressed in terms of W/m2 or kW/m2.

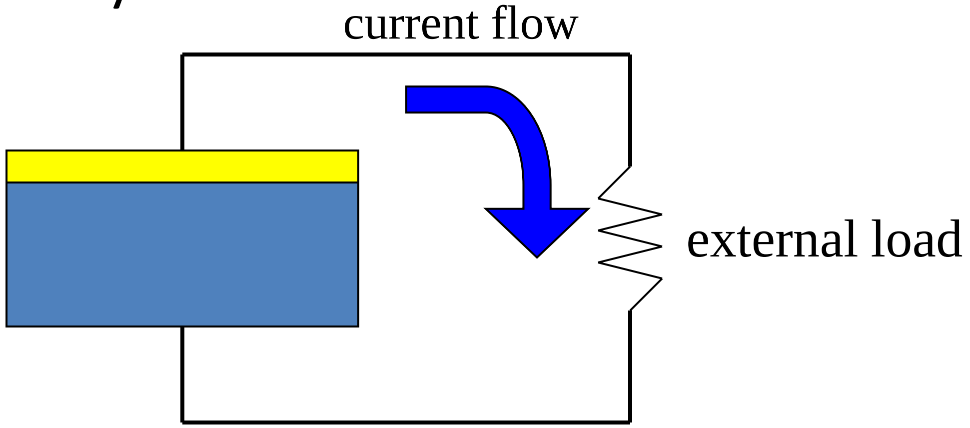
Photovoltaic (PV) Scheme

- Highly purified silicon (Si) from sand, quartz, etc. is “doped” with intentional impurities at controlled concentrations to produce a p-n junction
  – p-n junctions are common and useful: diodes, CCDs, photodiodes, transistors
- A photon incident on the p-n junction liberates an electron
  – photon disappears, any excess energy goes into kinetic energy of electron (heat)
  – electron wanders around drunkenly, and might stumble into “depletion region” where electric field exists (electrons, being negative, move *against* field arrows)
  – electric field sweeps electron across the junction, constituting a current
  – more photons → more electrons → more current → more power

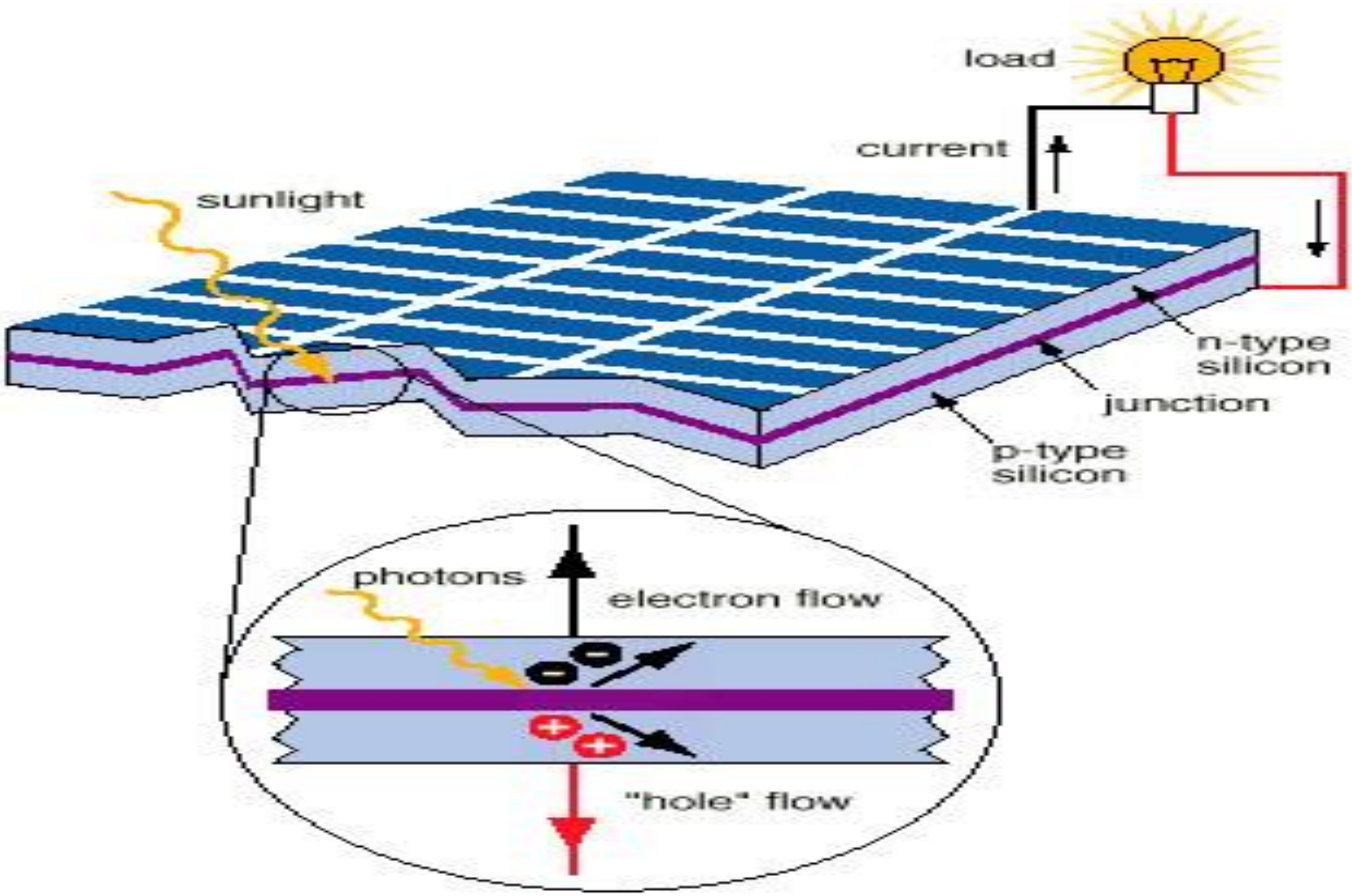


Provide a circuit for the electron flow

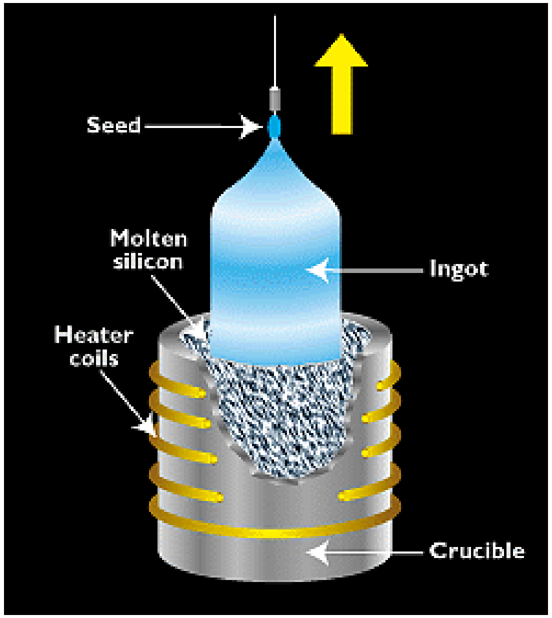
- Without a path for the electrons to flow out, charge would build up and end up canceling electric field
  - must provide a way out
  - direct through external load
  - PV cell acts like a battery

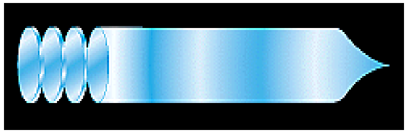


How PV cell works



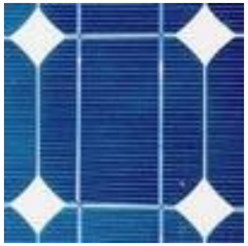
How silicon cells are made

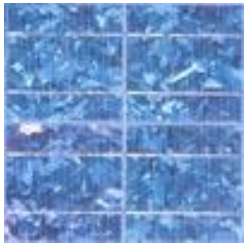


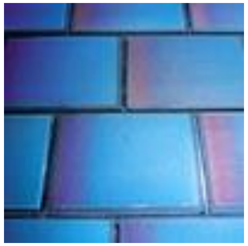


PV types

- Single-crystal silicon
  - 15–18% efficient, typically
  - expensive to make (grown as big crystal)
- Poly-crystalline silicon
  - 12–16% efficient, slowly improving
  - cheaper to make (cast in ingots)
- Amorphous silicon (non-crystalline)
  - 4–8% efficient
  - cheapest per Watt
  - called "thin film", easily deposited on a wide range of surface types

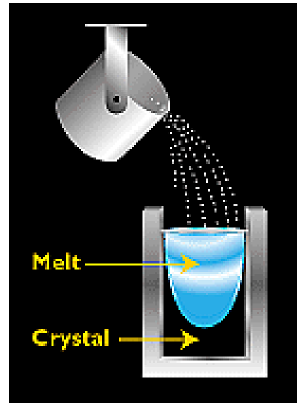




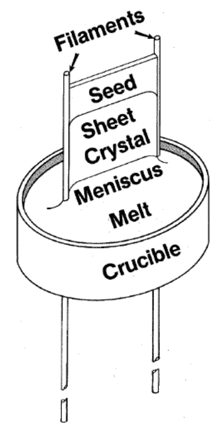


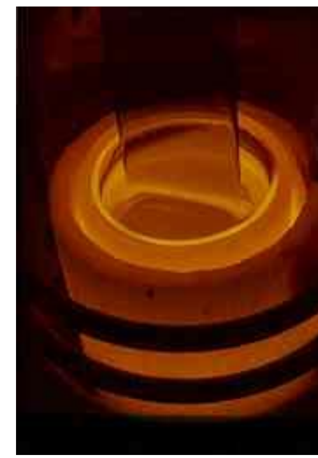
Other Types of Solar Cells

- Poly-crystal



- Ribbon type ------------>



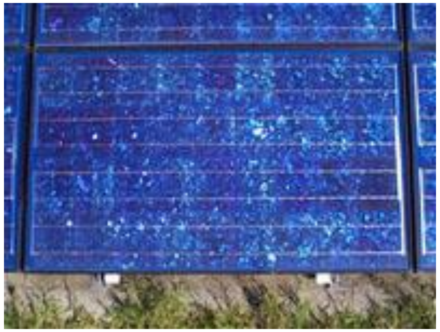


- Thin Film

Commercial Solar Cells

- Single crystal silicon

- Poly-Crystal Silicon

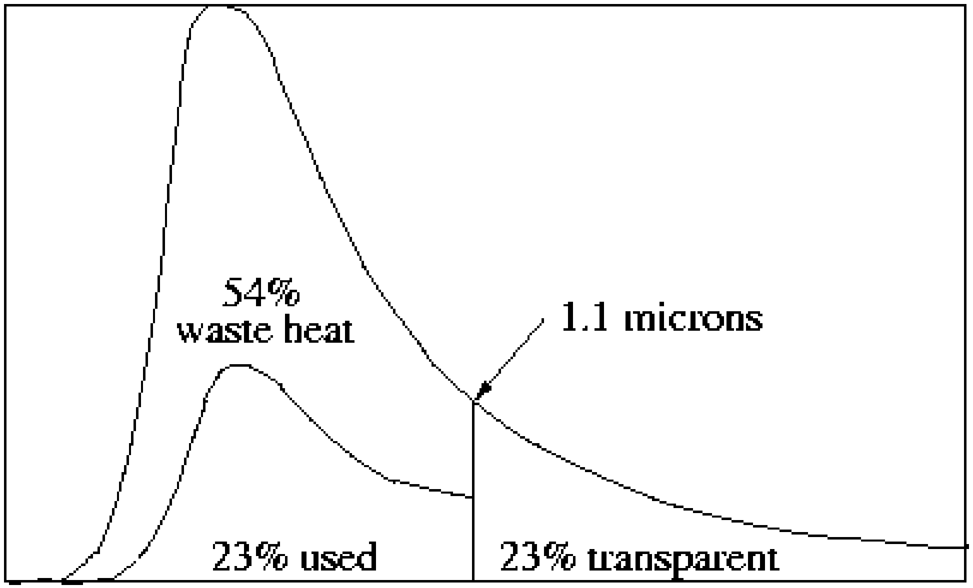


- Thin Films

How good can it get

- Silicon is transparent at wavelengths longer than 1.1 microns (1100 nm)
  - 23% of sunlight passes right through with no effect
- Excess photon energy is wasted as heat
  - near-infrared light (1100 nm) typically delivers only 51% of its photon energy into electrical current energy
    - roughly half the electrons stumble off in the wrong direction
  - red light (700 nm) only delivers 33%
  - blue light (400 nm) only delivers 19%
- All together, the maximum efficiency for a silicon PV in sunlight is about 23%
  - defeating “recombination loss” puts the limit in the low 30’s %

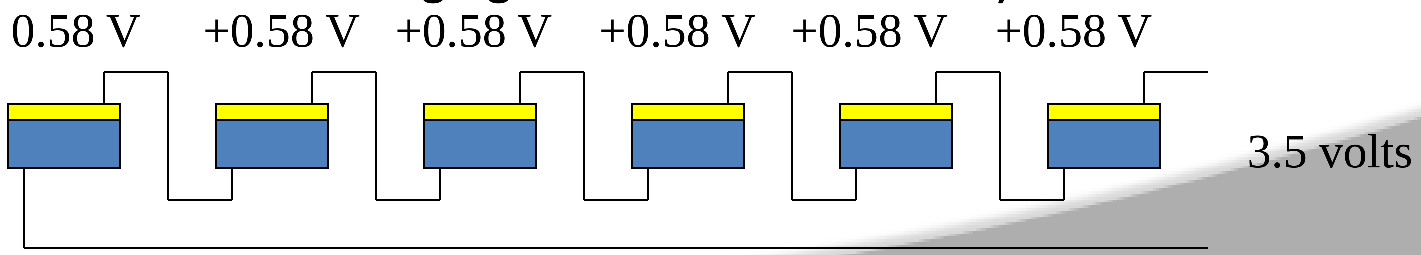
Silicon Photovoltaic Budget



- Only 77% of solar spectrum is absorbed by silicon
- Of this, ~30% is used as electrical energy
- Net effect is 23% maximum efficiency

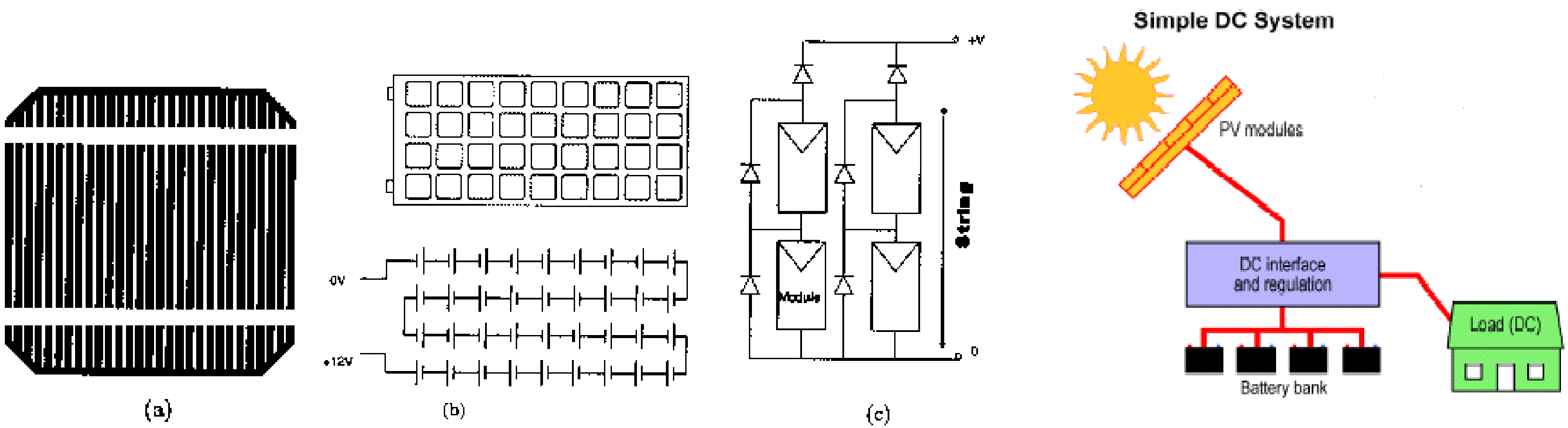
PV Cells as “Batteries”

- A single PV cell (junction) in the sun acts like a battery
  - characteristic voltage is 0.58 V
  - power delivered is current times voltage
  - current is determined by the rate of incoming solar photons
- Stack cells in series to get usefully high voltages
  - voltage ≠ power, but higher voltage means you can deliver power with less current, meaning smaller wiring, greater transmission efficiency
- A typical panel has 36 cells for about 21 V open-circuit (no current delivered)
  - but actually drops to ~16 V at max power
  - well suited to charging a nominal 12 V battery



Photovoltaic Cells, Modules and Systems

- Solar cell is the basic building blocks of solar PV
- Cells are connected together in series and encapsulated into models
- Modules can be used singly, or connected in parallel and series into an array with a larger current & voltage output
- PV arrays integrated in systems with components for charge regulation and storage



Cell module array system

Thin Film Solar Cells

"thin film" refers more to solar cell technologies with mass-production possibilities Rather than the film thickness.

- ✓ requirement for suitable materials: low cost, high absorption, doping, transport, robust and stable
  leading materials for TFSC: CdTe, $CuInSe_2$, (CIS) ,a-SI…

- ✓ advantages:
  -- low material requirement
  -- variety of processing methods
  -- light weight modules

- ✓ disadvantages:

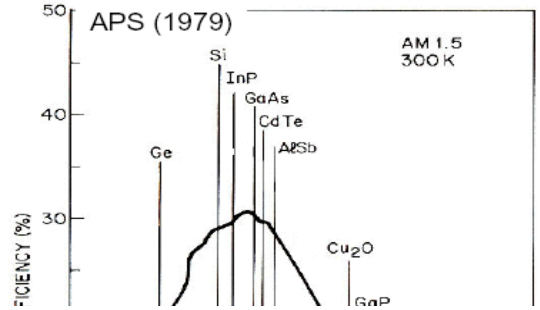
  -- low achieved efficiency

Solar Cell Efficiency

- Ideal cell efficiency

$$\eta = \frac{E_g \int_{E_g}^{\infty} b_s(E)dE}{\int_0^{\infty} Eb_s(E)dE}$$

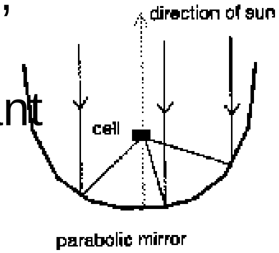
- Effect of bandgap on efficiency



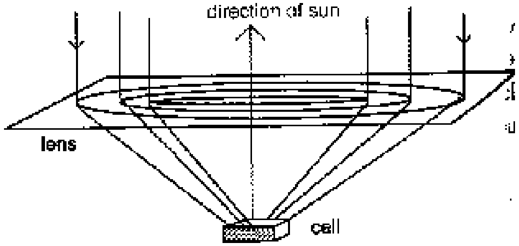
- ▪ GaAs, InP have E_g close to the optimum, favored for high η cells
- ▪ Si less favorable E_g but cheap & abundant

- Effect of spectrum on efficiency

- ▪ improving η by concentrating light 100 suns or more illumination



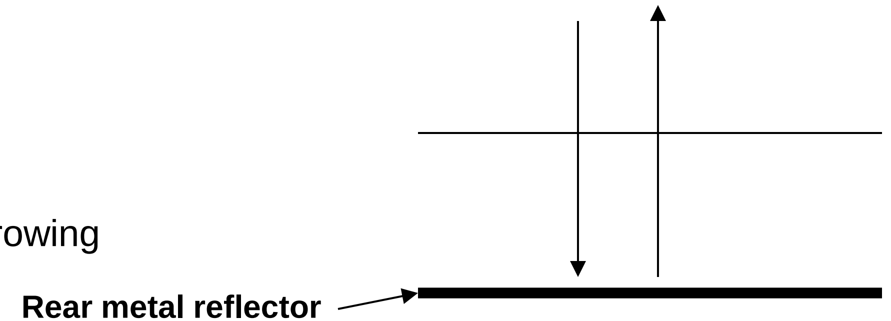
Parabolic reflector



Fresnel lens

Minimize Losses in Real SC

- Optical loss
  - Concentration of light
  - Trapping of light:
    - ✓ AR coatings
    - ✓ Mirrors (metallization rear surface or growing active layers on top of a Bragg stack)
    - ✓ textured surface



Double path length in metallized cell

  - Photon recycling

    reabsorption of photons emitted by radiative recombination inside the cell

- Electrical loss
  - Surface passivation
  - Resistive loss

  ……

Thermo photovoltaic (TPV)

- TPV solar energy conversion

Photovoltaic conversion with the addition of an intermediate thermal absorber/emitter is known as thermophotovoltaic (TPV) energy conversion.

Solar radiation is used to heat absorber/emitter to temperature of 1200-2500 K → emitter radiates photons → PV cell converts the energy of radiation into electrical power.

- Advantage

By matching the spectrum of the emitter to the PV cells, efficiency improved.

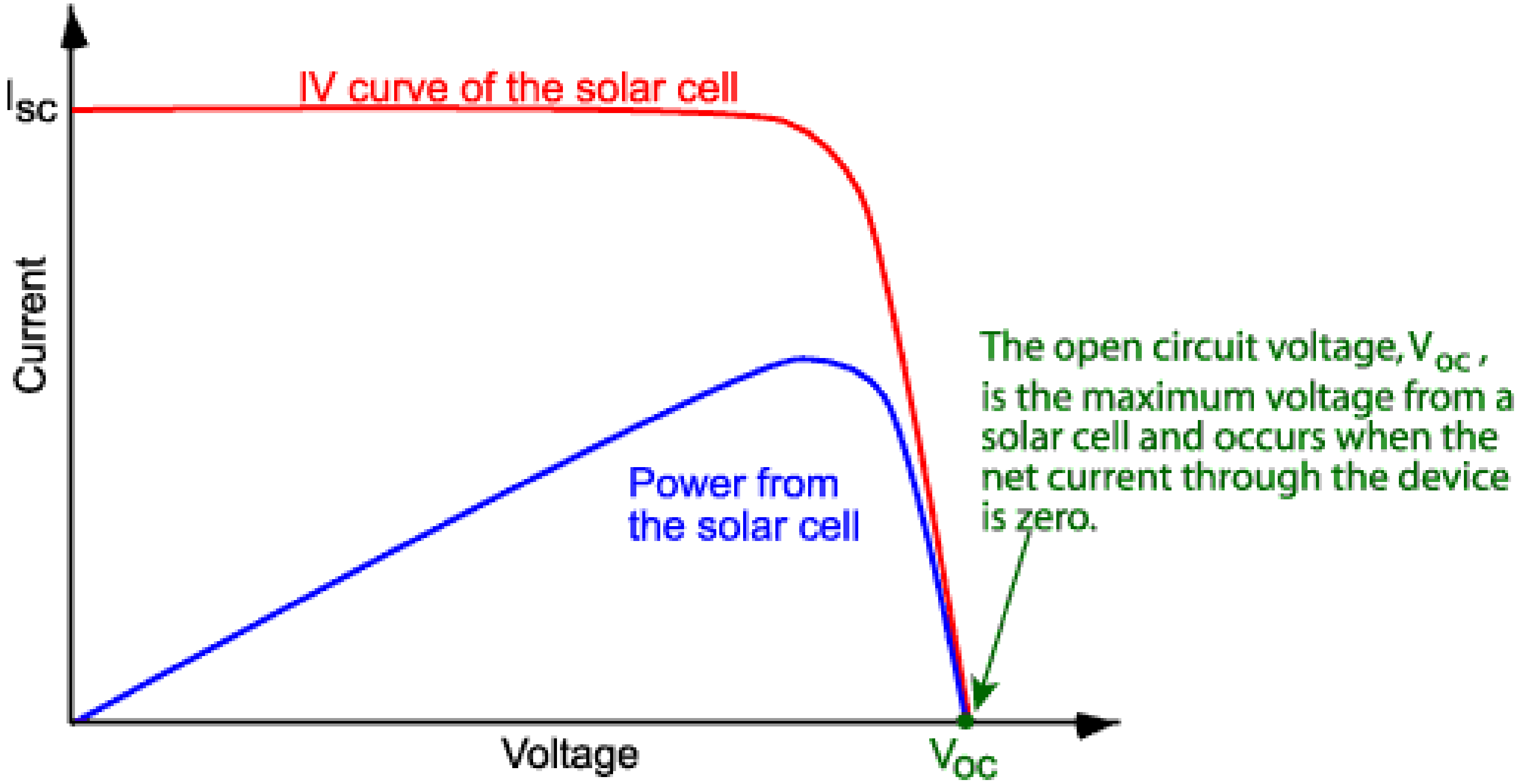
Open-Circuit Voltage

- The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current.

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

- Dark Saturation Current, I_0
- A Light Generated Current, I_L
- A Ideality Factor, n
- Temperature, T
- Open Circuit Voltage, V_{OC}

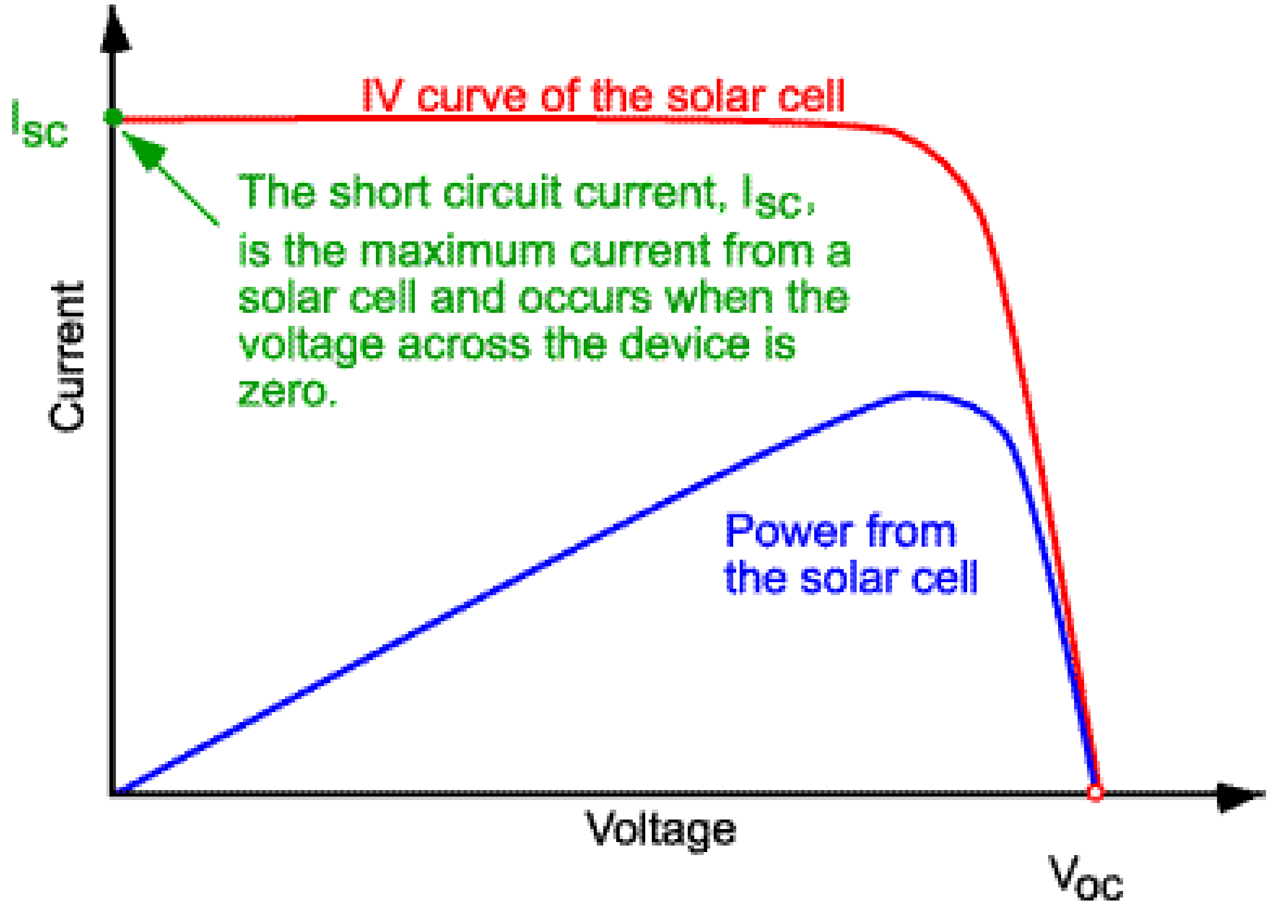
IV curve of a solar cell showing the open-circuit voltage.



Shot circuit current

- The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited).
- The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

IV curve of a solar cell showing the short-circuit current.



The short-circuit current depends on a number of factors which are described below:

- **the area of the solar cell.** To remove the dependence of the solar cell area, it is more common to list the short-circuit current **density** (J_{sc} in mA/cm^2) rather than the short-circuit current;
- **the number of photons** (i.e., the power of the incident light source). Isc from a solar cell is directly dependent on the light intensity as discussed in Effect of Light Intensity;
- **the spectrum of the incident light.** For most solar cell measurement, the spectrum is standardized to the AM1.5 spectrum;
- **the optical properties** (absorption and reflection) of the solar cell (discussed in Optical Losses); and
- **the collection probability** of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base.

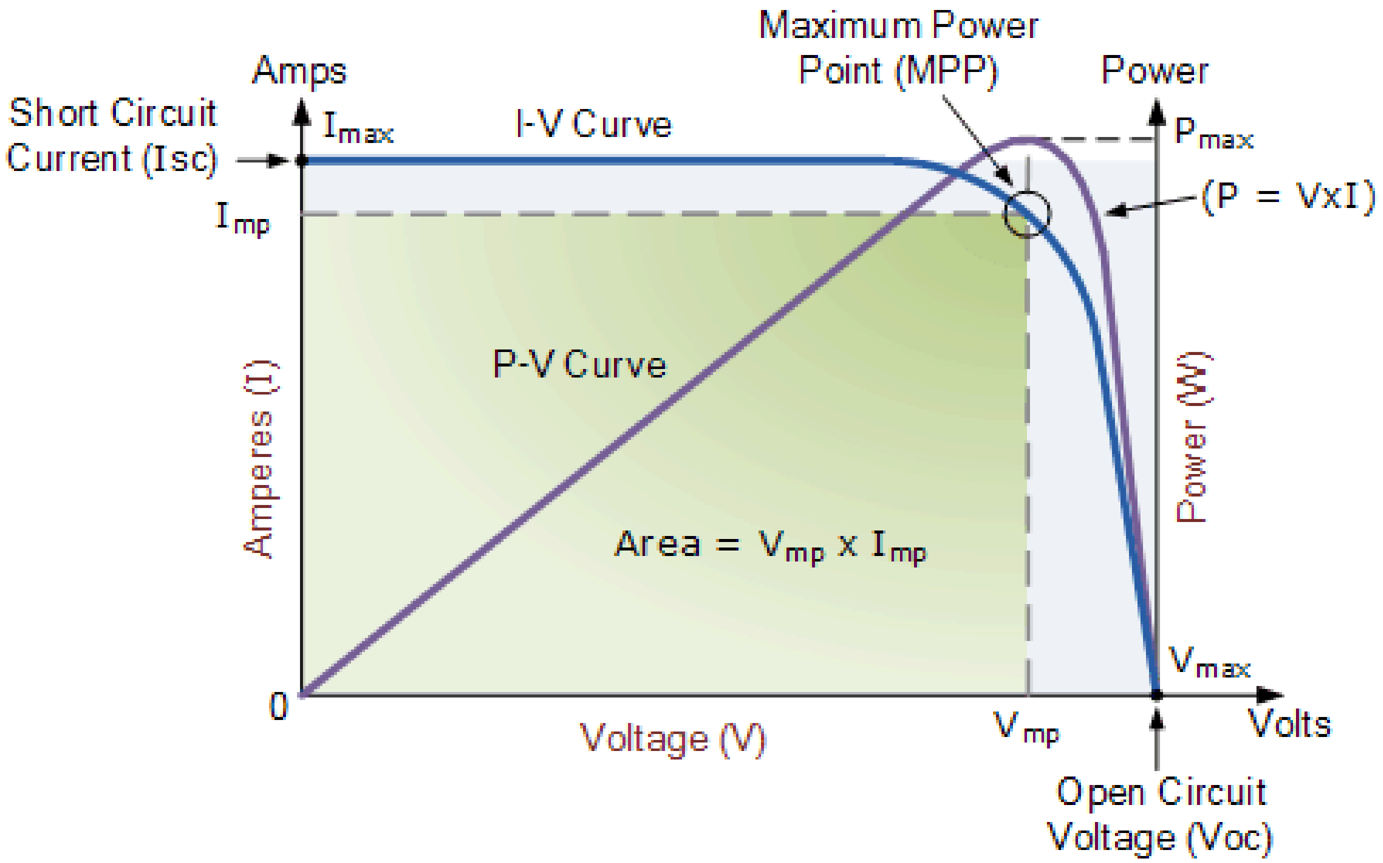
$$J_{SC} = qG\left(L_n + L_p\right)$$

where G is the generation rate, and L_n and L_p are the electron and hole diffusion lengths respectively. Although this equation makes several assumptions which are not true for the conditions encountered in most solar cells, the above equation nevertheless indicates that the short-circuit current depends strongly on the generation rate and the diffusion length.

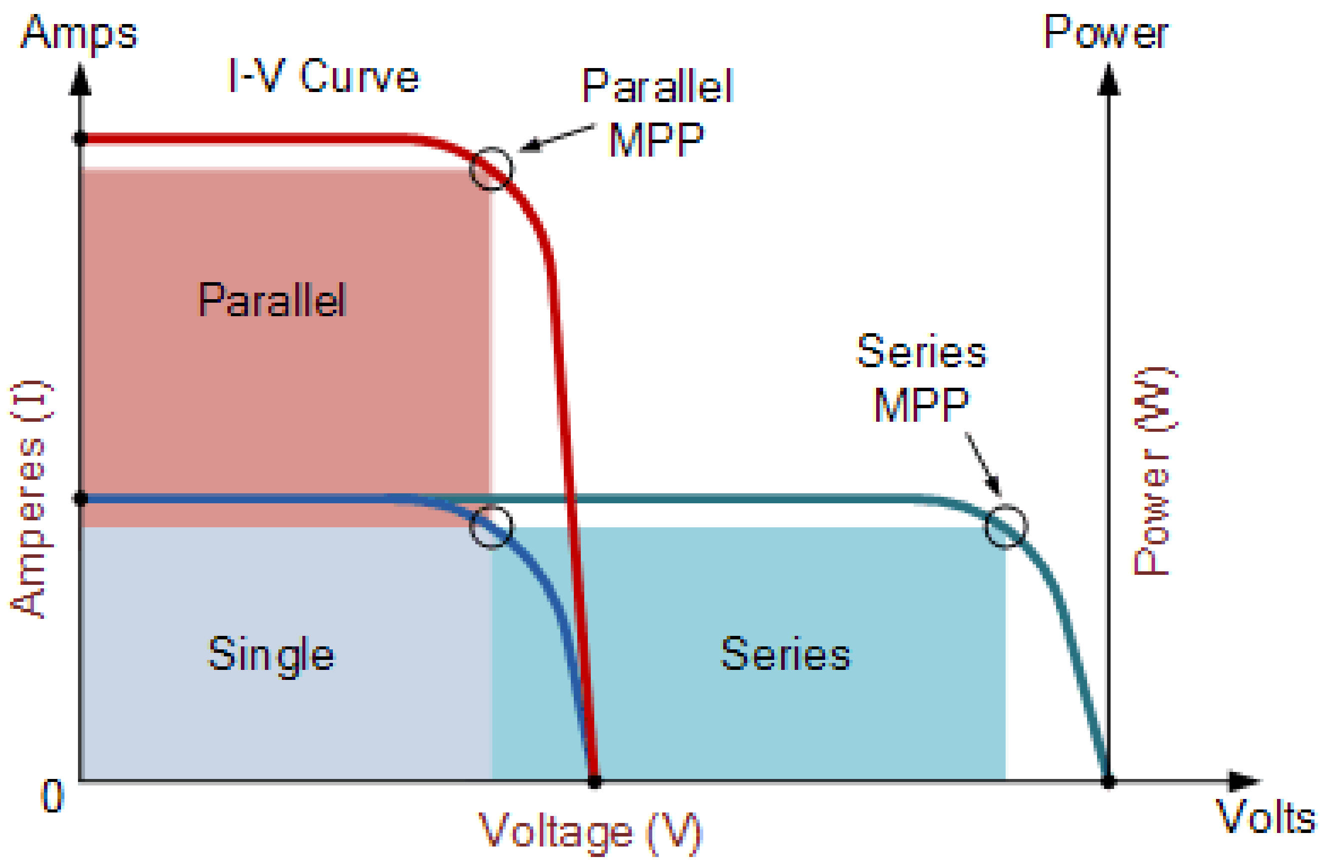
Current-Voltage characteristics of PV cell

Solar Cell I-V Characteristics Curves are basically a graphical representation of the operation of a solar cell or module summarizing the relationship between the current and voltage at the existing conditions of irradiance and temperature. I-V curves provide the information required to configure a solar system so that it can operate as close to its optimal peak power point (MPP) as possible

Current-Voltage characteristics of PV cell



Solar panel Current-Voltage characteristics



- **MPP** = maximum power point – This relates to the point where the power supplied by the array that is connected to the load (batteries, inverters) is at its maximum value, where MPP = Imp x Vmp. The maximum power point of a photovoltaic array is measured in Watts (W) or peak Watts (Wp).
- **FF** = fill factor – The fill factor is the relationship between the maximum power that the array can actually provide under normal operating conditions and the product of the open-circuit voltage multiplied by the short-circuit current, (V_{OC} x I_{SC}) This fill factor value gives an idea of the quality of the array and the closer the fill factor is to 1 (unity), the more power the array can provide. Typical values are between 0.7 and 0.8.

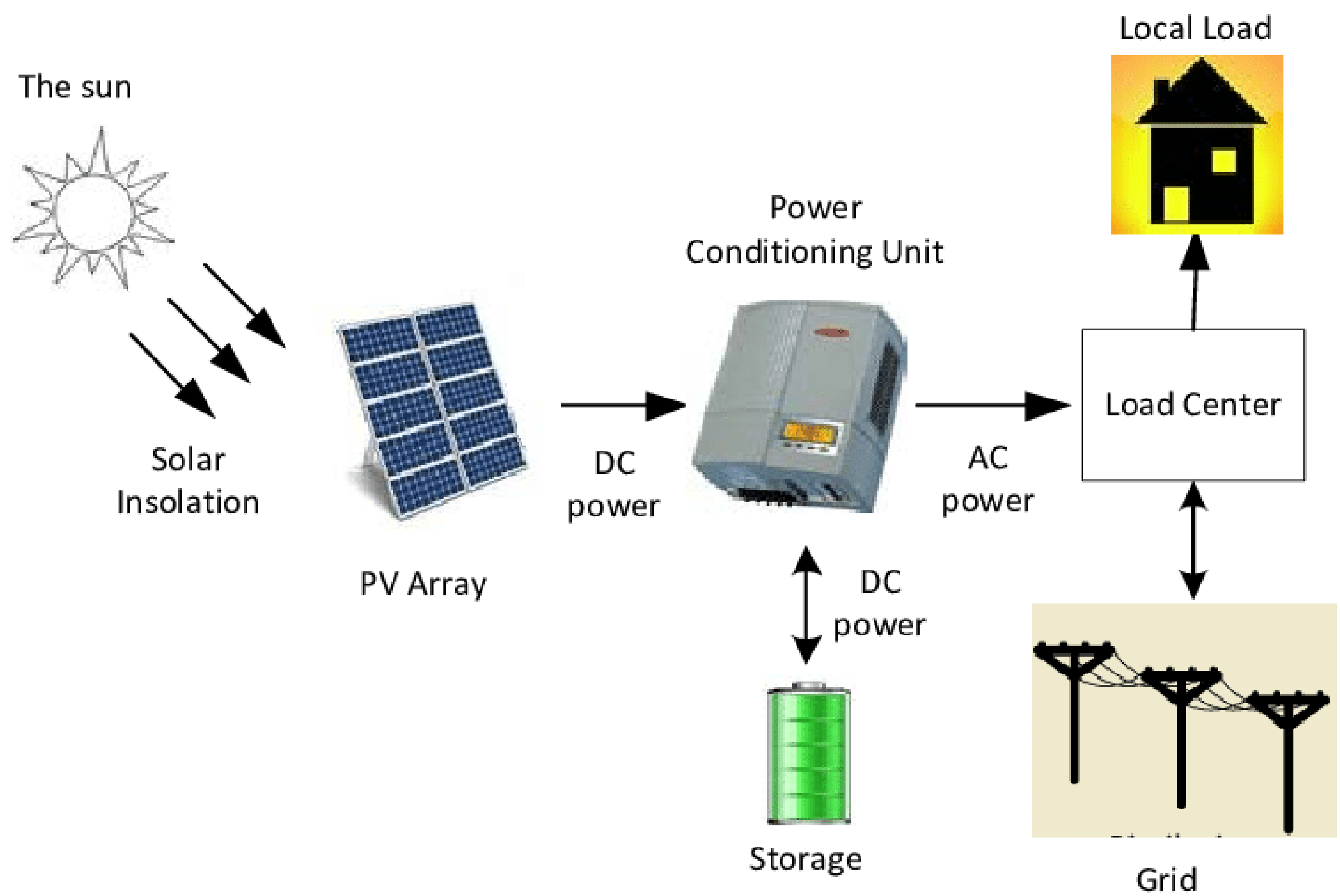
- **%eff** = percent efficiency – The efficiency of a photovoltaic array is the ratio between the maximum electrical power that the array can produce compared to the amount of solar irradiance hitting the array. The efficiency of a typical solar array is normally low at around 10-12%, depending on the type of cells (mono crystalline, polycrystalline, amorphous or thin film) being used.

PV system components

Photovoltaic systems generally consist of six individual components:

- the solar PV array
- a charge controller
- a battery bank
- an inverter
- a utility meter
- an electric grid.

PV system components



Solar Photovoltaic Array

- A solar photovoltaic array consists of a number of solar PV panels that are electrically connected. The solar PV array generates DC electricity from sunlight.
- Thanks to the flexibility of modular photovoltaic arrays, PV systems offer many different designs and a wide variety of electrical needs, regardless of how large or small the installation surface is.
- It is important to keep in mind that photovoltaic systems must be installed on stable mounting structures that can support the array and withstand weather conditions like wind, rain, and corrosion for the next few decades.

Charge Controller

- Charge controllers regulate the DC from the solar panels to make sure that the batteries don’t overcharge. A charge controller can measure whether the batteries are fully charged, and can stop the current from flowing in order to prevent the batteries from permanent damage.
- Charge controllers can be divided into two types: Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT). The PWM is a standard type and is suitable for smaller photovoltaic systems and battery banks, as they vary between 4 and 60 amperes.
- On the other hand, the MPPT charge controllers are more suitable for photovoltaic systems with a high voltage of — in most cases — up to 160 volts DC.

Battery Bank

- A battery bank makes sure that none of your unused energy goes to waste, as it stores the energy that is being produced by the PV array and is not consumed immediately. It can then, for example, supply your home with electricity during the night or during very cloudy weather when there is insufficient sunlight.
- Including a battery bank in your photovoltaic systems is optional, but it can double the amount of solar energy you can use. With a battery system, your home will be able to use 80% of its generated energy, whereas without a battery system, this would only be 40%.

Inverter

- A solar power inverter is a key part of any solar photovoltaic system, as it converts electricity from DC to AC. This is necessary, since you need AC power for the energy supply of your home appliances.

Utility Meter

- Regardless of your solar PV system, your household has a power meter that measures the electricity consumption per house or apartment.
- The utility meter is connected to the PV system and measures how much electricity you are using in your home. The electricity that you have generated from the photovoltaic panels that and is not stored or used will be fed back into the electric grid.

Electric Grid

- If your home is connected to an electric grid, the extra power that is generated once your battery bank is full, will be sent to the grid. This also means that during periods when the PV system doesn’t cover your energy needs, you will be able to supply your home with power from the electric grid, if necessary.

How much does it cost?

- Solar PV is usually priced in dollars per peak Watt
  - or full-sun max capacity: how *fast* can it produce energy
  - panels cost $2.50 per Watt (and falling), installed cost $5/W
  - so a 3kW residential system is $15,000 to install
  - State rebates and federal tax incentives can reduce cost substantially
    - so 3kW system can be < $10,000 to install
- To get price per kWh, need to figure in exposure
  - rule of thumb: 4–6 hours per day full sun equiv: 3kW system produces ~15 kWh per day
- Mythbusting: the energy it takes to manufacture a PV panel is recouped in 3–4 years of sunlight
  - contrary to myth that…
  - they *never* achieve energy payback

Solar constant and solar radiation on tilted surface

Solar constant:

- The total radiation energy received from the Sun per unit of time per unit of area on a theoretical surface perpendicular to the Sun’s rays and at Earth’s mean distance from the Sun.
- It is most accurately measured from satellites where atmospheric effects are absent.
- The value of the constant is approximately 1.366 kilowatts per square meter.
- The “constant” is fairly constant, increasing by only 0.2 percent at the peak of each 11-year solar cycle .

solar radiation on tilted surface:

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

Essential subsystems in a solar energy plant:

1. **Solar collector or concentrator:** It receives solar rays and collects the energy. It may be of following types:

a) Flat plate type without focusing

b) Parabolic trough type with line focusing

c) Parabolic dish with central focusing

d) Fresnel lens with centre focusing

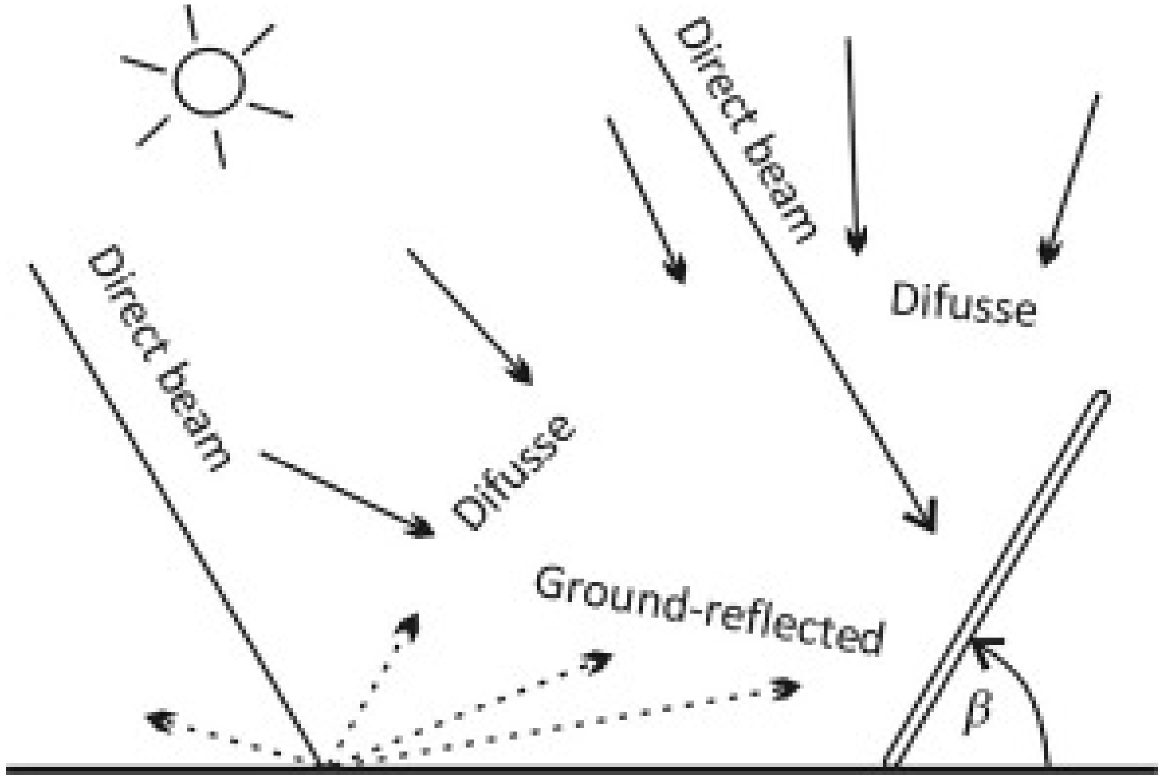
e) Heliostats with centre receiver focusing

SOLAR RADIATION

The solar radiation that fills our sky can be direct, diffuse or reflected radiation.

- "Direct radiation" is also sometimes called "beam radiation" or "direct beam radiation". It is used to describe solar radiation traveling on a straight line from the sun down to the surface of the earth.
- "Diffuse radiation", on the other hand, describes the sunlight that has been scattered by molecules and particles in the atmosphere but that has still made it down to the surface of the earth.
- Direct radiation has a definite direction but diffuse radiation is just going any which way. Because when the radiation is direct, the rays are all travelling in the same direction, an object can block them all at once. This is why shadows are only produced when direct radiation is blocked.

SOLAR RADIATION



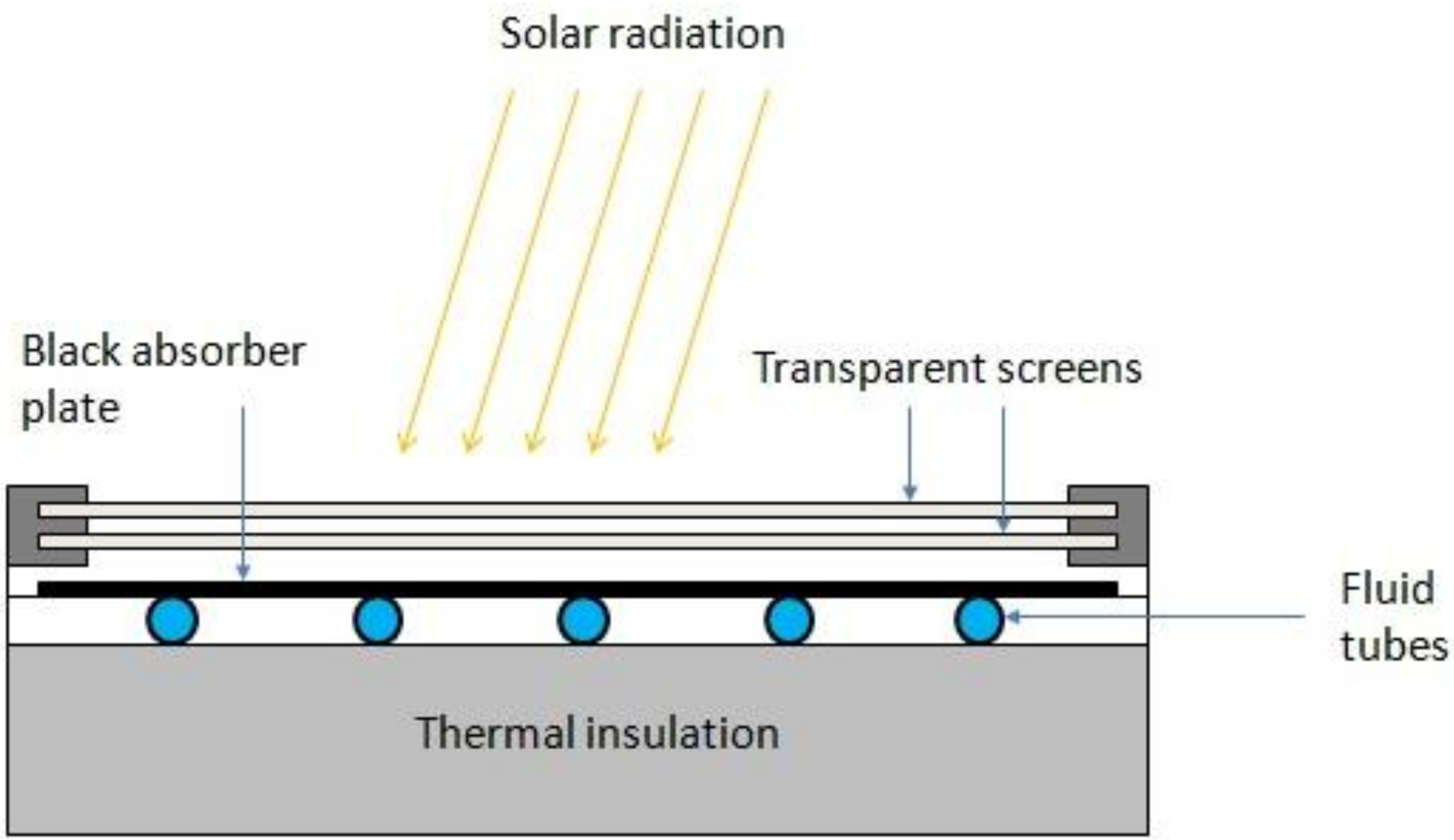
Flat plate collectors

The flat-plate solar collectors are probably the most fundamental and most studied technology for solar-powered domestic hot water systems.

These are the main components of a typical flat-plate solar collector:

- Black surface - absorbent of the incident solar energy
- Glazing cover - a transparent layer that transmits radiation to the absorber, but prevents radiative and convective heat loss from the surface
- Tubes containing heating fluid to transfer the heat from the collector
- Support structure to protect the components and hold them in place
- Insulation covering sides and bottom of the collector to reduce heat losses

Flat plate collectors



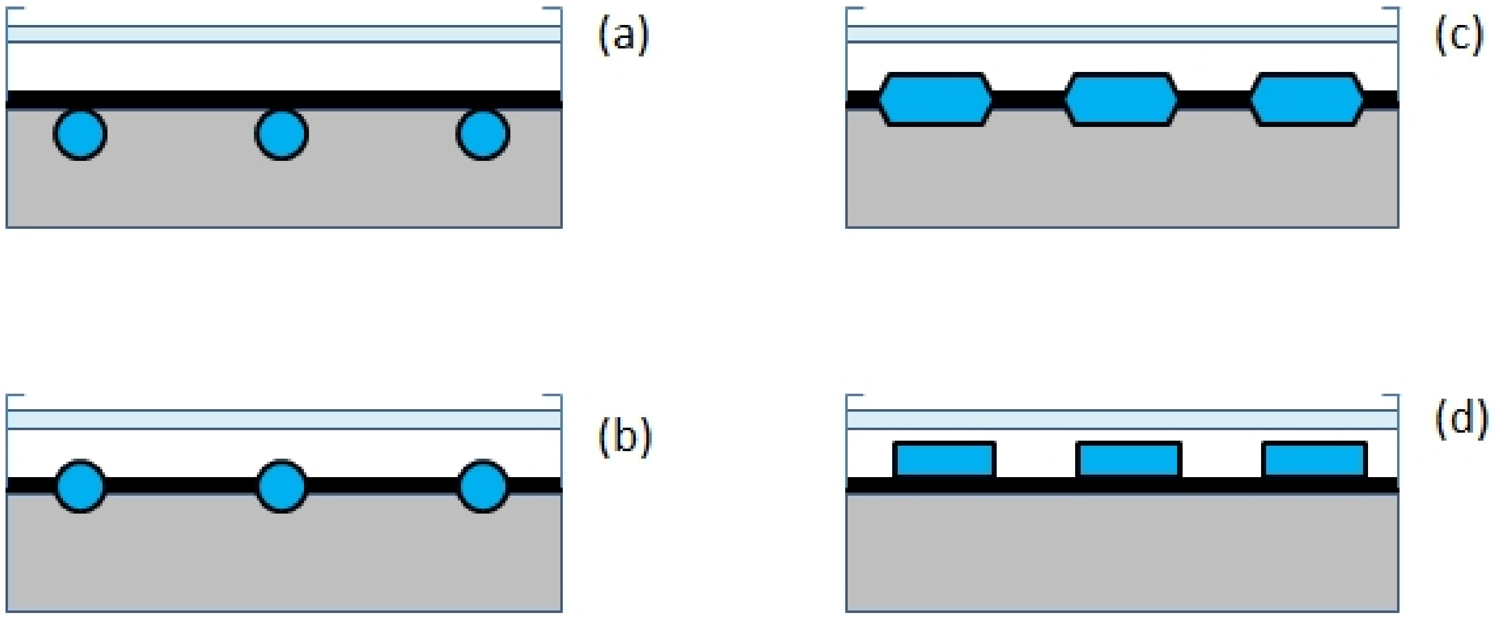
Flat plate collectors

Some advantages of the flat-plate collectors are that they are:

- Easy to manufacture
- Low cost
- Collect both beam and diffuse radiation
- Permanently fixed (no sophisticated positioning or tracking equipment is required)
- Little maintenance

Flat plate collectors

- The key considerations in flat plate collector design are maximizing absorption, minimizing reflection and radiation losses, and effective heat transfer from the collector plate to the fluids.
- One of the important issues is obtaining a good thermal bond between the absorber plate and changes



Various designs of flat-plate collector assembly. Color codes: light blue - glass cover, dark blue - fluid channels, black - absorber material, gray - insulation. Some constructions (b, c) include fluid channels in the absorber plate structure to maximize thermal conductance between the components. Other modifications (a, d) include tubes and channels soldered or cemented to the plate.

Applications of flat plate collector:

1. Solar water heating systems for residence, hotels, industry.
2. Desalination plant for obtaining drinking water from sea water.
3. Solar cookers for domestic cooking.
4. Drying applications.
5. Residence heating

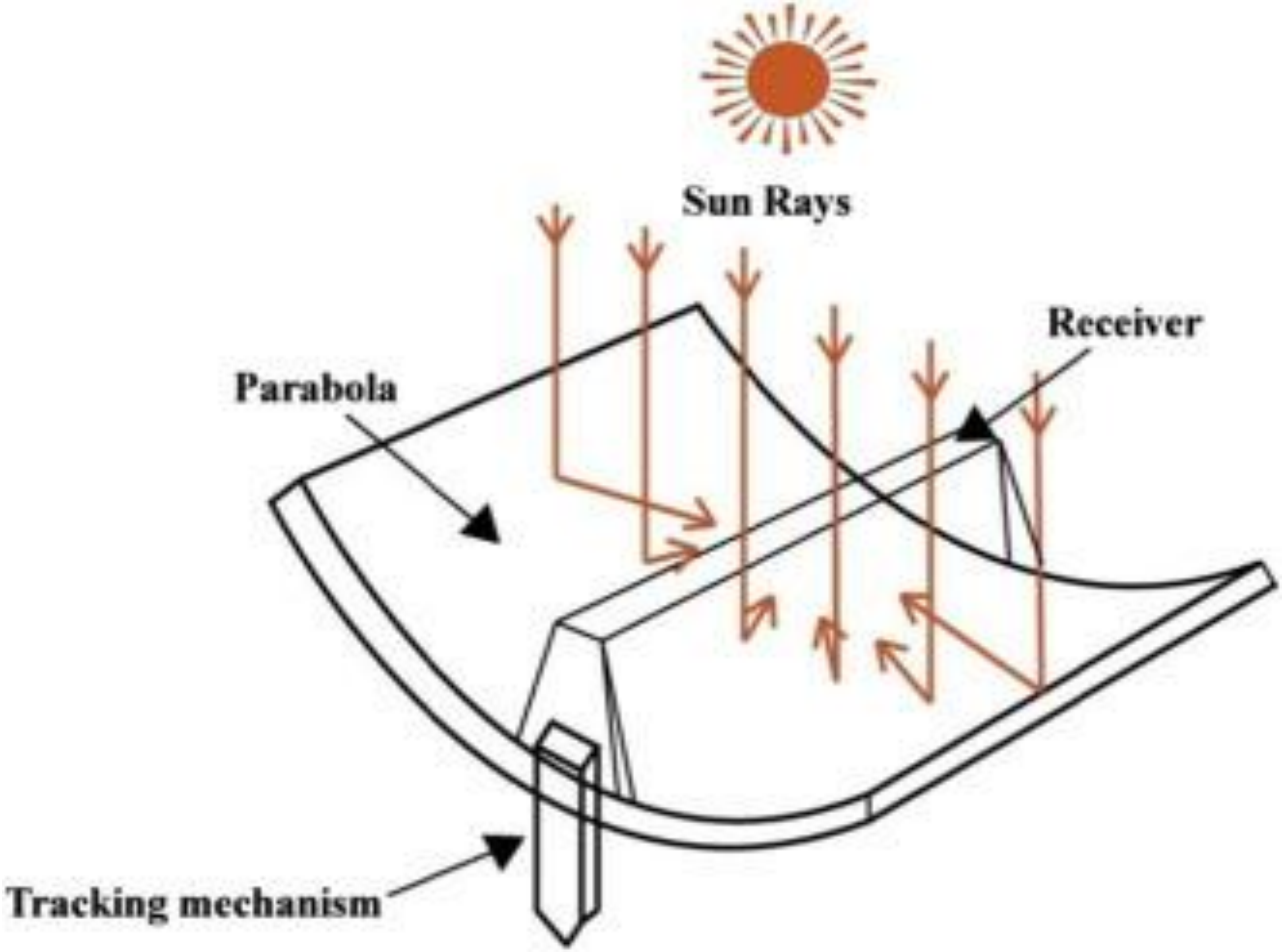
Maintenance of flat plate collector:

1. Daily cleaning
2. Seasonal maintenance (cleaning, touch-up paint)
3. Yearly overhaul (change of seals, cleaning after dismantling

Parabolic trough type with line focusing

Parabolic-trough solar concentrating systems are parabolic-shaped collectors made of reflecting materials. The collectors reflect the incident solar radiation onto its focal line toward a receiver that absorbs the concentrated solar energy to raise the temperature of the fluid inside

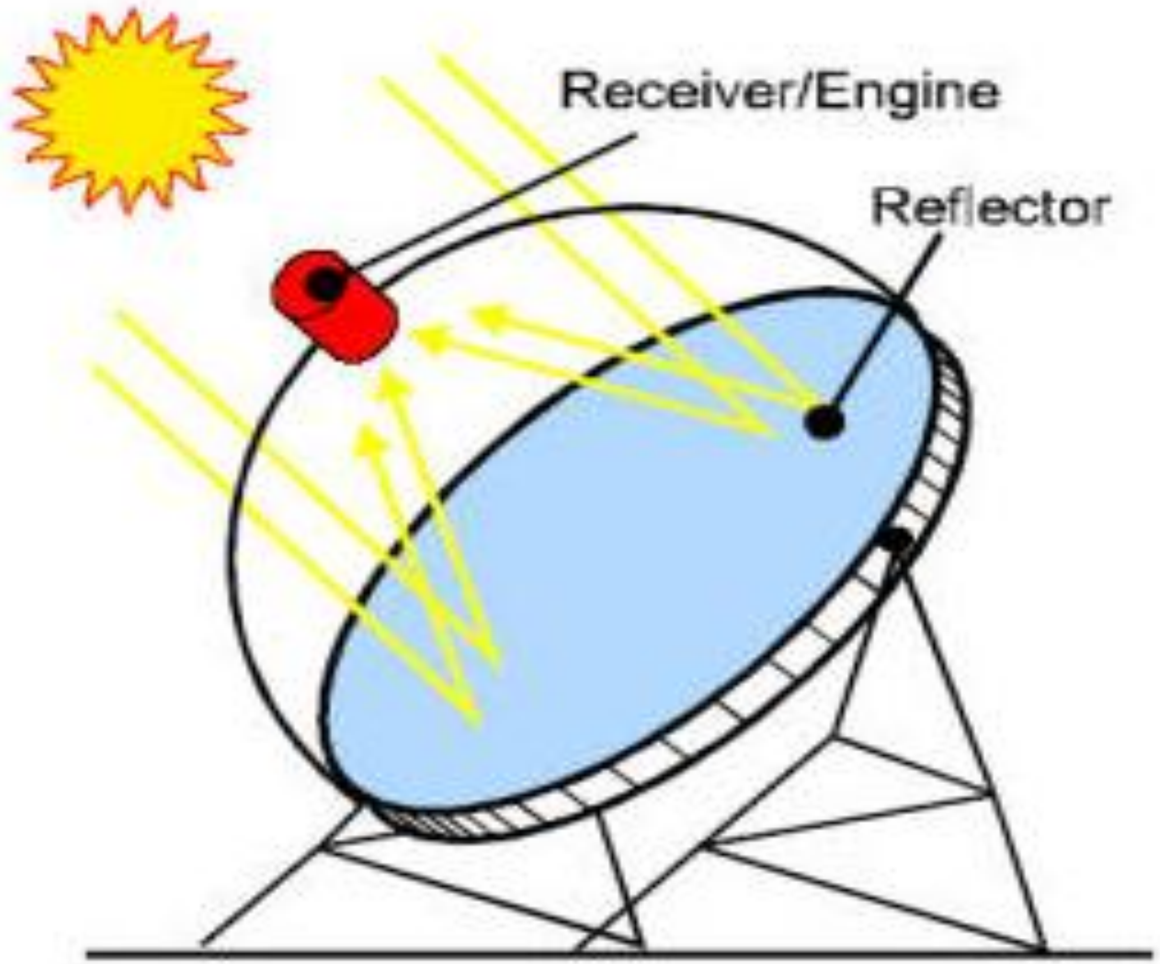
Parabolic trough type with line focusing



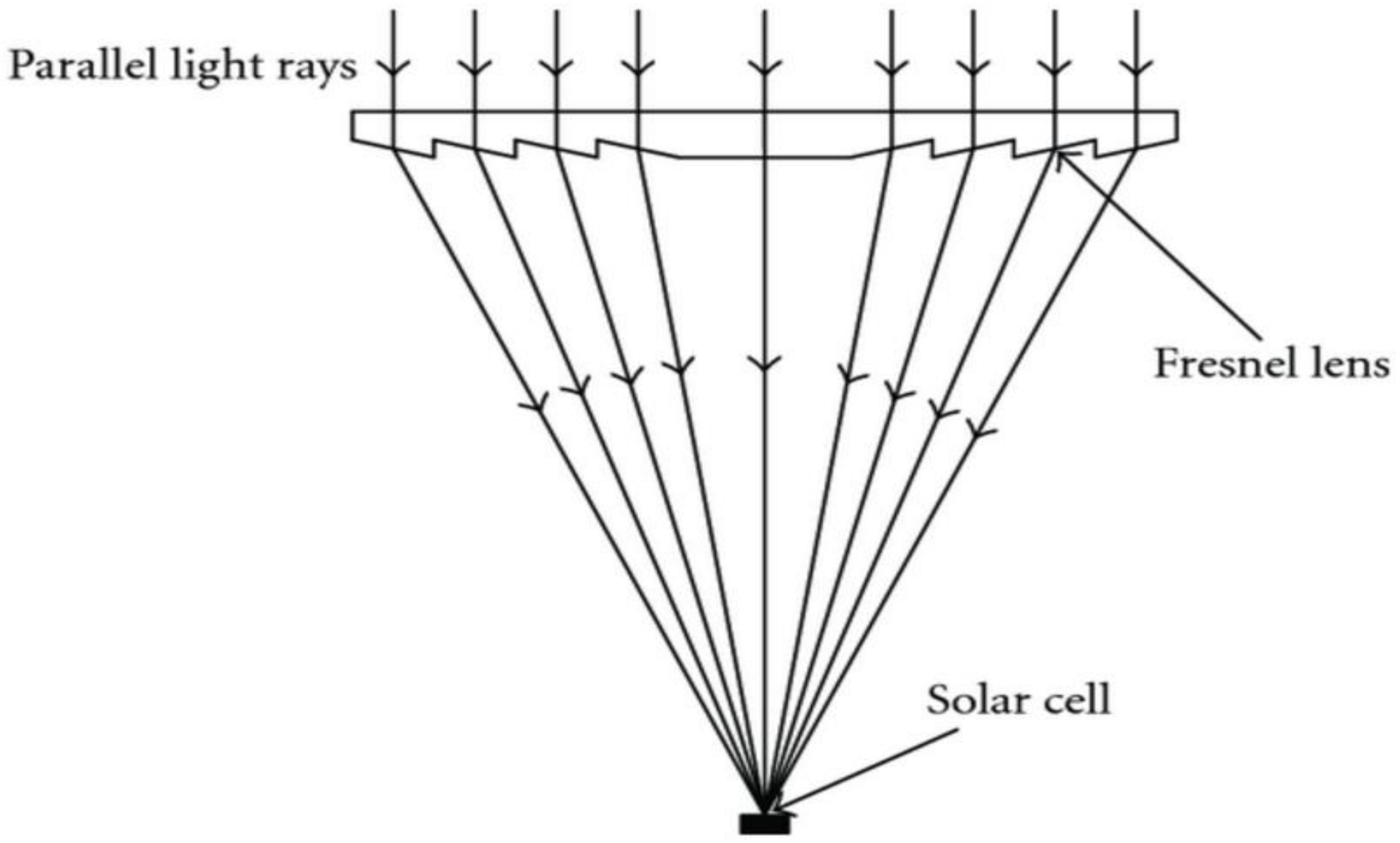
Parabolic dish with central focusing

- A Parabolic dish system consists of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point.
- These concentrators are mounted on a structure with a two-axis tracking system to follow the sun.
- The collected heat is typically utilized directly by a heat engine mounted on the receiver moving with the dish structure.
- Dish can attain extremely high temperatures, and holds promise for use in solar reactors for making solar fuels which require very high temperatures.
- Stirling and Brayton cycle engines are currently favored for power conversion, although dish has been seldom deployed commercially for power generation

Parabolic dish with central focusing



Fresnel lens with center focusing



Heliostats with center receiver focusing

- Unlike linear concentrating systems (troughs), which reflect light onto a focal line, the central receiver systems send concentrated light onto a remote central receiver.
- A typical example of such a system is a solar power tower system, which consists of multiple tracking mirrors (heliostats) positioned in the field around a main external receiver installed on a tower.
- Such systems are capable of reaching of much higher levels of concentration than linear systems.
- Concentrated radiation is further used as heat to produce steam and convert it to electricity (like in a regular power plant), or the generated thermal energy can be stored in a molten salt storage.

Heliostats with center receiver focusing

Comparison of Alternative Solar Thermal power system technologies

Technology	Solar concentration	Operating temperature on the hot side	Thermodynamic cycle efficiency
Parabolic trough Receiver	100	300-500 degree C	Low
Central receiver power tower	1000	500-1000 degree C	Moderate
Dish receiver with engine	3000	800-1200 degree C	High

2. **Energy transport medium:** Substances such as water/ steam, liquid metal or gas are used to

- transport the thermal energy from the collector to the heat exchanger or thermal storage.
- In solar PV systems energy transport occurs in electrical form.

3. **Energy storage:** Solar energy is not available continuously. So we need an energy storage medium for maintaining power supply during nights or cloudy periods.

There are three major types of energy:

storage: a) Thermal energy storage; b) Battery storage; c) Pumped storage hydro-electric

Solar radiation measurement

There are two important types of instruments to measure solar radiation:

- Pyrheliometer
- Pyranometer

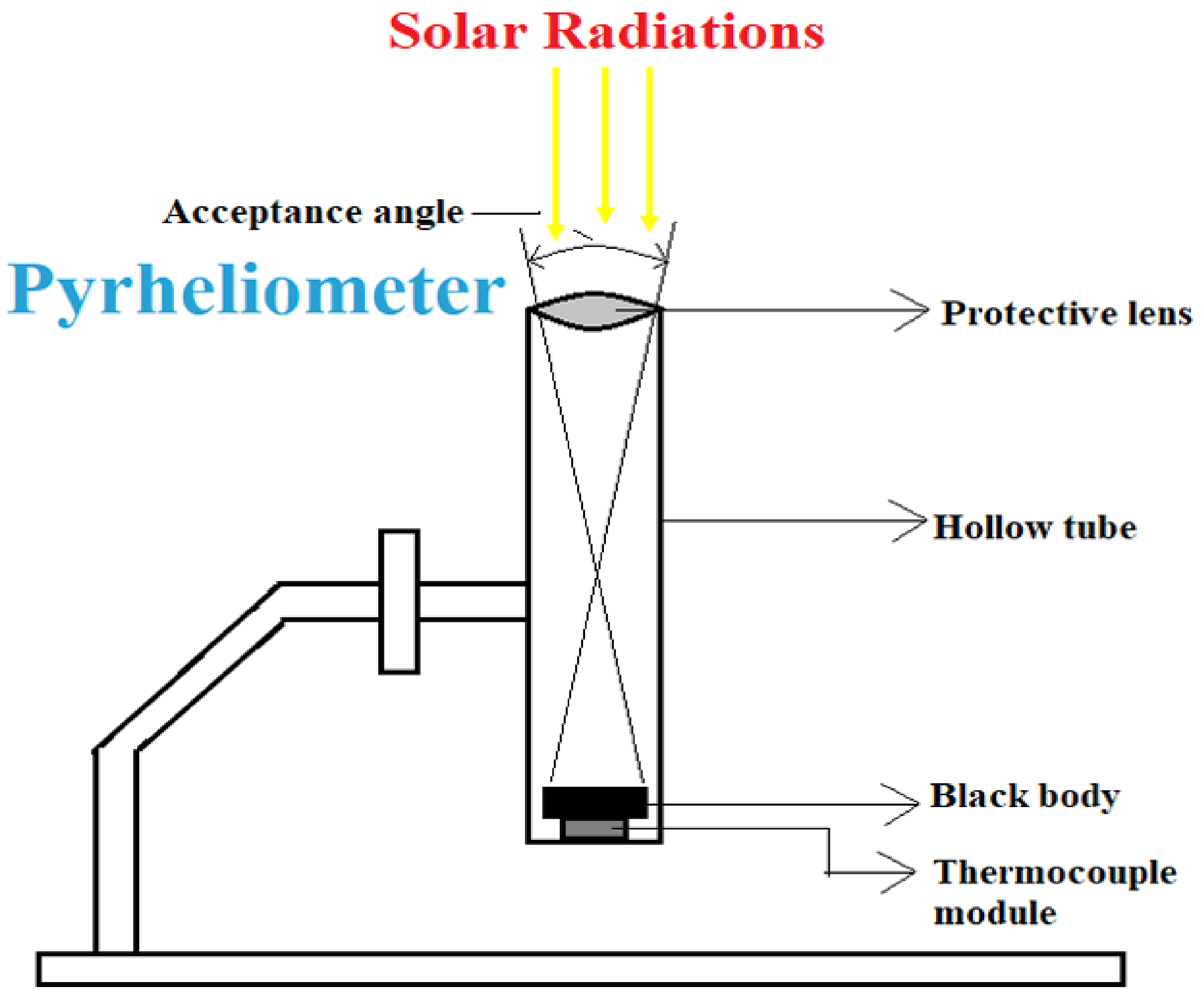
Pyrheliometer

- Pyrheliometer is used to measure direct beam radiation at normal incidence.
- There are different types of pyrheliometers.
- According to Duffie and Beckman (2013), *Abbot silver disc pyrheliometer* and *Angstrom compensation pyrheliometer* are important primary standard instruments.
- *Eppley normal incidence pyrheliometer (NIP)* is a common instrument used for practical measurements in the US, and *Kipp and Zonen actinometer* is widely used in Europe. Both of these instruments are calibrated against the primary standard methods.

Pyrheliometer

- Based on their design, the above listed instruments measure the beam radiation coming from the sun and a small portion of the sky around the sun.
- Based on the experimental studies involving various pyrheliometer design, the contribution of the circumsolar sky to the beam is relatively negligible on a sunny day with clear skies. However, a hazy sky or a uniform thin cloud cover redistributes the radiation so that contribution of the circumsolar sky to the measurement may become more significant.

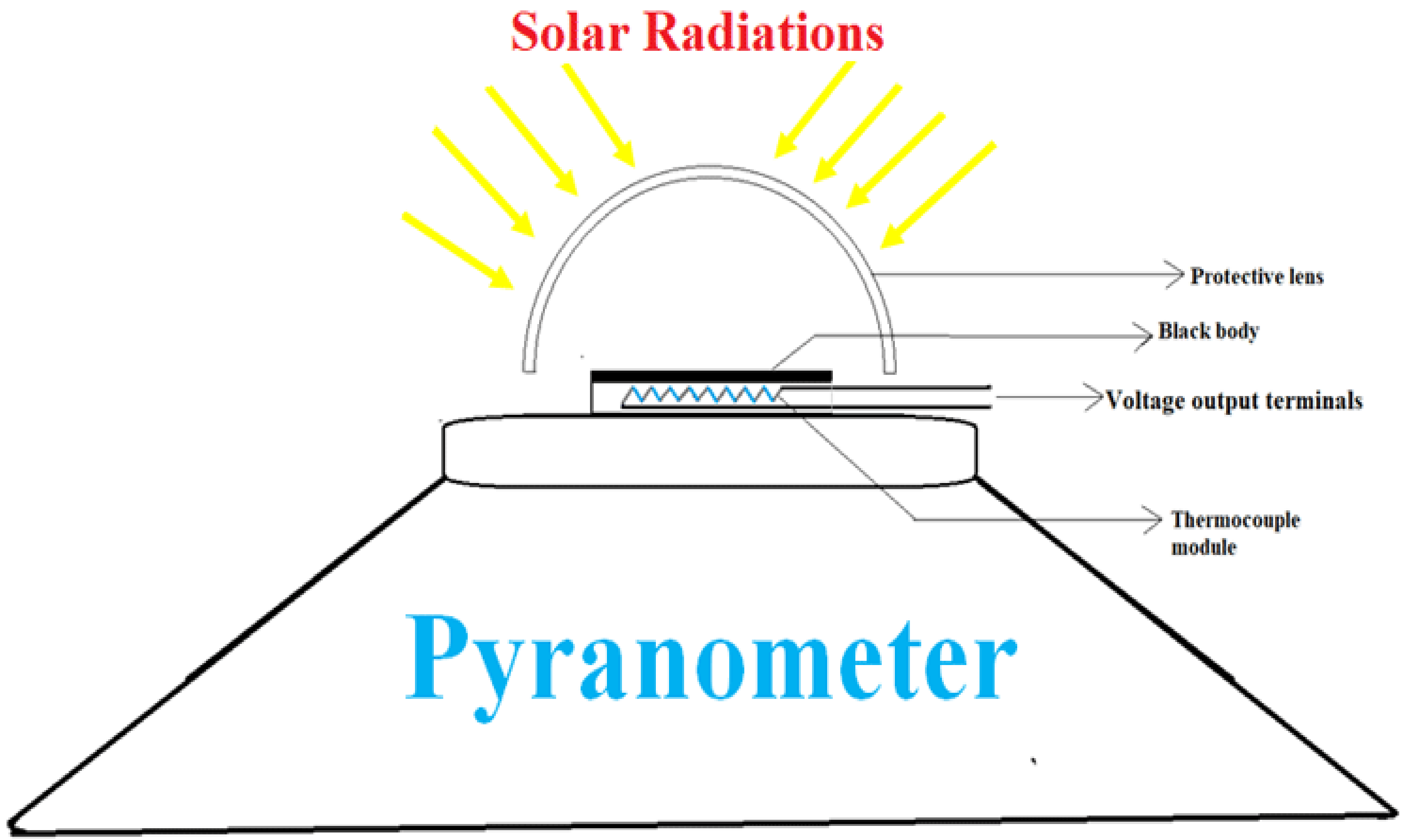
Pyrheliometer



Pyranometer

- Pyranometer is used to measure total hemispherical radiation - beam plus diffuse - on a horizontal surface.
- If shaded, a pyranometer measures diffuse radiation. Most of solar resource data come from pyranometers.
- The total irradiance (W/m^2) measured on a horizontal surface by a pyranometer is expressed as follows:
- $I_{tot} = I_{beam} \cos\vartheta + I_{diffuse}$
- where ϑ is the zenith angle (i.e., angle between the incident ray and the normal to the horizontal instrument plane).

Pyranometer



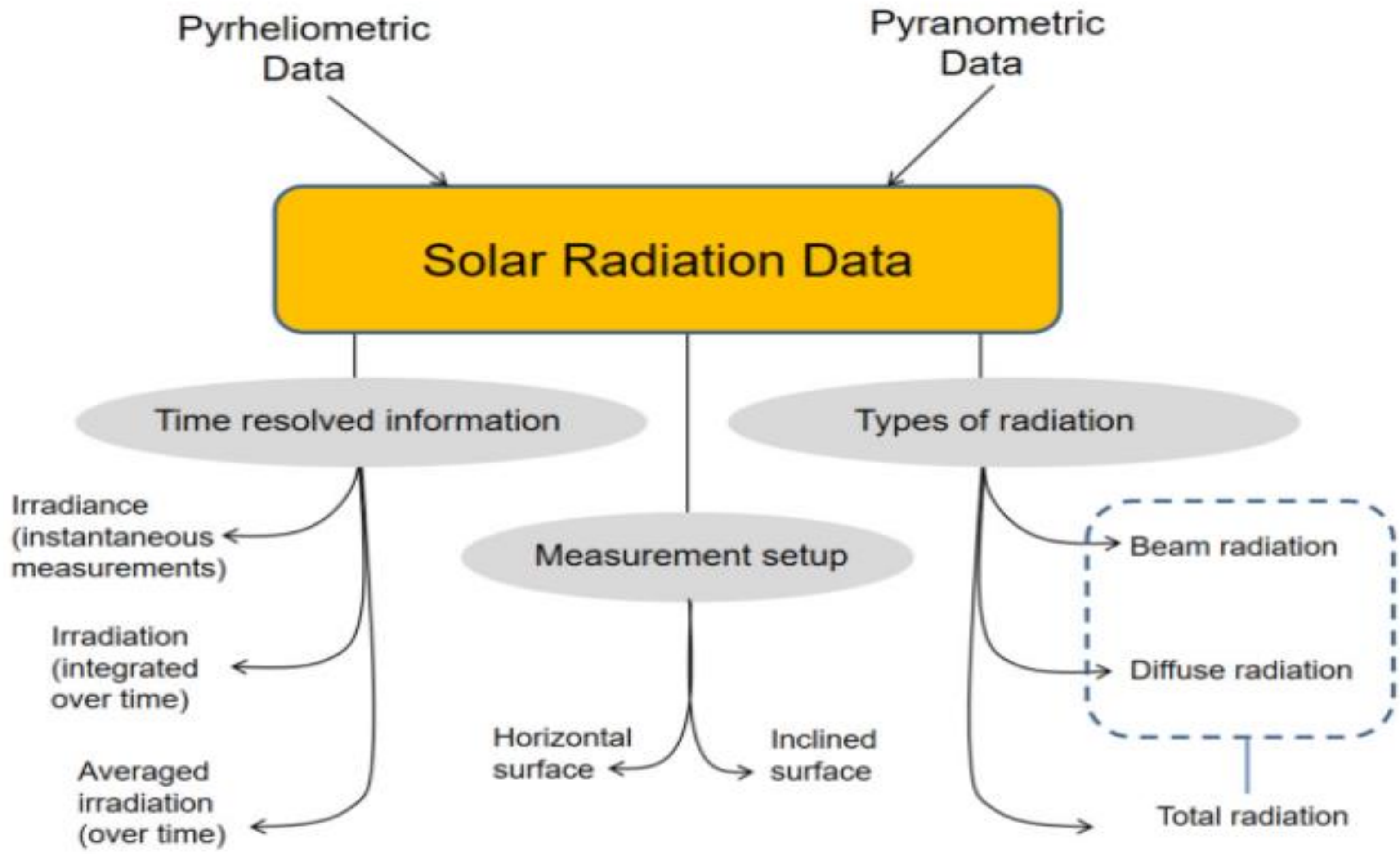
Pyranometer

- Examples of pyranometers are *Eppley 180^o or Eppley black-and-white* pyranometers in the US and *Moll-Gorczynsky* pyranometer in Europe.
- These instruments are usually calibrated against standard pyrheliometers.
- There are pyranometers with thermocouple detectors and with photovoltaic detectors.
- The detectors ideally should be independent on the wavelength of the solar spectrum and angle of incidence.
- Pyranometers are also used to measure solar radiation on inclined surfaces, which is important for estimating input to collectors. Calibration of pyranometers depends on the inclination angle, so experimental data are needed to interpret the measurements.

Photoelectric sunshine recorder.

- Photoelectric sunshine recorder. The natural solar radiation is notoriously intermittent and varying in intensity.
- The most potent radiation that creates the highest potential for concentration and conversion is the bright sunshine, which has a large beam component.
- The duration of the bright sunshine at a locale is measured, for example, by a photoelectric sunshine recorder.
- The device has two selenium photovoltaic cells, one of which is shaded, and the other is exposed to the available solar radiation. When there is no beam radiation, the signal output from both cells is similar, while in bright sunshine, signal difference between the two cells is maximized.
- This technique can be used to monitor the bright sunshine hours.

Overview of different types of solar radiation data



Solar thermal energy (STE)

Solar thermal energy (STE):

- Solar thermal energy (STE) is a form of energy and a technology for harnessing solar energy to generate thermal energy or electrical energy for use in industry, and in the residential and commercial sectors.
- The first installation of solar thermal energy equipment occurred in the Sahara Desert approximately in 1910 when a steam engine was run on steam produced by sunlight.
- Because liquid fuel engines were developed and found more convenient, the Sahara project was abandoned, only to be revisited several decades late.

- Solar thermal collectors are classified by the United States Energy Information Administration as low, medium, or high-temperature collectors.
- Low-temperature collectors are flat plates generally used to heat swimming pools.
- Medium-temperature collectors are also usually flat plates but are used for heating water or air for residential and commercial use.

Solar thermal plant

Solar thermal plant

- The central receiver technology with power tower is getting new development thrust in the U.S.A. as having a higher potential of generating lower cost electricity at large scale.
- An experimental 10 MW power plant using this technology has been built and commissioned in 1996 by the Department of Energy in partnership with the Solar II Consortium of private investors led by the Southern California Edison, the second largest electrical utility company in the U.S.A.
- It is connected to the grid, and has enough capacity to power 10,000 homes. The plant is designed to operate commercially for 25 to 30 years.
- It uses some components of Solar plant, which was built and operated at the site using the central receiver power tower technology.
- The Solar I plant, however, generated steam directly to drive the generator without the thermal storage feature of the Solar thermal plant.

Photovoltaic system

- The Kyoto agreement on global reduction of greenhouse gas emissions has prompted renewed interest in renewable energy systems worldwide.
- Many renewable energy technologies today are well developed, reliable, and cost competitive with the conventional fuel generators.
- The cost of renewable energy technologies is on a falling trend and is expected to fall further as demand and production increases.
- There are many renewable energy sources such as biomass, solar, wind, mini-hydro, and tidal power.

- One of the advantages offered by renewable energy sources is their potential to provide sustainable electricity in areas not served by the conventional power grid
- The growing market for renewable energy technologies has resulted in a rapid growth in the need for power electronics.
- Most of the renewable energy technologies produce DC power, and hence power electronics and control equipment are required to convert the DC into AC power.
- Inverters are used to convert DC to AC.
- There are two types of inverters: standalone and grid-connected.
- The two types have several similarities, but are different in terms of control functions.

Maximum Power Tracking

Peak Power Operation:

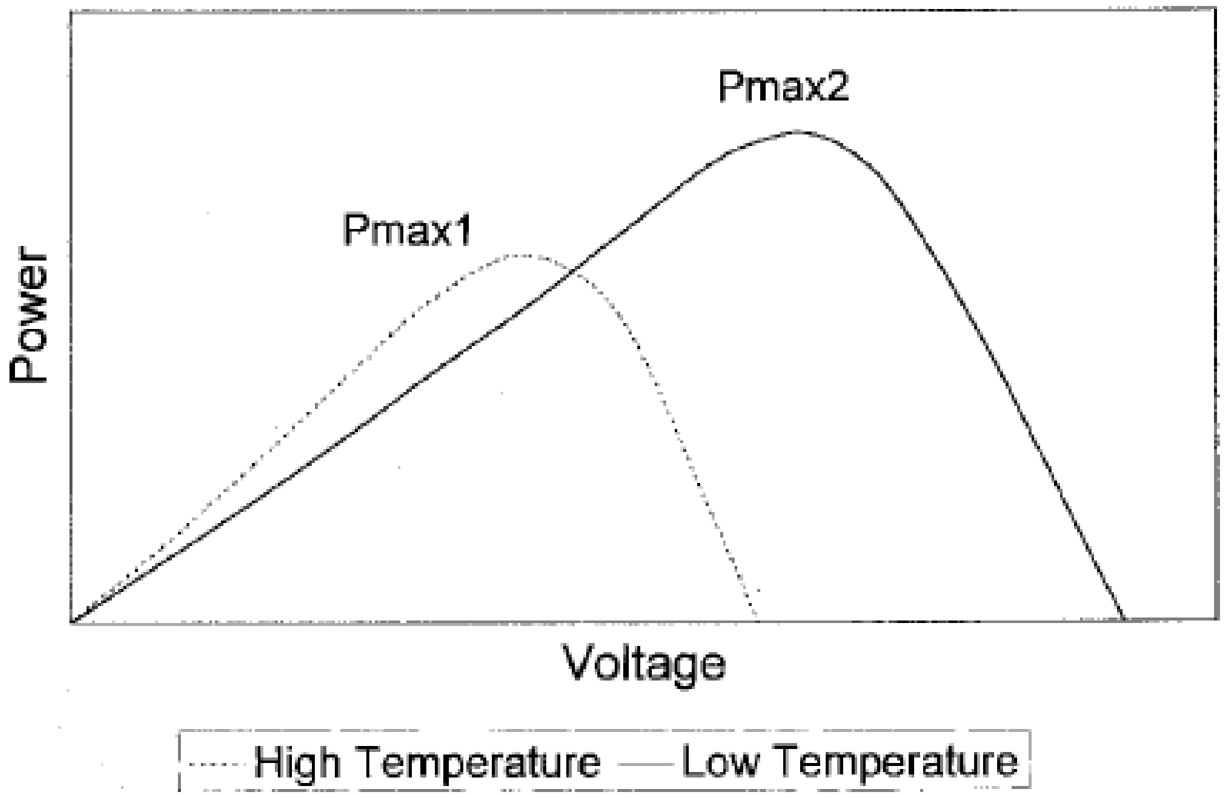
- The sun tracker drives the module mechanically to face the sun to collect the maximum solar radiation.
- However, that in itself does not guarantee the maximum power output from the module.
- As was seen in Figure, the module must operate electrically at a certain voltage that corresponds to the peak power point under a given operating condition.

There are three electrical methods of extracting the peak power from a PV source, as described in the following:

1. In the first method, a small signal current is periodically injected into the array bus, and the dynamic bus impedance ($Zd = dV/dI$) and the static bus impedance ($Zs = V/I$) are measured.
   – The operating voltage is then increased or decreased until Zd equals −Zs. At this point, the maximum power is extracted from the source.
2. In another method, the operating voltage is increased as long as dP/dV is positive. That is, the voltage is increased as long as we get more power. If dP/dV is sensed negative, the operating voltage is decreased. The voltage stays the same if dP/dV is near zero within a preset dead band.

3. The third method makes use of the fact that for most PV cells, the ratio of the voltage at the maximum power point to the open-circuit voltage (i.e., Vmp/Voc) is approximately constant, say K.

- For example, for high quality crystalline silicon cells, K = 0.72. An unloaded cell is installed on the array and kept in the same environment as the power-producing cells, and its open-circuit voltage is continuously measured.
- The operating voltage of the power producing array is then set at K*Voc, which will produce the maximum power.


Pmax2
Pmax1
Power
Voltage
High Temperature
Low Temperature

Solar GRID Connected Inverter

Solar GRID Connected Inverter:

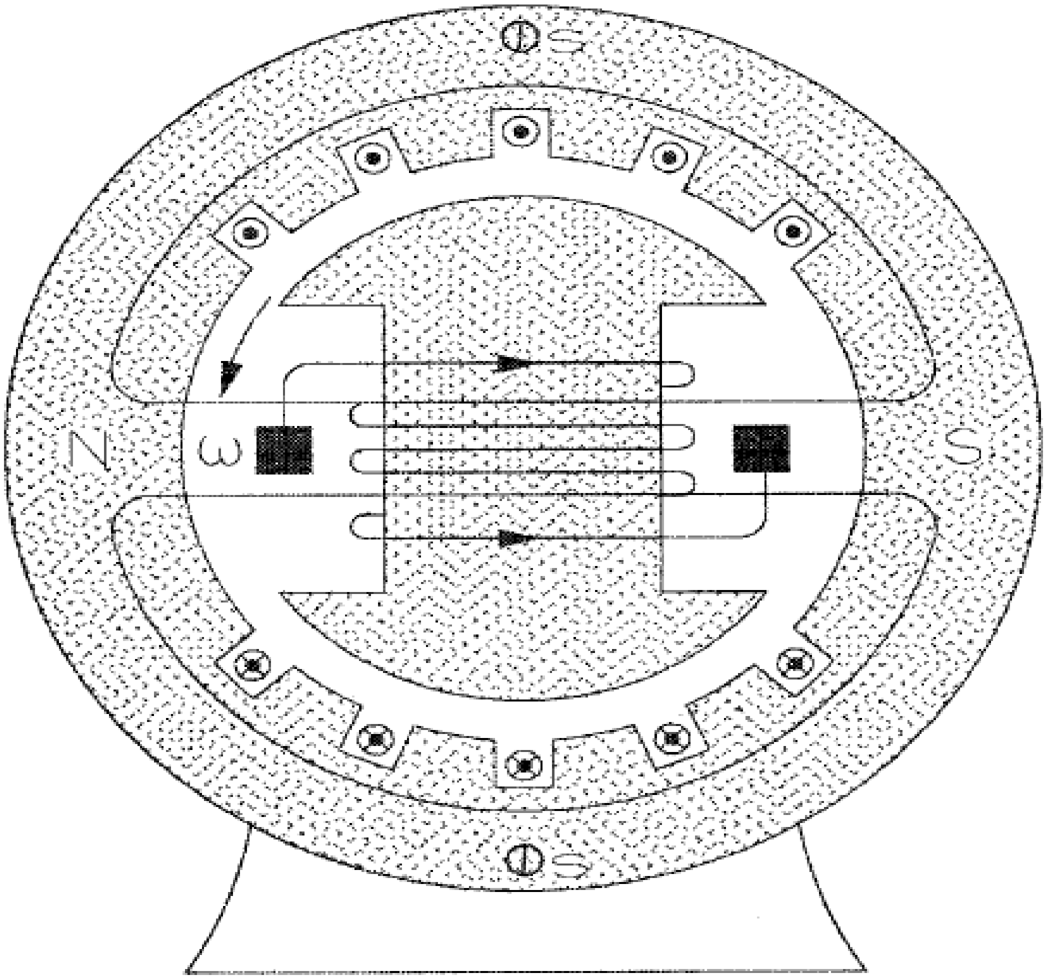
- Introduction for Solar Inverter Material, energy, and information are the three important elements for human survival and development.
- Each new discovery for energy use transformed and greatly promoted the development of modern civilization.
- The invention of the steam engine brought us into the machine age.
- The invention and use of electricity brought us into the electrical age.
- The invention of the semiconductor transistor brought into the information age.

- However, if the light-generated carriers are prevented from leaving the solar cell, then the collection of light-generated carriers causes an increase in the number of electrons on the n-type side of the p-n junction and a similar increase in holes in the p-type material.
- This separation of charge creates an electric field at the junction which is in opposition to that already existing at the junction, thereby reducing the net electric field.

Synchronous generator

- The electromechanical energy conversion in the solar thermal power system is accomplished by the synchronous machine, which runs at a constant speed to produce 60/50 Hz electricity.
- This power is then directly used to meet the local loads, and/or to feed the utility grid lines.

Synchronous generator



Synchronous generator

- The electromagnetic features of the synchronous machine are shown in Figure
- The stator is made of conductors placed in slots of magnetic iron laminations.
- The stator conductors are connected in three phase coils.
- The rotor consists of magnetic poles created by the field coils carrying direct current.
- The rotor is driven by steam turbine to create a rotating magnetic field. Because of this rotation, the rotor field coils use slip rings and carbon brushes to supply DC power from a stationary source.

Synchronous generator

- The stator conductors are wound in three groups, connected in three-phase configuration.
- Under the rotating magnetic field of the rotor, the three phase coils generate AC voltages that are 120 electrical degrees out of phase with each other.
- If the electromagnetic structure of the machine has p pole pairs and it is required to generate electricity at frequency f, then the rotor must rotate at N revolution per minute given by the following:

$$N = 120f/P$$

N- speen in rpm

f- frequency in Hz

P- No of poles

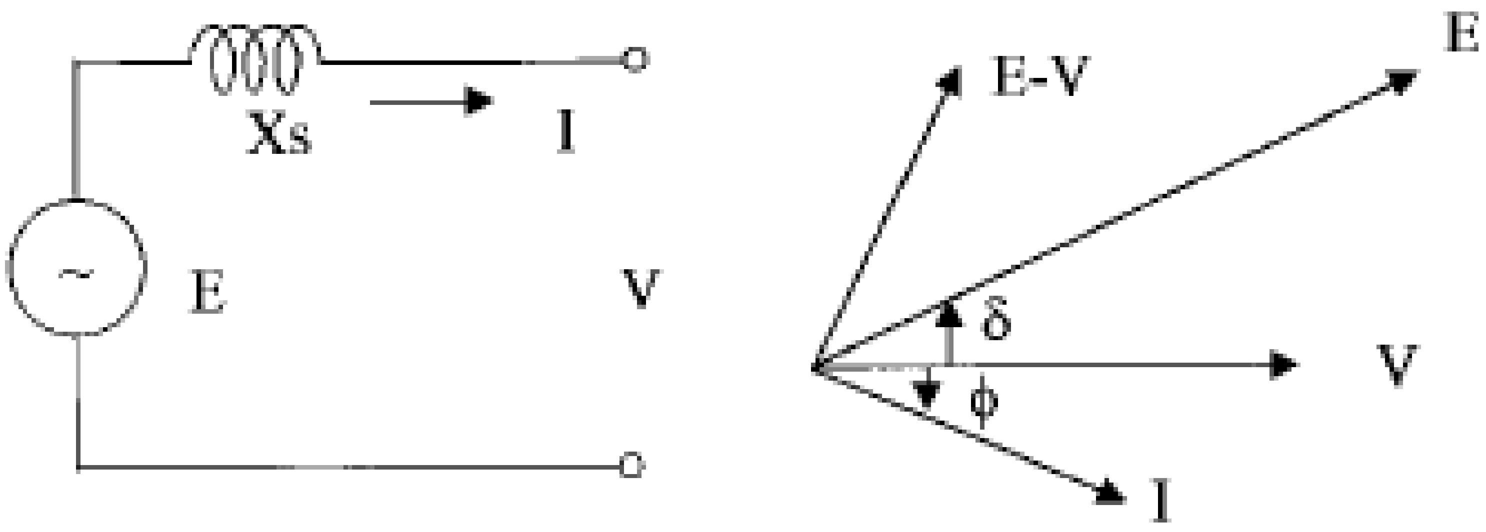
Synchronous generator

- The synchronous machine must operate at this constant speed to generate power at the specified frequency. In a stand-alone solar thermal system, small speed variations could be tolerated within the frequency tolerance band of the AC system.
- If the generator is connected to the grid, it must be synchronous with the grid frequency, and must operate exactly at the grid frequency at all times.
- Once synchronized, such a machine has inherent tendency to remain in synchronism.
- However, a large sudden disturbance such as a step load can force the machine out of the synchronism

Equivalent Electrical Circuit

- The equivalent electricity circuit of the synchronous machine can be represented by a source of alternating voltage E and an internal series resistance Rs and reactance Xs representing the stator winding.
- The resistance, being much smaller than the reactance, can be ignored to reduce the equivalent circuit to a simple form shown.
- If the machine is supplying the load current I lagging the terminal voltage V by phase angle ϕ, it must internally generate the voltage E, which is the phasor sum of the terminal voltage and the internal voltage drop IXs
- The phase angle between the V and E is called the power angle δ
- At zero power output, load current is zero and so is the Ixs vector, making V and E in phase having zero power angle.
- Physically, the power angle represents the angle by which the rotor position lags the stator-induced rotating magnetic field.

Equivalent Electrical Circuit

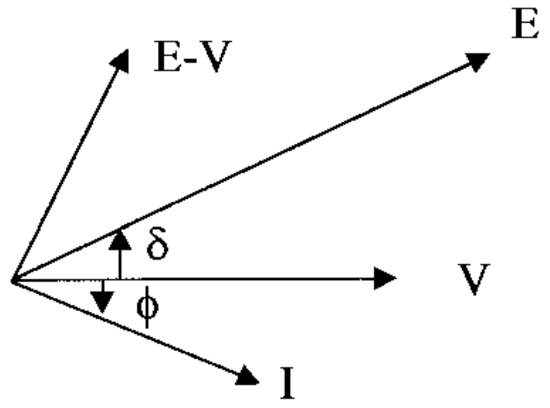


Equivalent Electrical Circuit

- The output power can be increased by increasing the power angle up to a certain limit, beyond which the rotor would no longer follow the stator field and will step out of the synchronous mode of operation.
- In the nonsynchronous mode, it cannot produce steady power

Excitation Methods

- The synchronous machine excitation system must be designed to produce the required magnetic field which is controllable to control the voltage and the reactive power of the system.
- In modern high power machines, Xs can be around 1.5 units of the base impedance of the machine
- With reactance of this order, the phasor diagram can show that the rotor field excitation required at rated load (100 percent load at 0.8 lagging power factor) is more than twice that at no load with the same terminal voltage



Excitation Methods

- The excitation system has the corresponding current and voltage ratings, with capability of varying the voltage over a wide range of 1 to 3 or even more without under saturation in the magnetic circuit
- For large machines, three types of excitation systems —

i. DC excitation,
ii. AC excitation and
iii. static excitation

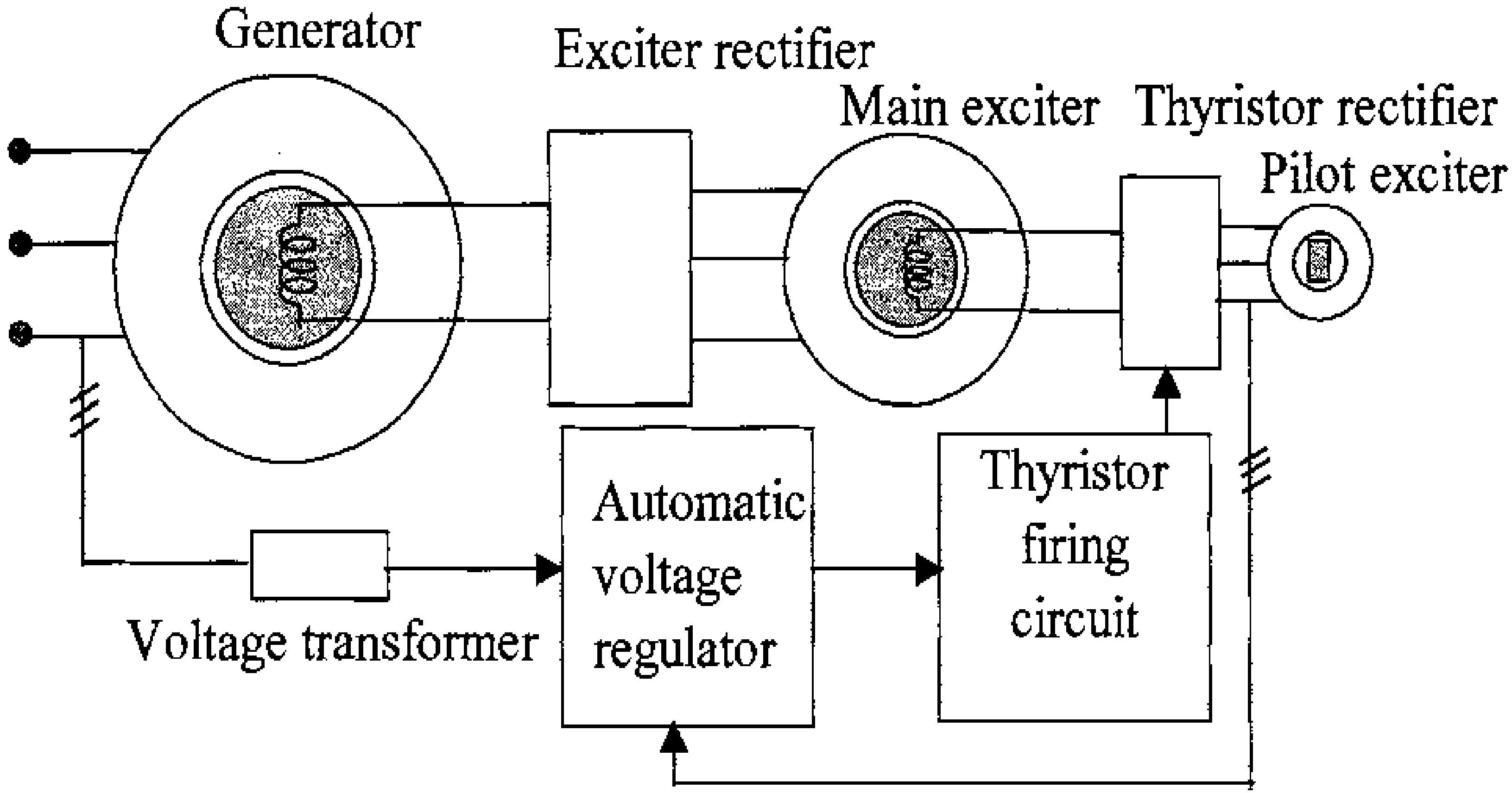
DC excitation system

- In the DC system, a suitably designed DC generator supplies the main field winding excitation through conventional slip rings and brushes.
- Due to low reliability and high maintenance requirement, the conventional DC machine is seldom used in the synchronous machine excitation system.

AC excitation system

- Most utility scale generators use the AC excitation system. The main exciter is excited by a pilot exciter.
- The AC output of a permanent magnet pilot exciter is converted into DC by a floor standing rectifier and supplied to the main exciter through slip rings.
- The main exciter's AC output is converted into DC by means of phase controlled rectifiers, whose firing angle is changed in response to the terminal voltage variations.
- After filtering the ripples, this direct current is fed to the synchronous generator field winding.

AC excitation system



Static excitation system

- In static excitation is opposed to the dynamic excitation.
- In the static excitation scheme, the controlled DC voltage is obtained from a suitable stationary AC source rectified and filtered.
- The DC voltage is then fed to the main field winding through slip rings. This excitation scheme has a fast dynamic response and is more reliable because it has no rotating exciters.
- The excitation control system modeling for analytical studies must be carefully done as it forms a multiple feedback control system that can become unstable.

Static excitation system

- The IEEE has developed industry standards for modeling the excitation systems.
- The model enters nonlinearly due to magnetic saturation present in all practical designs.
- The stability can be improved by supplementing the main control signal by auxiliary signals such as speed and power

Static excitation system

- The IEEE has developed industry standards for modeling the excitation systems.
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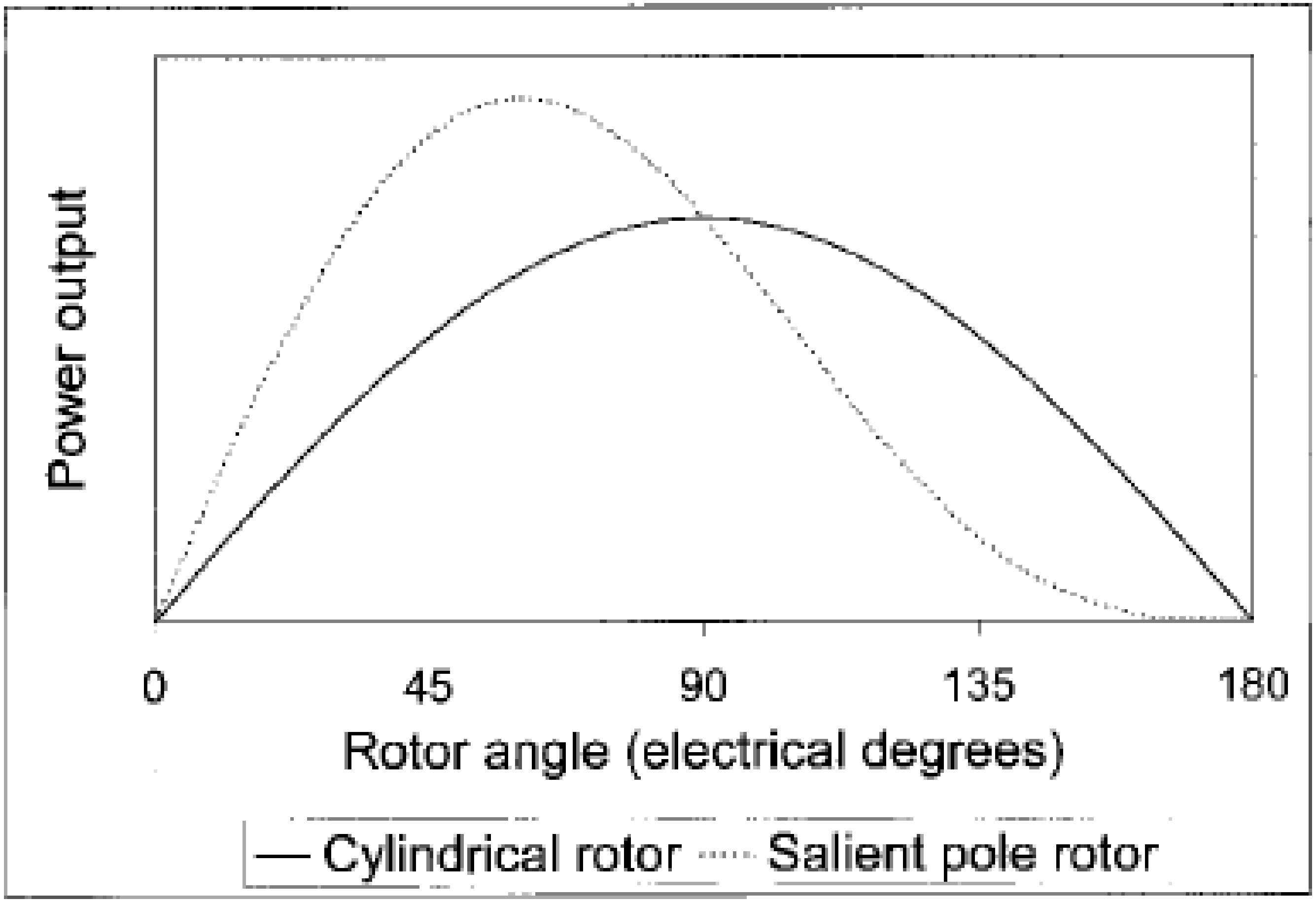
Electrical Power Output

- The electrical power output of the synchronous machine is as follows
- $P = VI \cos\phi$
- Using the phasor diagram the current can be expressed as follows
- $I = \frac{E - V}{jXs} = \frac{E\angle\delta - V\angle 0}{jXs} = \frac{E(\cos\delta + j\sin\delta) - V\angle 0}{jXs}$
- The real part of this current is Ireal = $\frac{E}{Xs}\sin\delta$
- This part, when multiplied with the terminal voltage V gives the output power
- $P = \frac{VE}{Xs}\sin\delta$

Electrical Power Output



Power versus power angle of round rotor and salient pole synchronous machine

Electrical Power Output

- The output power versus the power angle is a sine curve shown by the solid line, having the maximum value at $\delta = 90°$.
- The maximum power that can be generated by the machine is therefore
- $Pmax = \frac{VE}{Xs}$
- Some synchronous machine rotors have magnetic saliency in the pole structure.
- The saliency produces a small reluctance torque superimposed on the main torque, modifying the power angle curve as shown by the dotted line.

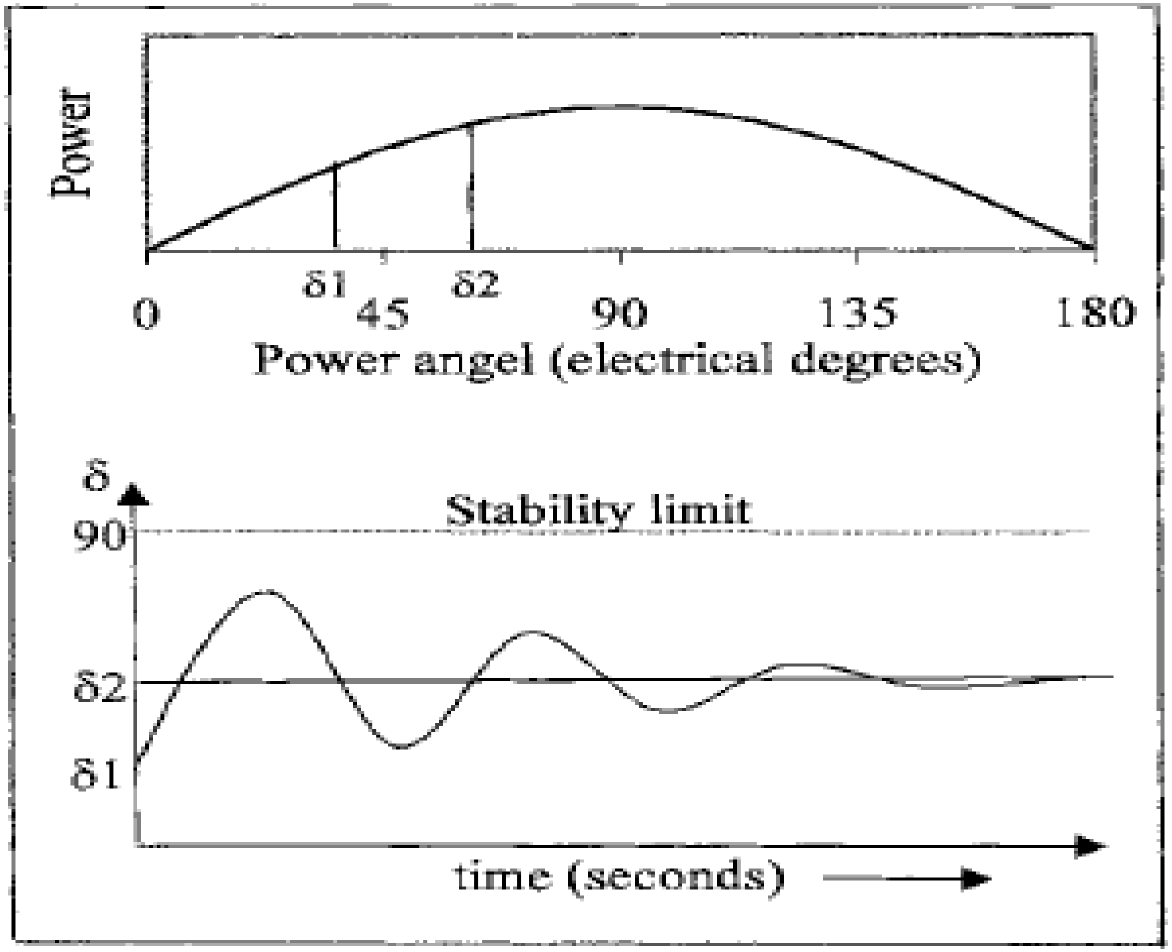
Electrical Power Output

- The electromechanical torque required at the shaft to produce this power is the power divided by the angular velocity of the rotor. That is as follows
- Te= $\frac{VE}{wXs}$sinδ
- The torque also has the maximum limit corresponding to the maximum power limit, and is given as follows
- Tmax= $\frac{VE}{wXs}$

Transient Stability Limit

- The maximum power limit just described is called the steady state stability limit.
- Any loading beyond this value will cause the rotor to lose synchronism and hence, the power generation capability.
- The steady state limit must not be exceeded under any condition, including those that can be encountered during transients.
- For example, if a sudden load step is applied to the machine initially operating in a steady state at load power angle $\delta 1$ the rotor power angle would increase from $\delta 1$ to $\delta 2$ corresponding to the new load that it must supply

Transient Stability Limit



Load step transient and stability limit of synchronous machine

Transient Stability Limit

- This takes some time depending on the electromechanical inertia of the machine. No matter how short or long it takes, the rotor inertia and the electromagnetic restraining torque will set the rotor in a mass-spring type of oscillatory mode, swinging the rotor power angle beyond its new steady state value.
- If the power angle exceeds 90° during this swing, the machine stability and the power generation are lost.

Transient Stability Limit

- For this reason, the machine can be loaded only to the extent that even under the worst-case step load, planned or accidental, or during all possible faults, the power angle swing will remain below 90° with sufficient margin.
- This limit on loading the machine is called the transient stability limit
- the stability limit at given voltages can be increased by designing the machine with low synchronous reactance Xs, which is largely made of the stator armature reaction component

Commercial power plants

- The commercial power plants using the solar thermal system are being explored in a few hundred MWe capacity.
- For comparison, the conventional coal thermal plants typically operate at 40 percent conversion efficiency, and the photovoltaic power systems have the overall solar-to-electricity conversion efficiency of 8 to 10 percent with amorphous silicon and 15 to 20 percent with crystalline silicon technologies

Commercial power plants

- Comparison of 10 MWe Solar II and 100 MWe Prototype Design

Performance Parameter	Solar II Plant 10 MWe	Commercial Plant 100 MWe
Mirror reflectivity	90%	94%
Field efficiency	73%	73%
Mirror cleanliness	95%	95%
Receiver efficiency	87%	87%
Storage efficiency	99%	99%
Electromechanical conversion efficiency of generator	34%	43%
Auxiliary components efficiency	90%	93%
Overall solar-to-electric conversion efficiency	16%	23%

Commercial power plants

Major conclusions of the studies to date are the following

1. First plants as large as 100–200 MWe are possible to design and build based on the demonstrated technology to date. Future plants could be larger.
2. The plant capacity factors up to 65 percent are possible, including outage.
3. Fifteen percent annual average solar-to-electric conversion efficiency is achievable.
4. The energy storage feature of the technology makes possible to meet the peak demand on the utility lines.
5. Leveled energy cost is estimated to be 6 to 7 cents per kWh.

Commercial power plants

6. A 100 MWe plant with a capacity factor of 40 percent requires 1.5 square miles of land.

7. The capital cost of $2,000 per kWe capacity for first few commercial plants and less for future plants.

8. A comparable combined cycle gas turbine plant would cost $1,000 kWe, which includes no fuel cost.

9. Solar-fossil hybrids are the next step in development of this technology.

Commercial power plants

- Compared to the pv and wind power, the solar thermal power technology is less modular.
- Its economical size is estimated to be in the 100 to 300 MWe range.
- The cost studies at the National Renewable Energy Laboratory have shown that a commercially designed utility-scale power plant using the central receiver power tower can produce electricity at a cost of 6 to 11 cents per kWh

MODULE-III
POWER CONDITIONING SCHEMES FOR SOLAR ENERGY SYSTEMS

MODULE III - SYLLABUS

Switching devices for solar energy conversion: DC power conditioning converters, maximum power point tracking algorithms.

AC Power conditioners, Line commutated inverters, synchronized operation with grid supply, Harmonic reduction.

COURSE OUTCOMES MAPPED WITH MODULE III

CO	Course Outcomes	Blooms Taxonomy
CO 5	**Demonstrate** the functioning of various components involved in solar thermal systems for designing commercial solar power plants.	Understand
CO 6	**Develop** the suitable scheme for extracting maximum power from solar PV module using MPPT algorithms.	Apply
CO 7	**Utilize** the power conditioners and inverters for grid synchronization and harmonic reduction in solar PV systems.	Understand

PROGRAM OUTCOMES MAPPED WITH MODULE III

PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
PO 3	**Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

MAPPING OF COs AND POS FOR MODULE III

COs	PROGRAM OUTCOMES											
	1	2	3	4	5	6	7	8	9	10	11	12
CO5	√	√										
CO6	√	√										
CO7	√	√	√									

Switching devices for solar energy conversion:

A typical output voltage of PV panels can be on the order of 30 V, and it is too low for being converted to AC and fed to the grid. Therefore DC/DC conversion is often a necessary step before the DC current from the PV system is supplied to the inverter.

Most of power conditioning units include some type of DC/DC converter. Direct current converter transforms the DC voltage V1 to DC voltage V2 via adjusting the current (I):

$$V_1 I_1 = V_2 I_2$$

This is an ideal case, when input power is equal to the output power. In reality, there are always conversion losses, which lead to typical efficiencies in the range 90-95%.

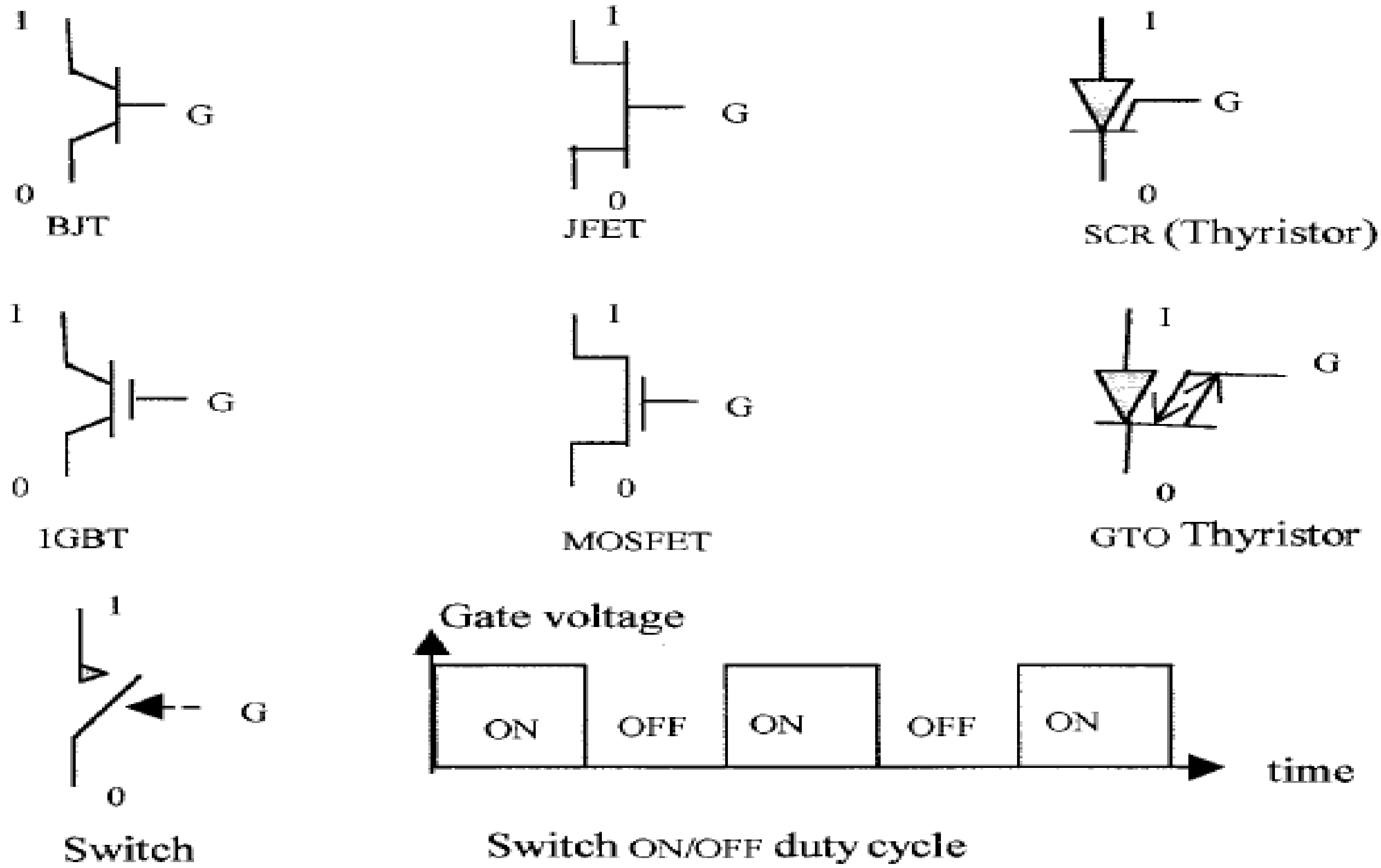
Switching devices for solar energy conversion:

A great variety of solid state devices is available in the market.

Some of the more commonly used devices are as follows:

- bipolar junction transistor (BJT).
- metal-oxide semiconducting field effect transistor (MOSFET).
- insulated gate bipolar transistor (IGBT).
- silicon controlled rectifier (SCR), also known as the thyristor.
- gate turn off thyristor (GTO)

Switching devices for solar energy conversion:



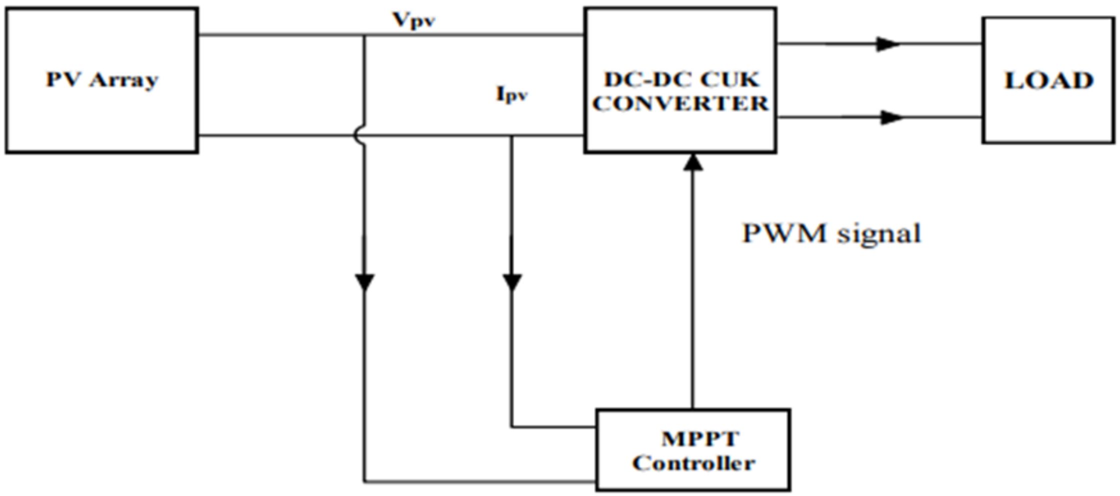
Maximum voltage and current ratings of power electronic switching devices

Device	Voltage rating in volts	Current rating in amperes	Remark
BJT	1500	200	Requires large current signal to turn on
IGBT	1200	100	Combines the advantages of BJT, MOSFET and GTO
MOSFET	1000	100	Higher switching speed
SCR	6000	3000	Once turned on, requires heavy turn-off circuit

OPERATION AND DESIGN ANALYSIS OF DC- DC CONVERTERS

- In a PV module directly coupled to a load, the MPP changes as the module temperature and the solar irradiation change.
- This leads to mismatching of maximum power tracking and hence results in oversizing of the PV array and thus increases the overall system cost.
- MPPT controller can be solution to the problem.
- The MPPT maintains the PV module operating point at the MPP. The three basic components in MPPT design as shown in Figure are:

A switchmode DC-DC converter, a control circuit, and tracking algorithm. The heart of the MPPT hardware is a DC-DC converter. MPPT uses the converter for regulating the input voltage at the MPP and to provide load matching for the maximum power transfer



PV Array
Vpv
Ipv
DC-DC CUK CONVERTER
LOAD
PWM signal
MPPT Controller

Basic DC-DC Converter Topologies

Three basic DC- DC converter topologies are used in PV systems:

Step down (buck), step up (boost) and step down and up (buck boost and Cuk) converters. The performance of a DC-DC converter topology can be described by the following parameters:

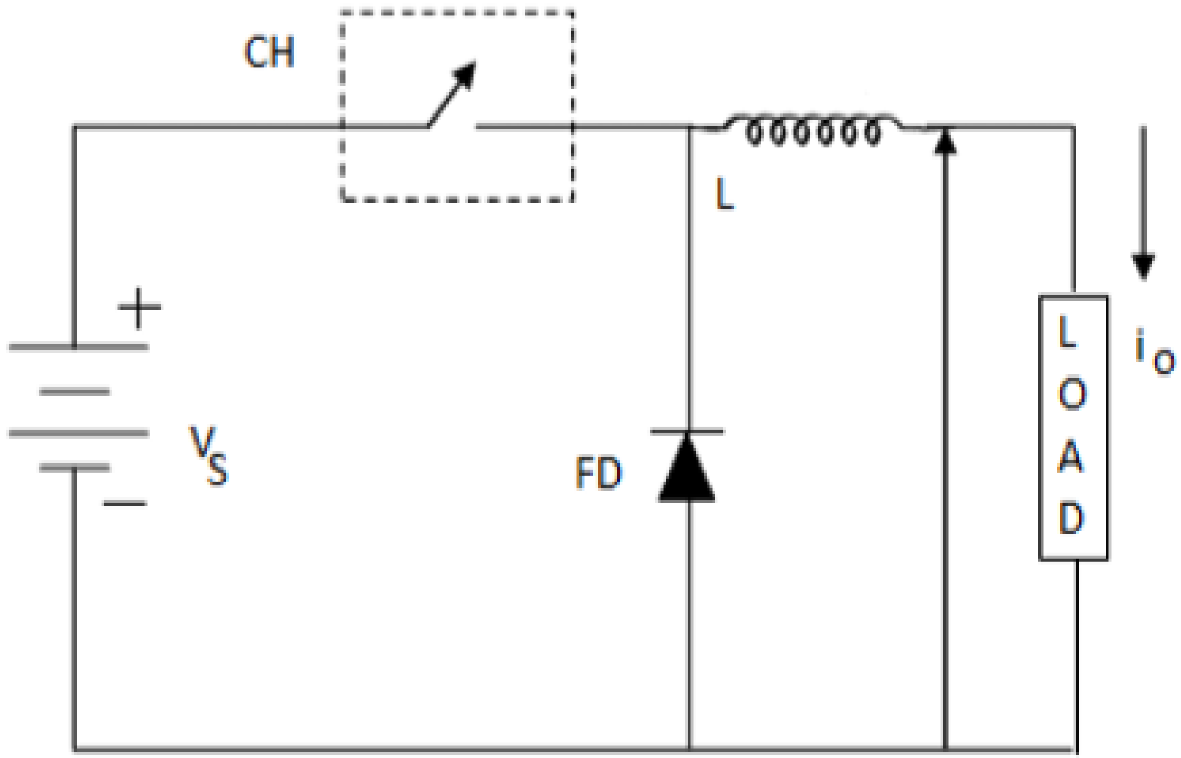
(a) Voltage gain (AV),

(b) Current gain (Ai),

(c) Input impedance (Ri),

(d) Boundary filter inductance (Lb), and

(e) Minimum filter capacitance (Cmin).



Step down chopper

$$\frac{V_S - V_0}{L} T_{ON} = \frac{V_0}{L} T_{OFF}$$

$$\frac{V_S - V_0}{V_0} = \frac{T_{OFF}}{T_{ON}}$$

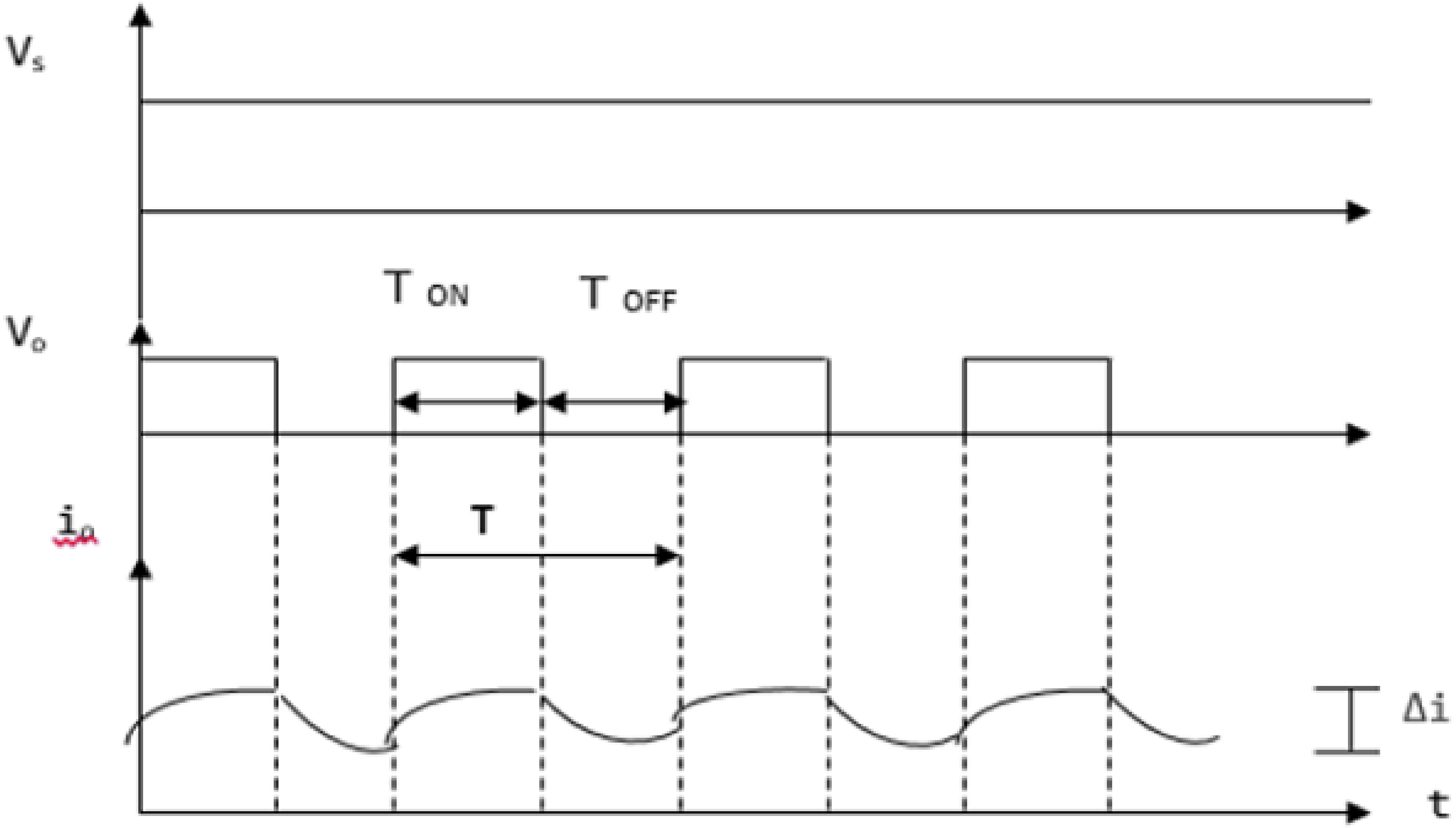
$$\frac{V_S}{V_0} = \frac{T_{ON} - T_{OFF}}{T_{ON}}$$

$$V_0 = \frac{T_{ON}}{T} V_S = DV_S$$

$$\Delta i = \frac{V_S - DV_S}{L} DT, \text{ from } D = \frac{T_{ON}}{T}$$

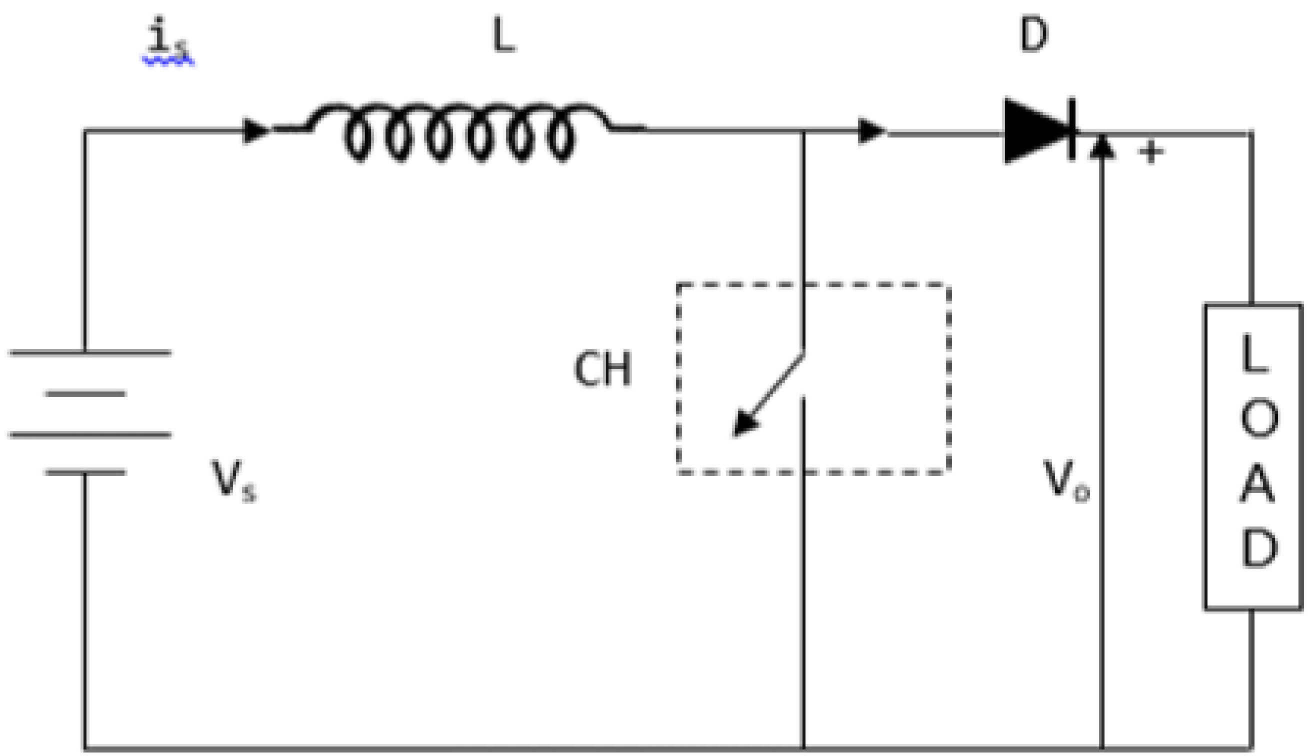
$$= \frac{V_S - (1 - D)D}{Lf}$$

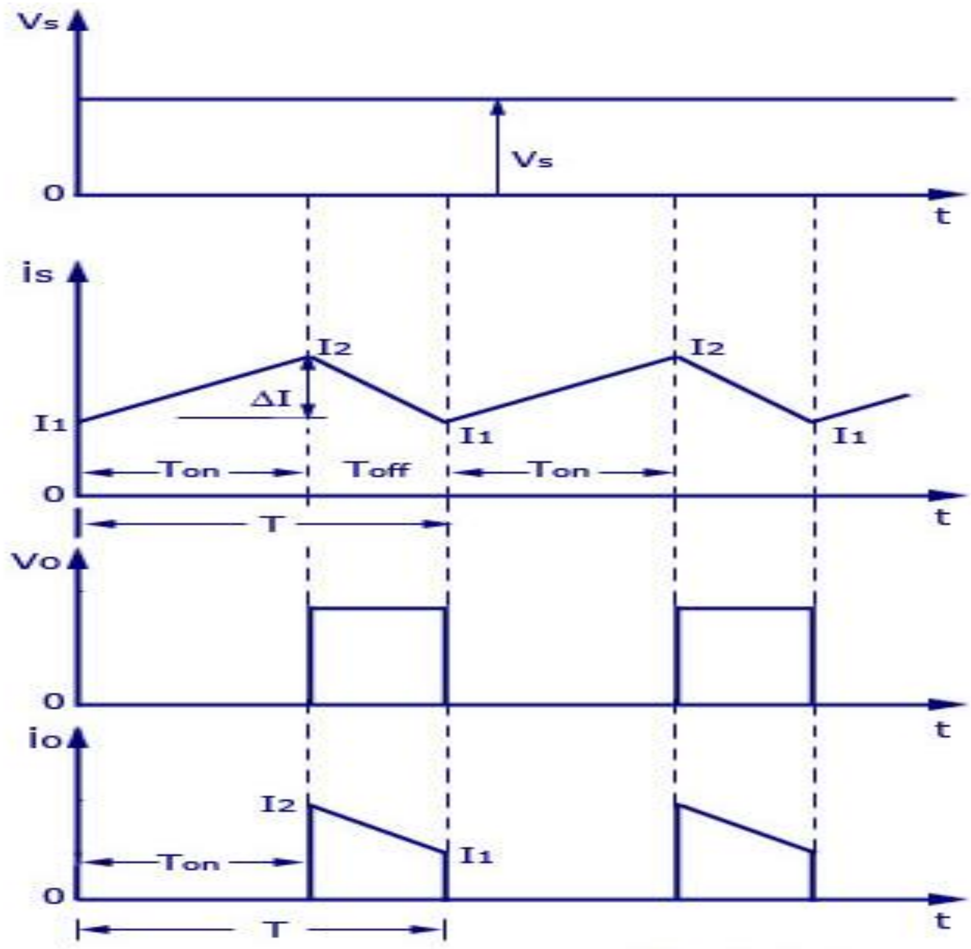
$f = \frac{1}{T}$ =chopping frequency



Vs
T ON
T OFF
Vo
io
T
Δi
t

Step Up Chopper





Input and output waveforms of step up chopper

$$V0=\frac{1}{T}\int_{0}^{Ton} Vs\,dt$$

$$Vs=L\,\frac{di}{dt},\ \frac{\Delta i}{Ton}=\frac{Vs}{L}$$

$$\Delta i=\frac{Vs}{L}\times Ton$$

V0=VS+VL, VL=V0−VS

$$L\,\frac{di}{dt}=Vo-Vs$$

$$L\,\frac{\Delta i}{Toff}=Vo-Vs$$

$$\Delta i=\frac{Vo-Vs}{L}Toff$$

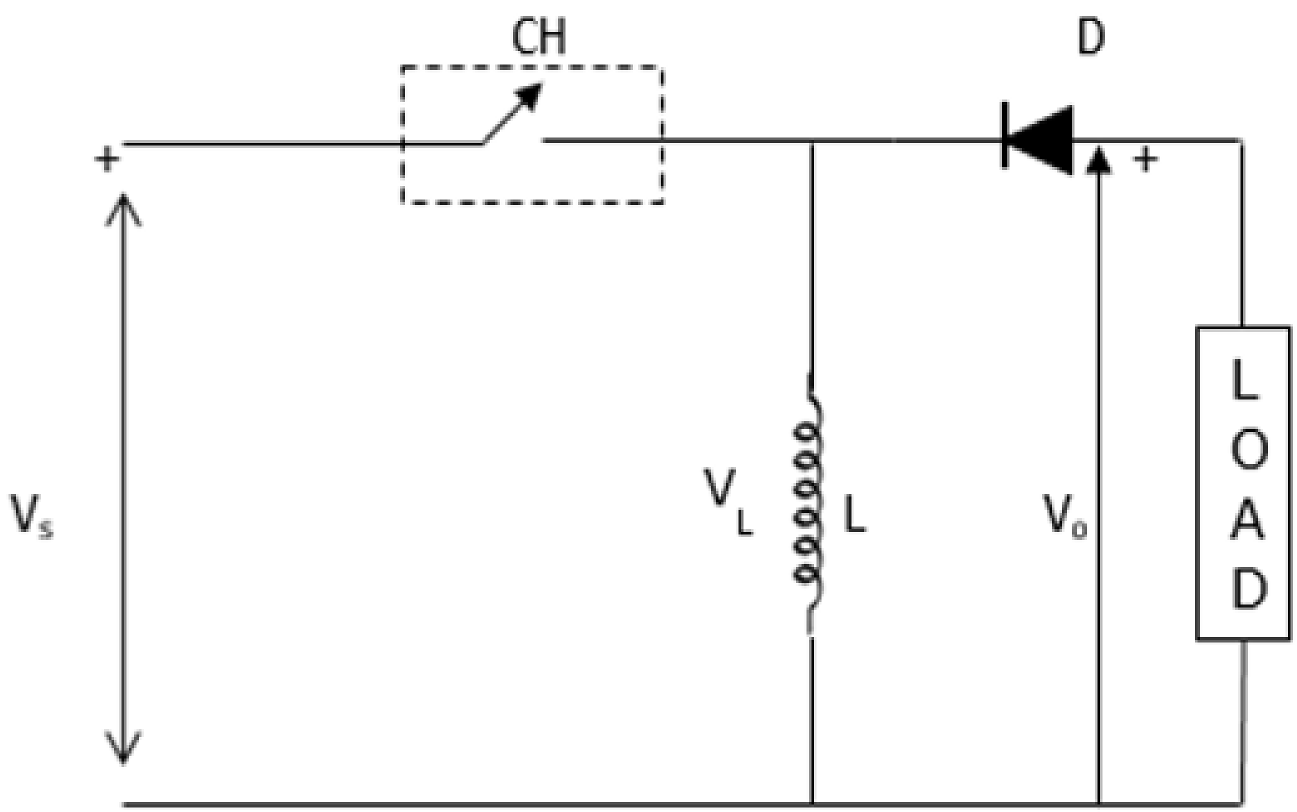
Equating Δi from on state to off state

$$\frac{Vs}{L} \times Ton = \frac{Vo-Vs}{L} Toff$$

$$Vo = \frac{TVs}{Toff}$$

$$Vo = \frac{Vs}{1-D}$$

Step Up/ Step Down Chopper



$$Vs = L\frac{di}{dt}, \quad \frac{\Delta i}{Ton} = \frac{Vs}{L}$$

$$\Delta i = \frac{Vs}{L} Ton \times \frac{T}{T}$$

$$\Delta i = \frac{DVs}{Lf}$$

$$\mathrm{V0} = -\mathrm{VL}$$

$$L\,\frac{di}{dt} = -VL$$

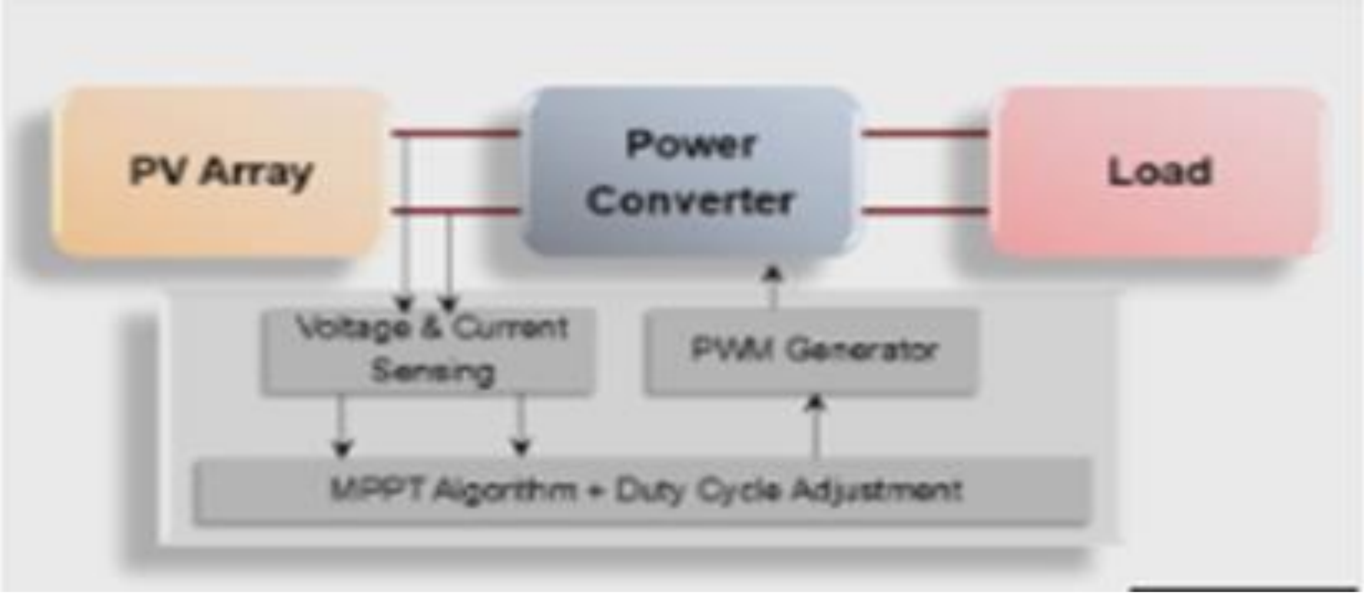
$$\frac{\mathrm{L}\,\Delta \mathrm{i}}{\mathrm{Toff}} = -\mathrm{VL}$$

$$\Delta i = -\frac{VL\,Toff}{L}$$

$$\frac{DVs}{Lf} = -\frac{VL\,Toff}{L}$$

$$\mathrm{V_0} = \frac{DVs}{1-D}$$

Performance Parameters	Buck	Boost	Buck Boost	Cuk
A_v	D	$\frac{1}{(1-D)}$	$-\frac{1}{(1-D)}$	$-\frac{D}{(1-D)}$
A_i	$\frac{1}{D}$	$(1-D)$	$-\frac{(1-D)}{D}$	$-\frac{(1-D)}{D}$
R_i	$\frac{R_L}{D^2}$	$(1-D)^2 R_L$	$\frac{(1-D)^2}{D^2} R_L$	$R_{i-CCM} = \frac{(1-D)^2}{D^2} R_L$ $R_{i-DCM} = \frac{kR_L}{D^2}$
L_b	$\frac{(1-D)R_L}{2f}$	$\frac{(1-D)^2 DR_L}{2f}$	$\frac{(1-D)^2 R_L}{2f}$	$L_1 = \frac{(1-D)^2 R_L}{2Df}$ $L_2 = \frac{(1-D)R_L}{2f}$
C_{min}	$\frac{(1-D)V_o}{8V_r L f^2}$	$\frac{V_o D}{V_r L f}$	$\frac{V_o D}{V_r L f}$	$C_2 = \frac{(1-D)}{8V_r L_2 f^2}$ $C_1 = \frac{DV_o}{V_r R_L f}$


PV Array
Power Converter
Load
Voltage & Current Sensing
PWM Generator
MPPT Algorithm + Duty Cycle Adjustment

MPPT ALGORITHM

- Maximum power point tracking (MPPT) is an algorithm implemented in photovoltaic (PV) inverters to continuously adjust the impedance seen by the solar array to keep the PV system operating at, or close to, the peak power point of the PV panel under varying conditions, like changing solar irradiance, temperature, and load.
- Engineers developing solar inverters implement MPPT algorithms to maximize the power generated by PV systems.
- The algorithms control the voltage to ensure that the system operates at “maximum power point” (or peak voltage) on the power voltage curve, as shown below.
- MPPT algorithms are typically used in the controller designs for PV systems. The algorithms account for factors such as variable irradiance (sunlight) and temperature to ensure that the PV system generates maximum power at all times.

Peak power point operation

- The sun tracker drives the module mechanically to face the sun to collect the maximum solar radiation.
- However, that, in itself, does not guarantee the maximum power output from the module.
- The module must operate electrically at a certain voltage which corresponds to the peak power point under the given operating conditions.
- First we examine the electrical principle of the peak power operation

Peak power point operation

- If the array is operating at voltage V and current I on the i-v curve, the power generation is P = V · I watts.
- If the operation moves away from the above point, such that the current is now I +ΔI, and the voltage is V +ΔV,

  the new power is as follows

$$P + \Delta P = (V + \Delta V)\cdot(I + \Delta I)$$

Which, after ignoring a small term, simplifies to the following

$$\Delta P = \Delta V\cdot I + \Delta I \cdot V$$

- The ΔP should be zero at peak power point, which necessarily lies on a locally flat neighborhood.
- Therefore, at peak power point, the above expression in the limit becomes as follows
- $\frac{dV}{dI} = \frac{V}{I}$

Peak power point operation

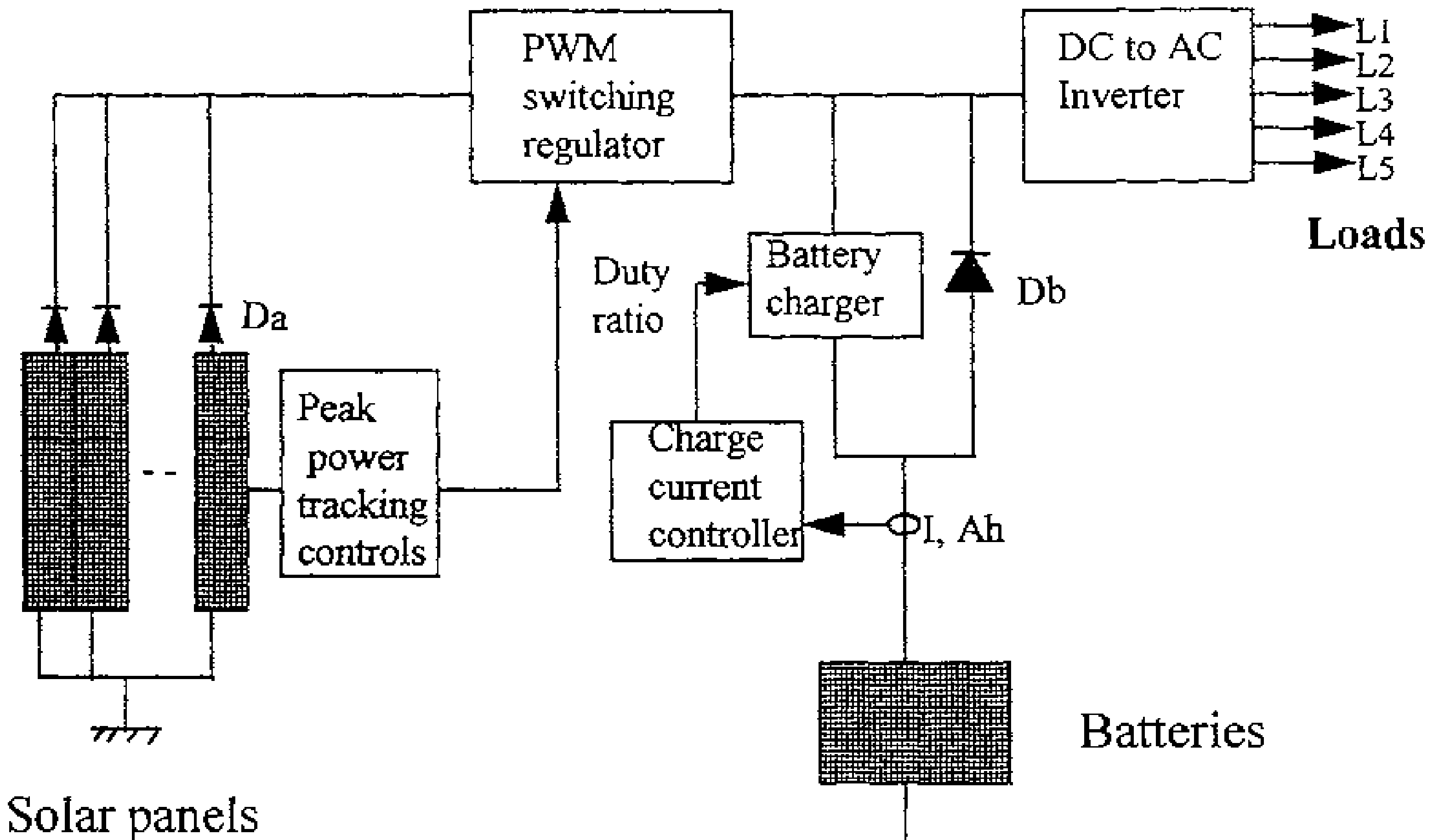
- We take note here that dV/dI is the dynamic impedance of the source, and V/I is the static impedance.
- There are three electrical methods of extracting the peak power from the module, as described below

1. In the first method, a small signal current is periodically injected into the array bus, and the dynamic bus impedance (Zd = dV/dI) and the static bus impedance (Zs = V/I) are measured.
   – The operating voltage is then increased or decreased until Zd equals −Zs. At this point, the maximum power is extracted from the source.
2. In another method, the operating voltage is increased as long as dP/dV is positive. That is, the voltage is increased as long as we get more power. If dP/dV is sensed negative, the operating voltage is decreased. The voltage stays the same if dP/dV is near zero within a preset dead band.

3. The third method makes use of the fact that for most PV cells, the ratio of the voltage at the maximum power point to the open-circuit voltage (i.e., Vmp/Voc) is approximately constant, say K.
   - For example, for high quality crystalline silicon cells, K = 0.72. An unloaded cell is installed on the array and kept in the same environment as the power-producing cells, and its open-circuit voltage is continuously measured.
   - The operating voltage of the power producing array is then set at K*Voc, which will produce the maximum power.

- The array by itself does not constitute the pv power system.
- We must also have a structure to mount it, point to the sun, and the components that accept the DC power produced by the array and condition the power in the form that is usable by the load.
- If the load is AC, the system needs an inverter to convert the DC power into AC, generally at 50 or 60 Hz

Peak power tracking photovoltaic power system



Peak power tracking photovoltaic power system

- The peak power tracker senses the voltage and current outputs of the array and continuously adjusts the operating point to extract the maximum power under the given climatic conditions.
- The output of the array goes to the inverter, which converts the 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. If excess power is still available after fully charging the battery, it is shunted in dump heaters, which may be space or room heaters in a stand-alone system.

Peak power tracking photovoltaic power system

- When the sun is not available, the battery discharges to the inverter to power the loads.
- The battery discharge diode Db is to prevent the battery from being charged when the charger is opened after a full charge or for other reasons.
- The array diode Da is to isolate the array from the battery, thus keeping the array from acting as load on the battery at night.
- The mode controller collects the system signals, such as the array and the battery currents and voltages, keeps track of the battery state of charge by bookkeeping the charge/discharge ampere-hours, and commands the charger, discharge converter, and dump heaters on or off as needed.
- The mode controller is the central controller for the entire system.

Peak power tracking photovoltaic power system

- In the grid-connected system, dump heaters are not required, as all excess power is fed to the grid lines.
- The battery is also eliminated, except for small critical loads, such as the start up controls and the computers.
- The DC power is first converted into AC by the inverter, ripples are filtered and then only the filtered power is fed into the grid lines

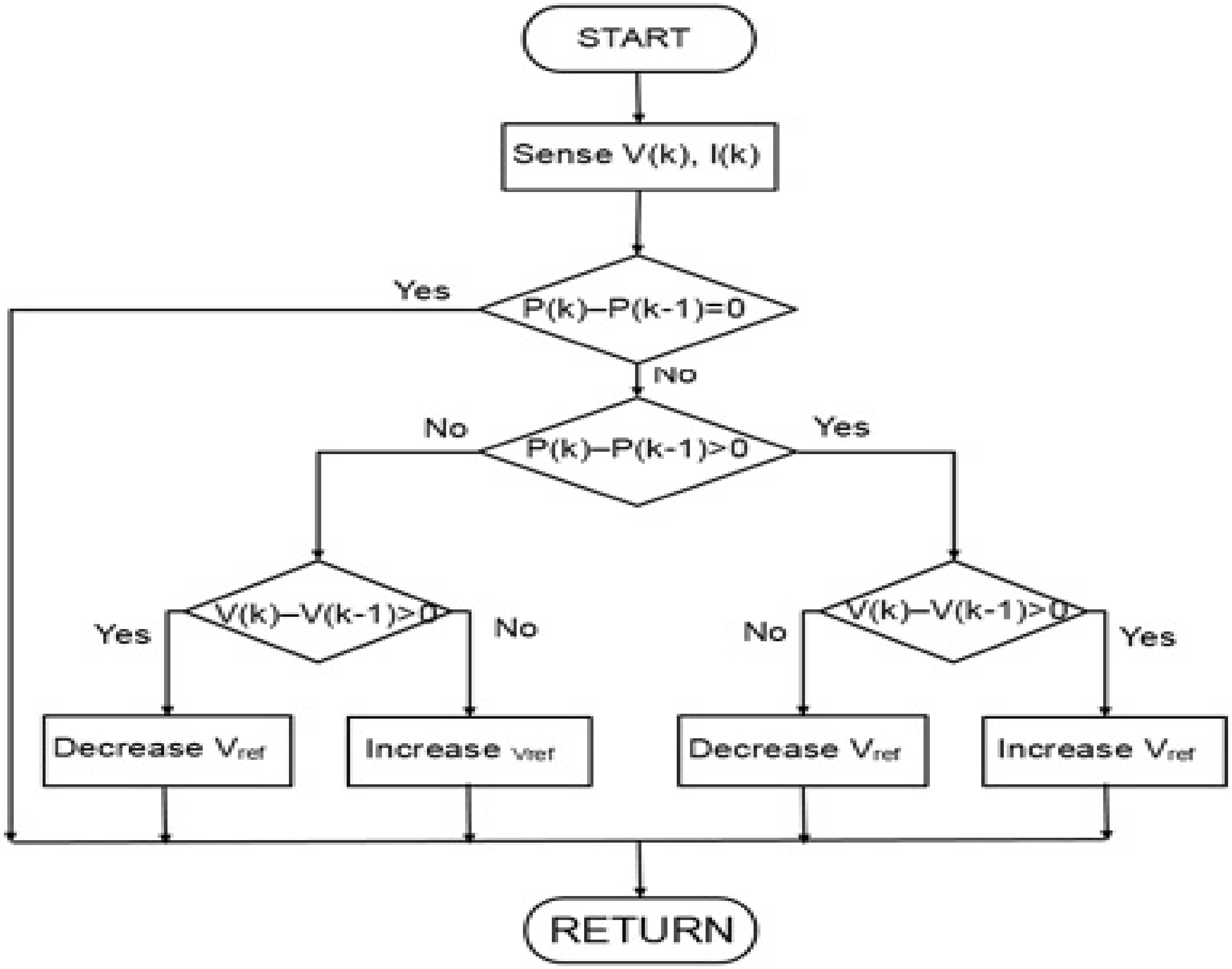
Peak power tracking photovoltaic power system

- For pv applications, the inverter is a critical component, which converts the array DC power into AC for supplying the loads or interfacing with the grid.
- A new product recently being introduced into the market is the AC-pv modules, which integrates an inverter directly in the module, and is presently available in a few hundred watts capacity.
- It provides utility grade 60 Hz power directly from the module junction box.
- This greatly simplifies the pv system design.

Peak power tracking photovoltaic power system

- **The three most common MPPT algorithms are**
- **Perturbation and observation (P&O):**
- This algorithm perturbs the operating voltage to ensure maximum power. While there are several advanced and more optimized variants of this algorithm, a basic P&O MPPT algorithm is shown below

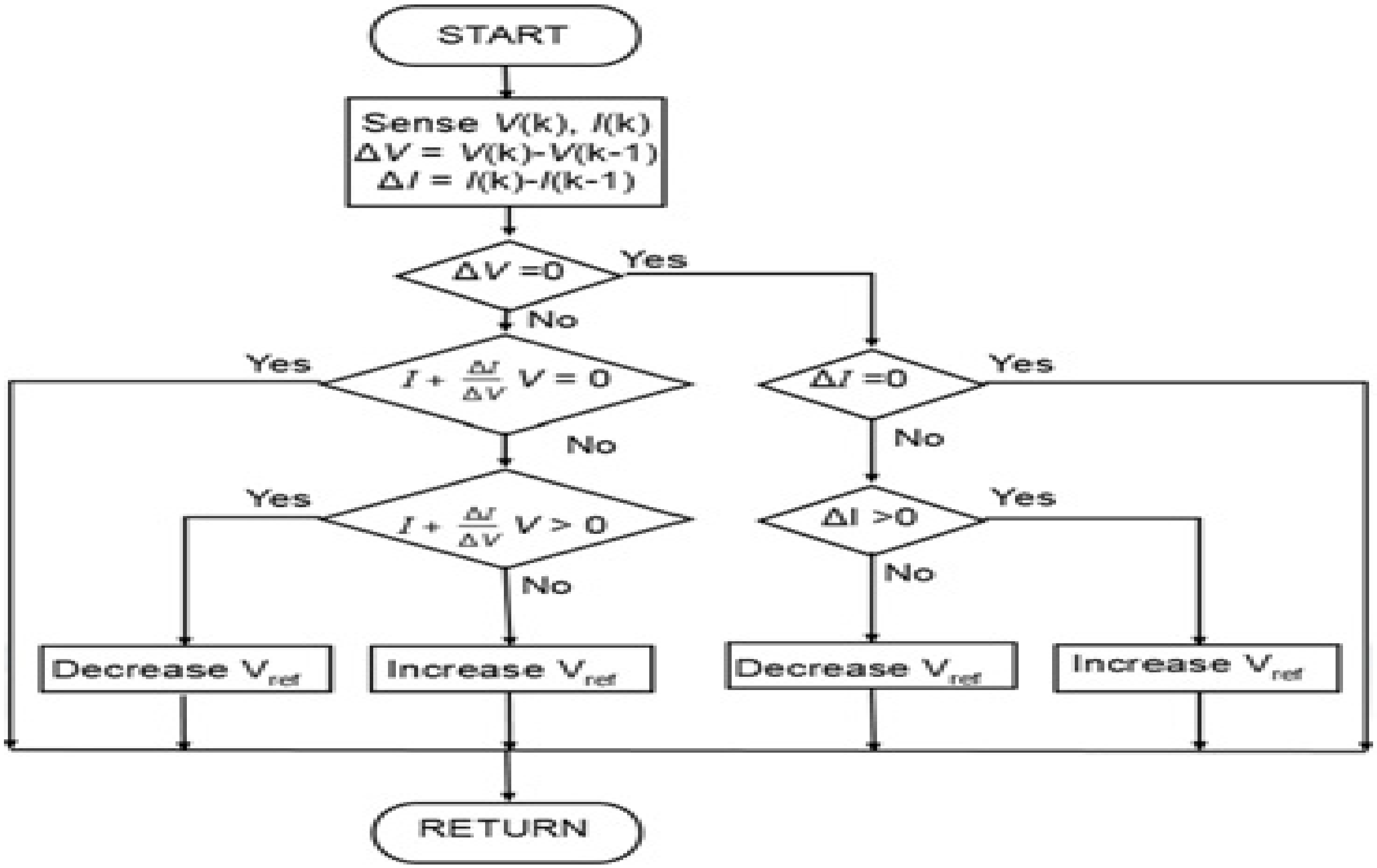
Perturbation and observation (P&O)



Incremental conductance

- This algorithm, shown below, compares the incremental conductance to the instantaneous conductance in a PV system. Depending on the result, it increases or decreases the voltage until the maximum power point (MPP) is reached. Unlike with the P&O algorithm, the voltage remains constant once MPP is reached.

Incremental conductance

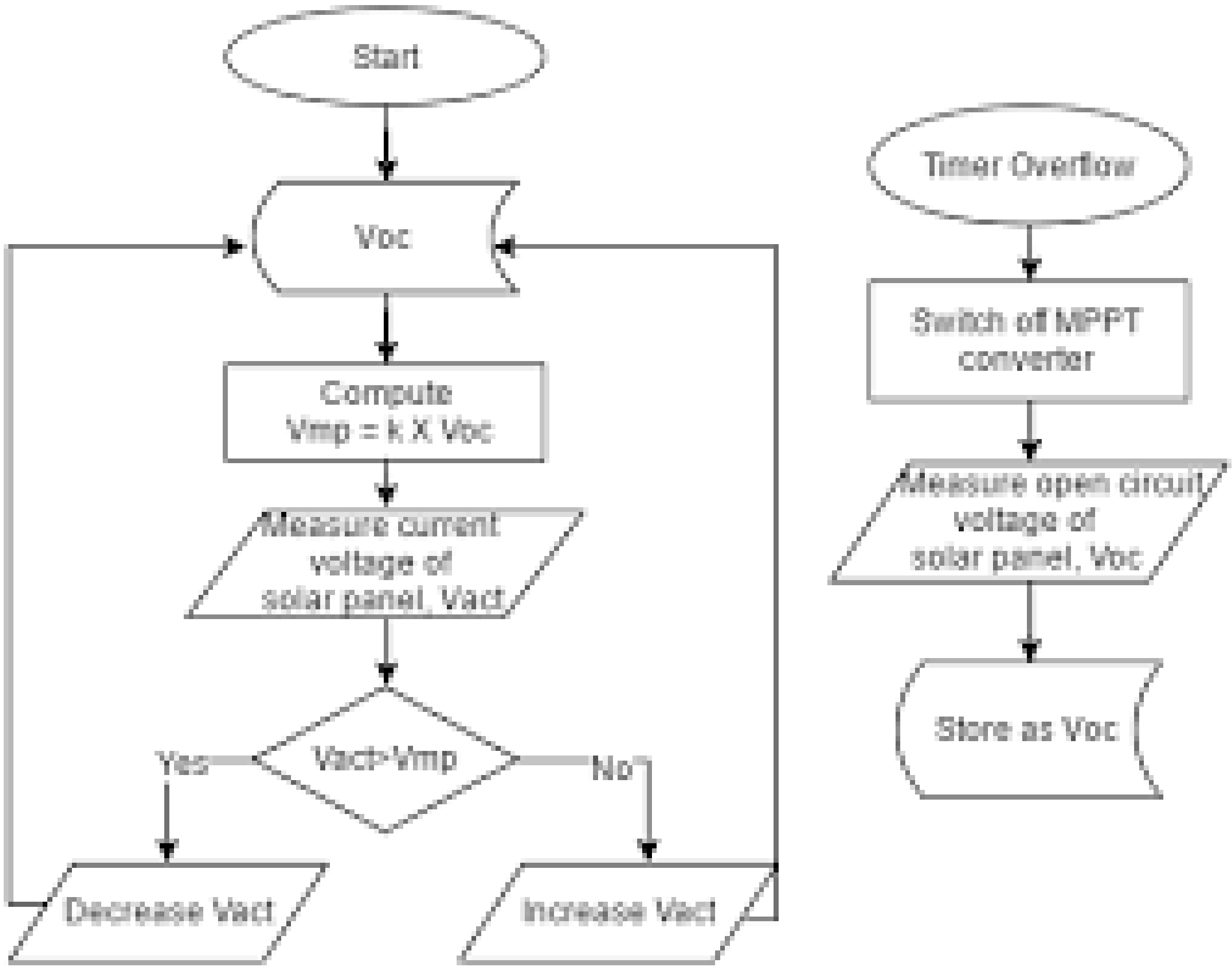


Incremental conductance algorithm.

Fractional open-circuit voltage

- This algorithm is based on the principle that the maximum power point voltage is always a constant fraction of the open circuit voltage.
- The open circuit voltage of the cells in the photovoltaic array is measured and used as in input to the controller.
- MATLAB® and Simulink® can be used as platforms to implement these algorithms

Fractional open-circuit voltage



AC Power conditioners

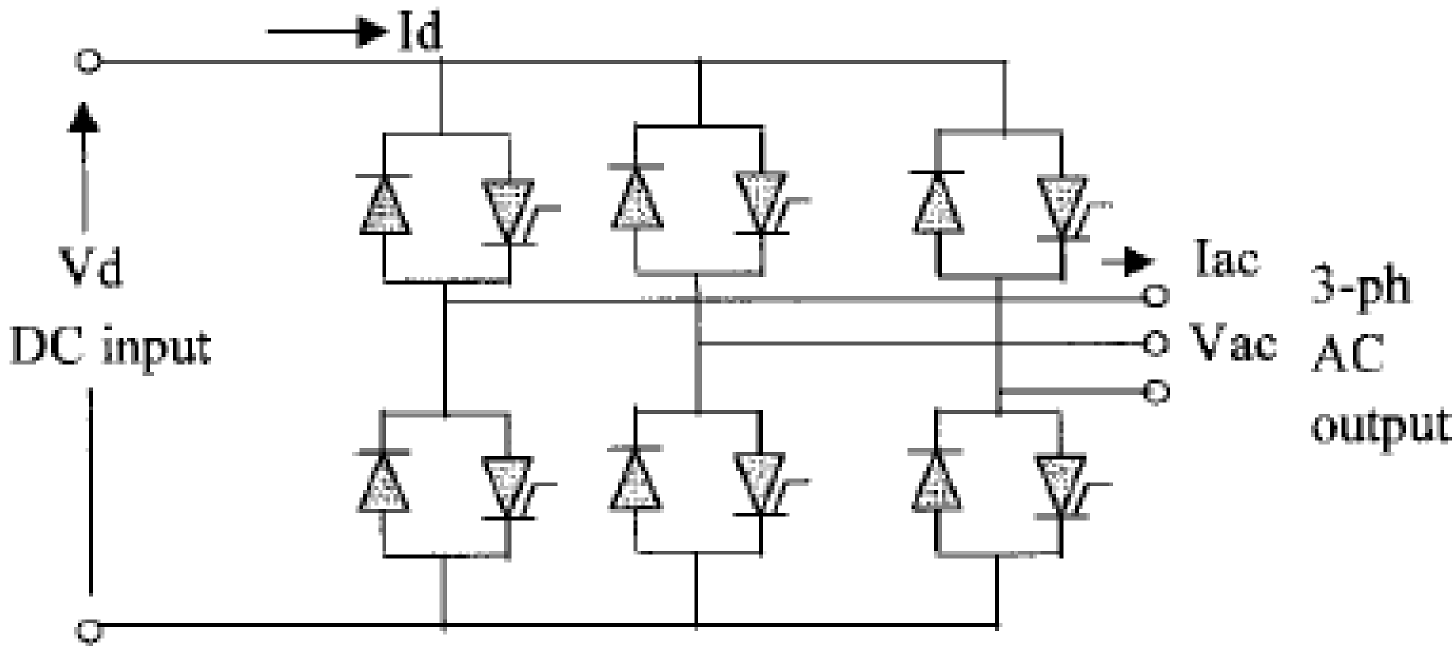
- A power conditioner (also known as a line conditioner or power line conditioner) is a device intended to improve the quality of the power that is delivered to electrical load equipment.
- The term most often refers to a device that acts in one or more ways to deliver a voltage of the proper level and characteristics to enable load equipment to function properly.
- In some uses, power conditioner refers to a voltage regulator with at least one other function to improve power quality (e.g. power factor correction, noise suppression, transient impulse protection, etc.)
- An AC power conditioner is the typical power conditioner that provides "clean" AC power to sensitive electrical equipment. Usually this is used for home or office applications and has up to 10 or more receptacles or outlets and commonly provides surge protection as well as noise filtering.

- Conditioners specifically work to smooth the sinusoidal A.C. wave form and maintain a constant voltage over varying loads.
- "Power Conditioning" is the ability to filter the AC line signal provided by the power company.
- "Power Regulation" is the ability to take a signal from the local power company, turn it into a DC signal that will run an oscillator, which generates a single frequency sine wave, determined by the local area needs, is fed to the input stage of power amplifier, and is then output as specified as the ideal voltage present at any standard wall outlet.

Inverters

- The power electronic circuit used to convert DC into AC is known as the inverter.
- The term “converter” is often used to mean either the rectifier or the inverter.
- The DC input to the inverter can be from any of the following sources:
- rectified DC output of the variable speed wind power system.
- DC output of the photovoltaic power modules.
- DC output of the battery used in the wind or photovoltaic power system.

Inverters



Inverters

- The DC source current is switched successively in a 60 Hz three-phase time sequence such as to power the three-phase load.
- The AC current contains significant harmonics
- The fundamental frequency (60 or 50 Hz) phase-to-neutral voltage is as follows

$$V_{ph} = \frac{2\sqrt{2}}{\pi} \cos\left(\frac{\pi}{6}\right) \cdot V_{DC}$$

Inverters

- The line-commutated inverter must be connected to the AC system into which they feed power.
- The design method is matured and has been extensively used in the high-voltage DC transmission line inverters.
- Such inverters are simple and inexpensive and can be designed in any size.
- The disadvantage is that they act as a sink of reactive power and generate high content of harmonics

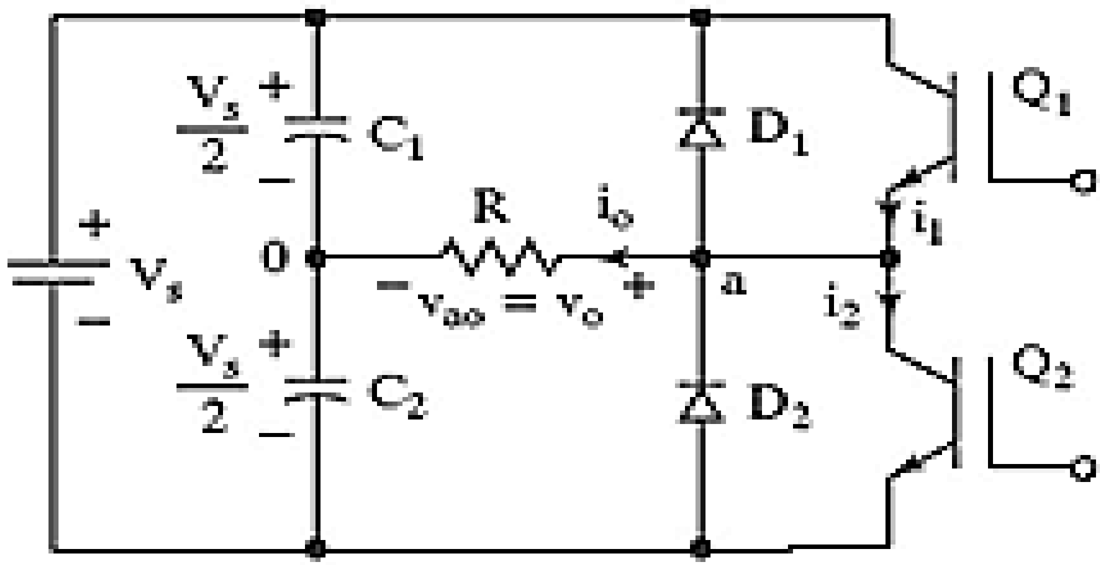
Inverters

- Poor power factor and high harmonic content in line commutated inverters significantly degrade the quality of power at the utility interface.
- This problem has been recently addressed by a series of design changes in the inverters.
- Among them is the 12-pulse inverter circuit and increased harmonic filtering.
- These new design features have resulted in today's inverters operating at near unity power factor and less than 3 to 5 percent total harmonic distortion.
- The quality of power at the utility interface at many modern wind power plants exceeds that of the grid they interface

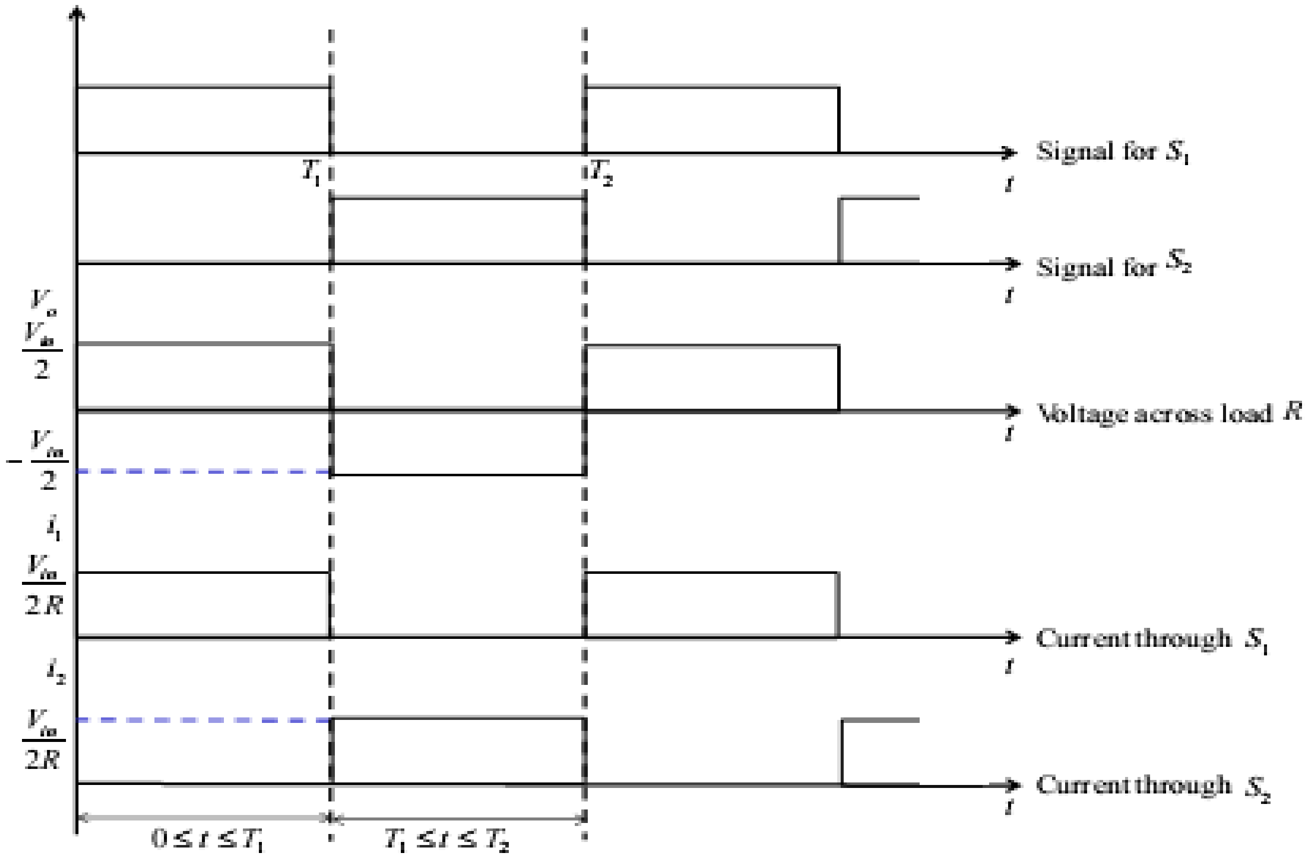
Inverters

- The force-commutated inverter does not have to be supplying load and can be free-running as an independent voltage source.
- The design is relatively complex and expensive.
- The advantage is that they can be a source of reactive power and the harmonics content is low

Single phase Half Bridge DC-AC inverter



Single phase Half Bridge DC-AC inverter with R load



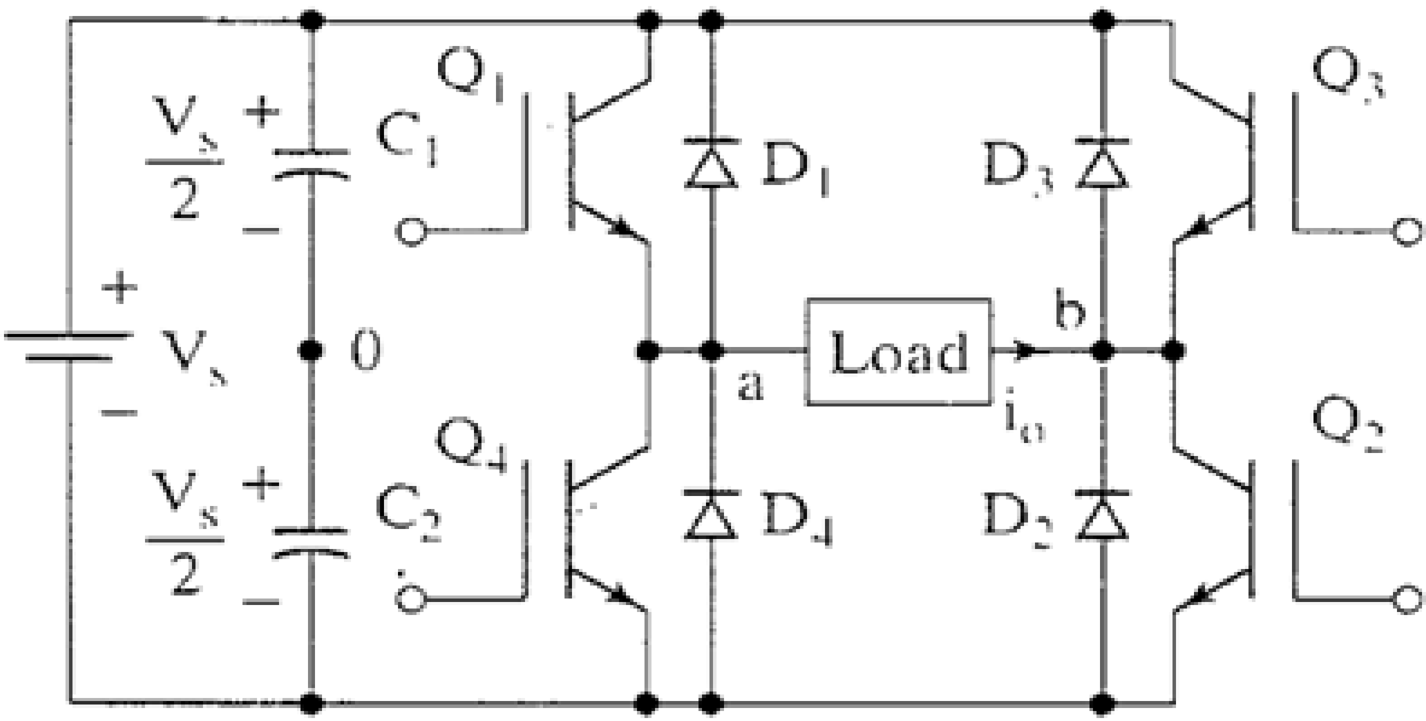
Single phase Half Bridge DC-AC inverter output waveforms

Operation of single phase full bridge inverter

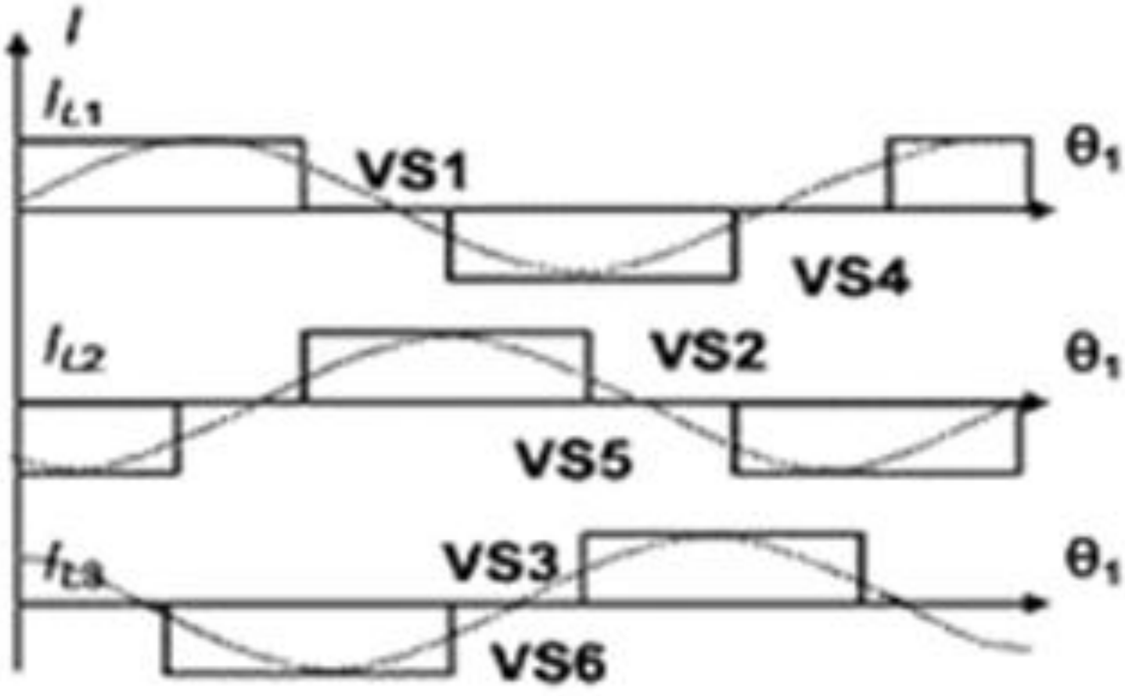
- A single phase bridge DC-AC inverter is shown in Figure below. The analysis of the single phase DC-AC inverters is done taking into account following assumptions and conventions.

  1) The current entering node a in Figure 8 is considered to be positive.

  2) The switches S1, S2, S3 and S4 are unidirectional, i.e. they conduct current in one direction.



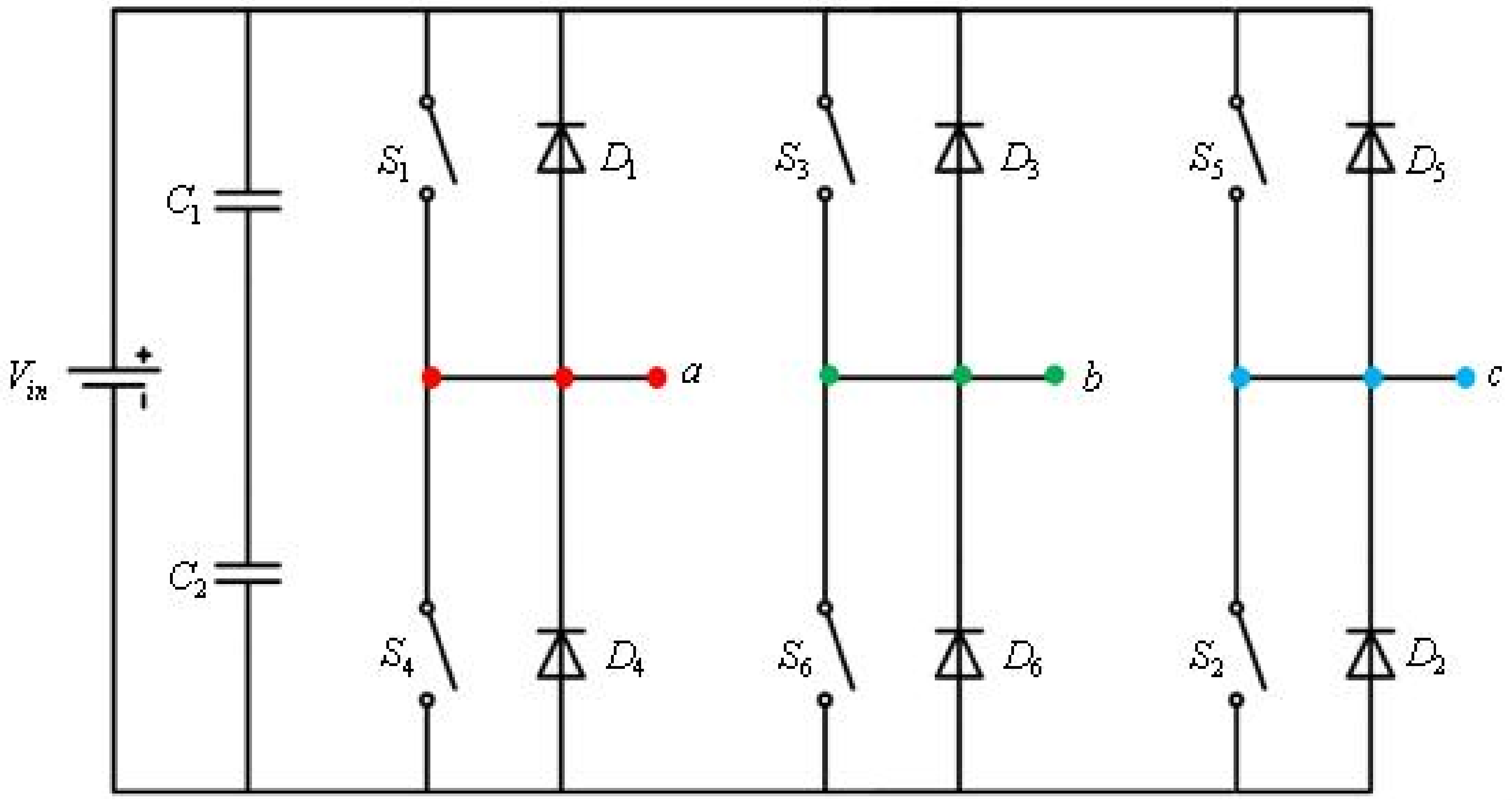
Single phase Full Bridge DC-AC inverter with R load



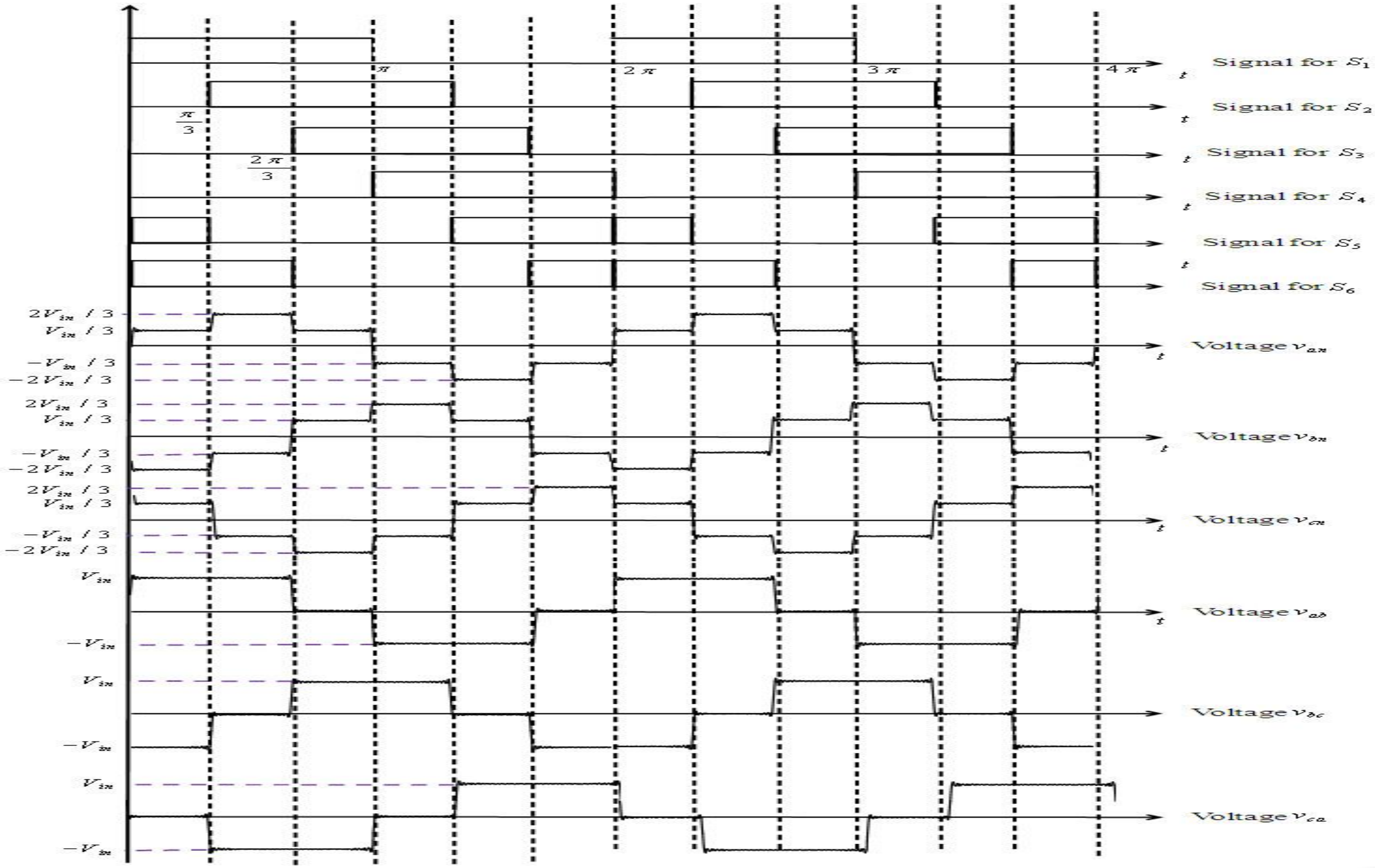
Single phase Full Bridge DC-AC inverter waveforms

Three Phase DC-AC Converters

- Three phase inverters are normally used for high power applications. The advantages of a three phase inverter are:
- The frequency of the output voltage waveform depends on the switching rate of the swtiches and hence can be varied over a wide range.
- The direction of rotation of the motor can be reversed by changing the output phase sequence of the inverter.
- The ac output voltage can be controlled by varying the dc link voltage.



Circuit diagram of three phase bridge inverter



Line and phase voltages of three phase bridge inverter

$$v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin(n\omega t)$$

$$v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t-\frac{2n\pi}{3}\right)$$

$$v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t-\frac{4n\pi}{3}\right)$$

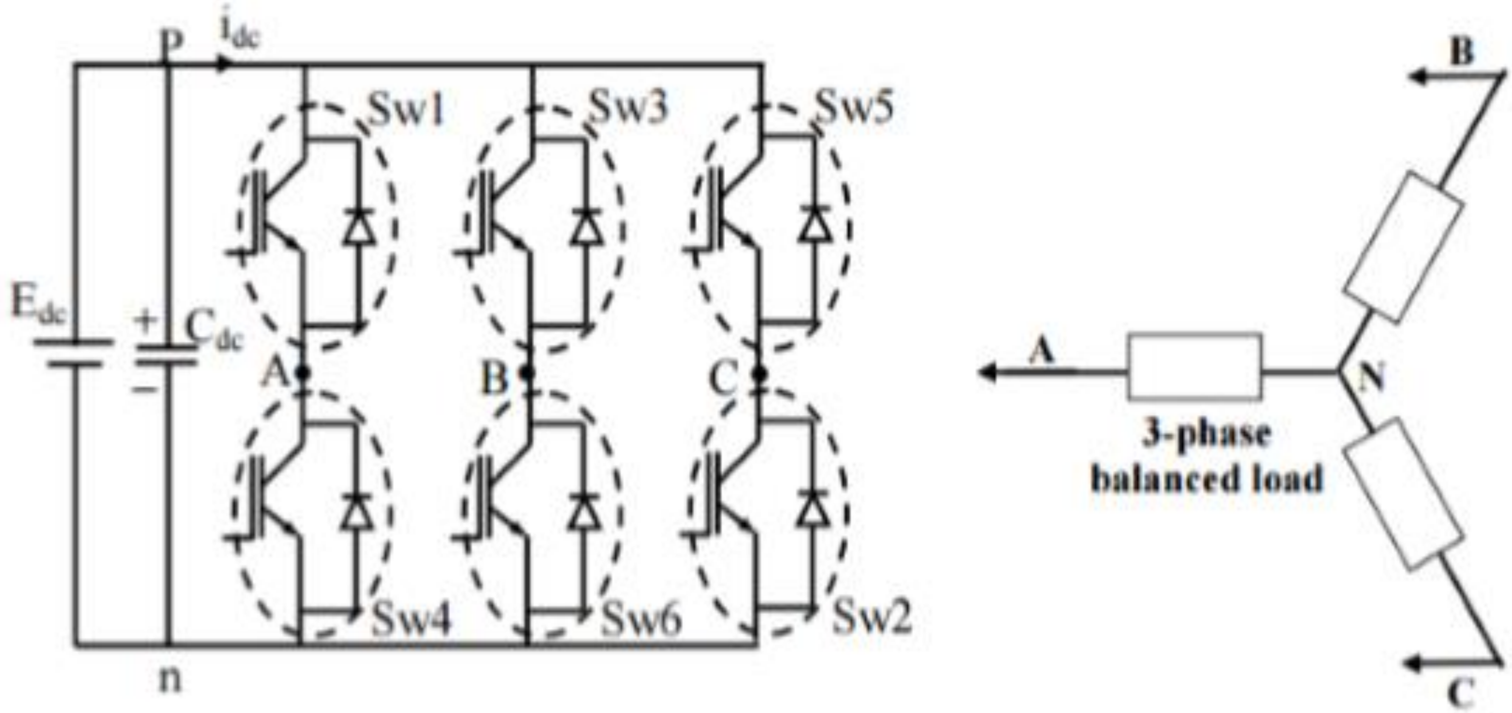
$$v_{ab} = v_{an} - v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t+\frac{n\pi}{6}\right)$$

$$v_{bc} = v_{bn} - v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t-\frac{n\pi}{2}\right)$$

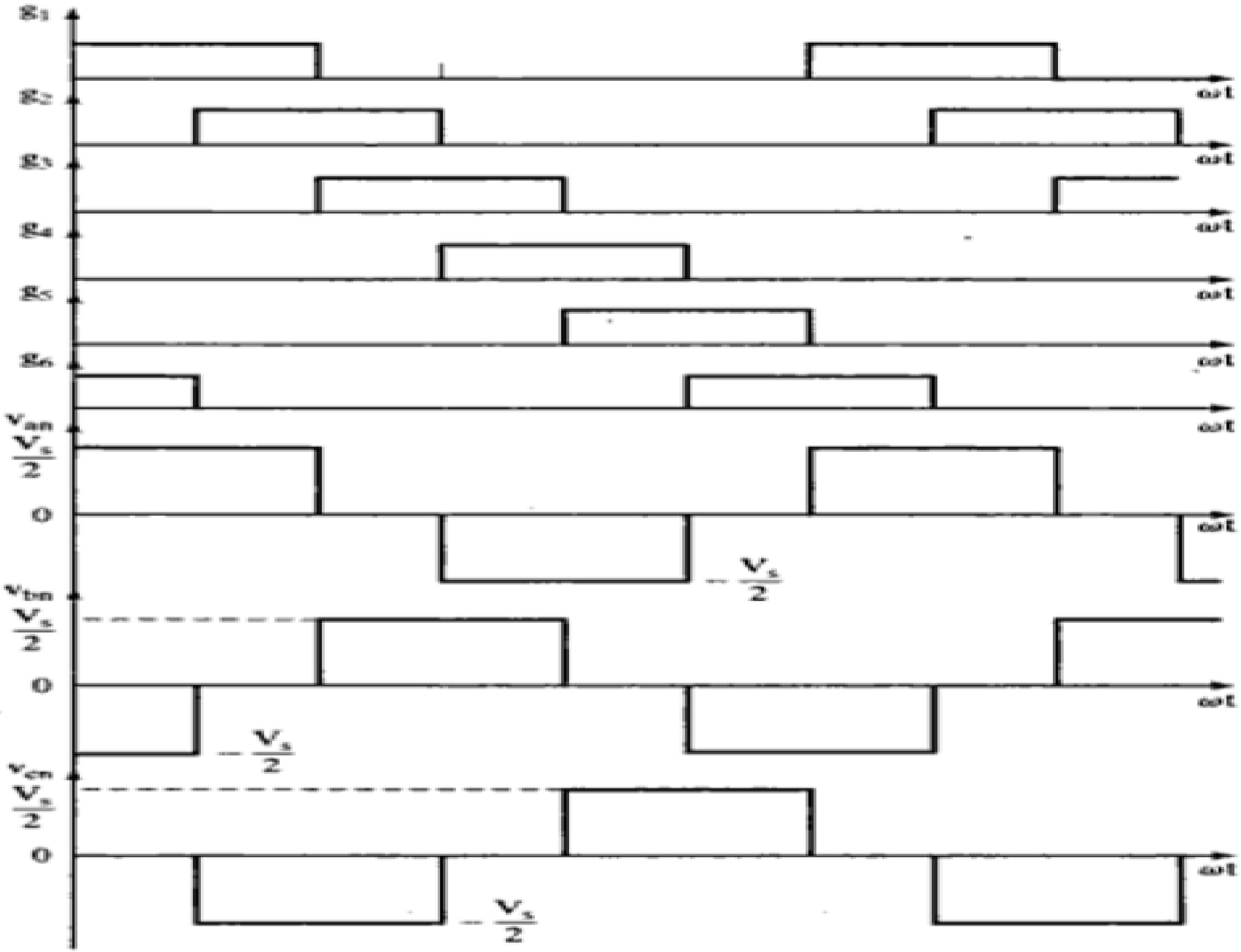
$$v_{ca} = v_{cn} - v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t-\frac{7n\pi}{6}\right)$$

Three Phase DC-AC Converters with 120 degree conduction mode

- In this mode of conduction, each electronic device is in a conduction state for 120°. It is most suitable for a delta connection in a load because it results in a six-step type of waveform across any of its phases. Therefore, at any instant only two devices are conducting because each device conducts at only 120°.
- The terminal A on the load is connected to the positive end while the terminal B is connected to the negative end of the source. The terminal C on the load is in a condition called floating state. Furthermore, the phase voltages are equal to the load voltages as shown below.
- Phase voltages = Line voltages
- $V_{AB} = V$
- $V_{BC} = -V/2$
- $V_{CA} = -V/2$



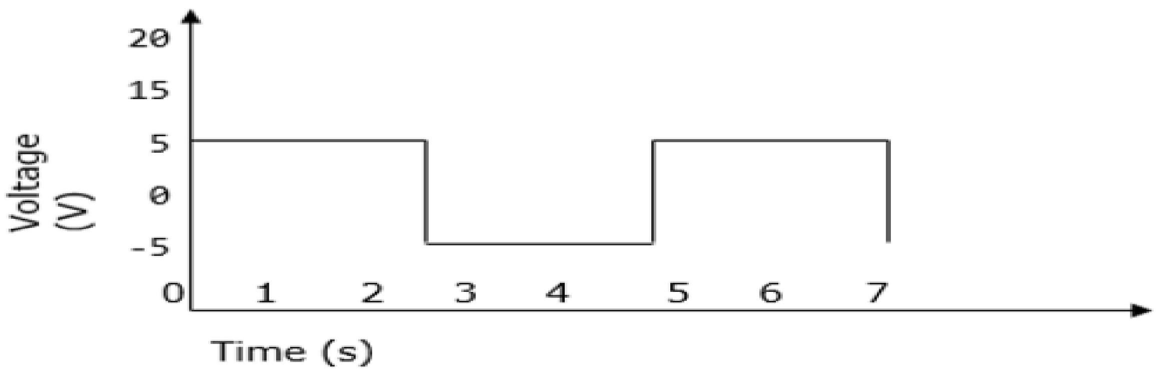
Circuit diagram of three phase bridge inverter



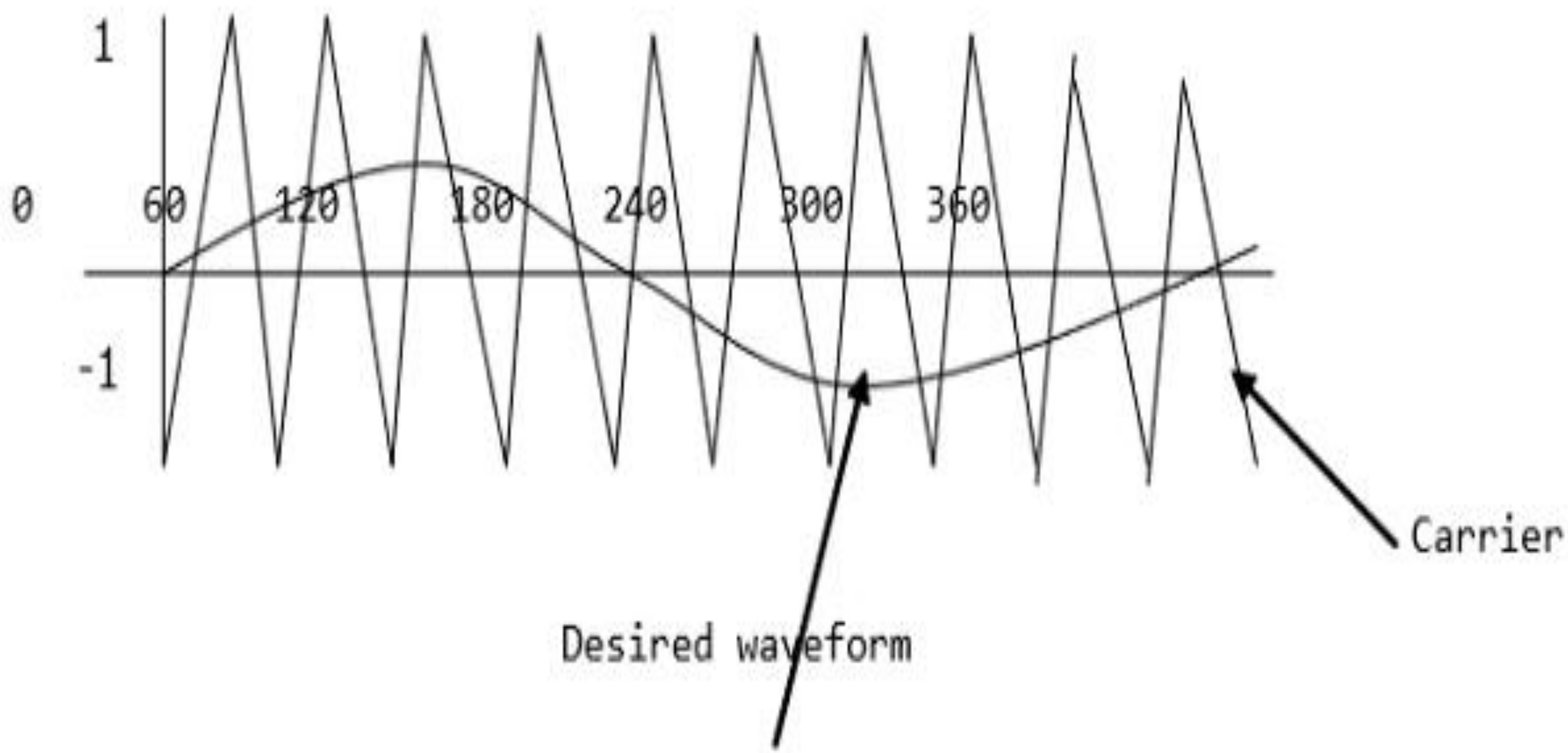
Line and phase voltages of three phase bridge inverter

Pulse width modulation techniques

- PWM is a technique that is used to reduce the overall harmonic distortion (THD) in a load current. It uses a pulse wave in rectangular/square form that results in a variable average waveform value f(t), after its pulse width has been modulated. The time period for modulation is given by T.



Sinusoidal Pulse Width Modulation



Pulse width modulation

- The usage of Passive filters, Active filter and Pulse Width Modulation (PWM), for reducing harmonics in grid systems.
- Stating the challenges of passive filters has being bulky as well as the introduction of resonances into the system while active filters provide a solution to these problems and gives improved efficiency.
- The researchers state that the most common methods for recent times have been the PWM method, which employs a voltage source inverter.
- The improvement in the decoupling techniques, led to the instantaneous real and reactive current technique (id-iq) that is used mostly and gives wonderful outcome when used with a proportional integral controller, which was used for several grid situations integrating, with hybrid renewable energy sources.

Synchronization Between Solar Panel & AC Grid

- A solar panel (also solar module, photovoltaic module or photovoltaic panel) is a packaged, connected assembly of photovoltaic cells. The solar panel can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications.
- Each panel is rated by its DC output power under standard test conditions, and typically ranges from 100 to 320 watts.

Synchronization Between Solar Panel & AC Grid

- Solar panels use light energy (photons) from the sun to generate electricity through the photovoltaic effect.
- The majority of modules use wafer-based crystalline silicon cells or thin-film cells based on cadmium telluride or silicon. The structural (load carrying) member of a module can either be the top layer or the back layer. Cells must also be protected from mechanical damage and moisture. Most solar panels are rigid, but semi-flexible ones are available, based on thin-film cells.

- Labview is a highly productive development environment for creating custom applications that interact with real-world data or signals in fields such as science and engineering. Labview itself is a software development environment that contains numerous components, several of which are required for any type of test, measurement, or control application.
- Each component is designed in some way to save you time or otherwise make you more productive by eliminating unnecessary details or making difficult operations easier.

- Labview programs are called virtual instruments, or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes and multimeters. In Labview, we build a user interface, or front panel, with controls and indicators. Controls are knobs, push buttons, dials, and other input mechanisms. Indicators are graphs, LEDs, and other output displays.

- Data acquisition is the process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer.
- Data acquisition systems (abbreviated with the acronym DAS or DAQ) typically convert analog waveforms into digital values for processing.

- DAQ hardware is what usually interfaces between the signal and a PC.
- A DAQ card, or a data acquisitions card, is used to transfer data into a computer.
- This method allows for seamless transfer of input and output data through either digital or analog signals or channels. DAQ cards operate by utilizing both DAQ hardware and software.

Grid Interface Controls

- At the utility interface, the power flow direction and magnitude depend on the voltage magnitude and the phase relation of the site voltage with respect to the grid voltage.
- The grid voltage being fixed, the site voltage must be controlled both in magnitude and in phase in order to feed power to the grid when available, and to draw from the grid when needed.
- If the inverter is already included in the system for frequency conversion, the magnitude and phase control of the site voltage is done with the same inverter with no additional hardware cost

Grid Interface Controls

- **Voltage Control**

For interfacing with the utility grid lines, the renewable power system output voltage at the inverter terminals must be adjustable. The voltage is controlled by using one of the following two methods

1. By controlling the alternating voltage output of the inverter using tap-changing autotransformer at the inverter output. The tap changing is automatically obtained in a closed-loop control system.

If the transformer has a phase-changing winding also, a complete control on the magnitude and phase of the site voltage can be achieved.

The advantages of this scheme are that the site output voltage waveshape does not vary over a wide range, and high input power factor is achieved by using uncontrolled diode rectifiers for the DC link voltage. The added cost of the transformer, however, can be avoided by using the method discussed below

Grid Interface Controls

2. Since the magnitude of the alternating voltage output from the static inverter is proportional to the direct voltage input from the rectifier, the voltage control can be achieved by operating the inverter with the variable DC link voltage.

Such a system also maintains the same output voltage, frequency and wave shape over a wide range. However, in circuits deriving the load current from the commutating capacitor voltage from the DC link, the commutating capability decreases when the output voltage is reduced.

This could lead to an operational difficulty when the DC link voltage varies over a wide range, such as in motor drives controlling the speed in ratio exceeding four to one. In renewable power applications, such commutation difficulty is unlikely as the speed varies over a narrow range.

Grid Interface Controls

The variable DC link voltage is obtained two ways:

- one way is to connect a variable ratio transformer on the input side of the rectifier. The secondary tap changing is automatically obtained in a closed-loop control system.
- the other way is to use the phase-controlled rectifier in place of the uncontrolled rectifier. At reduced output voltage, this method gives poor power factor and high harmonic content, and requires filtering the DC voltage before feeding to the inverter

Grid Interface Controls

Frequency Control

- The output frequency of the inverter solely depends on the rate at which the switching thyristors or transistors are triggered into conduction.
- The triggering rate is determined by the reference oscillator producing a continuous train of timing pulses, which are directed by logic circuits to the thyristor gating circuits.
- The timing pulse train is also used to control the turnoff circuits.
- The frequency stability and accuracy requirements of the inverter dictate the selection of the reference oscillator.

Grid Interface Controls

- A simple temperature compensated R-C relaxation oscillator gives the frequency stability within 0.02 percent.
- When better stability is needed, a crystal-controlled oscillator and digital counters may be used, which can provide stability of .001 percent or better.
- The frequency control in a stand-alone power system is an open loop system.
- The steady state or transient load changes do not affect the frequency.
- This is one of the major advantages of the power electronics inverter over the old electromechanical means of frequency controls.

Harmonic Elimination Techniques

Filters

- The conventional method of reducing harmonics in power systems is the use ofpassive filters, active filters, filters in shunt orientation and even hybrid filter.
- Several research efficient method for reducing harmonic content in both the current and voltage.
- This harmonic reduction technique according to the researchers, is cheaper ers have reported the use of a filter as the best means of harmonic mitigation in power systems.

Harmonic Elimination Techniques

- An efficient method for reducing harmonic content in both the current and voltage.
- This harmonic reduction technique according to the researchers, is cheaper compared to the use of active filter and easy to implement.
- The most used passive filter in harmonic mitigation is that which consist of tuned series inductive-capacitive (LC) circuit.

- Some proposes the use of active filters in two different topologies (in series and shunt active) to mitigate the challenges caused by matrix converters of power system pollution.
- A method using a synchronous reference frame for controlling a three-phase hybrid active and passive filters was proposed for reducing harmonics in a power system.
- This method achieved improved mitigation of current source harmonics, as the active and passive filters complimented each other's effectiveness.

Selective elimination pulse width modulation

- The recent improvement in power system, with fast switching IGBTs, make semiconductor device less attractive in inverter configurations such as inverters connected in series, inverters connected in parallel, multilevel reactive power compensator, multiple rectifiers, neutral point clamp and optimization inverters.

- First, is the Selective Harmonics Elimination Pulse Width Modulation (SHEPWM) technique that implements phase-shift harmonic suppression, while the second method utilizes mirror harmonic reduction techniques.

MODULE-IV
WIND ENERGY CONVERSION SYSTEMS

MODULE IV - SYLLABUS

Wind energy Conversion system (WECS): Performance of Induction generators for WECS, Self-excited induction generator (SEIG) for isolated power generators. Controllable DC power from SEIGs, system performance, Grid related problems, generator control, AC voltage controllers, Harmonic reduction and Power factor improvement.

COURSE OUTCOMES MAPPED WITH MODULE IV

CO	Course Outcomes	Blooms Taxonomy
CO 1	**Recall** the power conversions involved in windmills/ PV Systems for production of electricity.	Remember
CO 3	**Summarize** the control schemes, environmental aspects and classification of wind energy conversion systems for reliable operation.	Understand
CO 8	**Make use of** AC voltage controllers for power factor improvement and harmonic reduction in Isolated induction generators	Apply

PROGRAM OUTCOMES MAPPED WITH MODULE IV

PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
PO 3	**Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

MAPPING OF COs AND POS FOR MODULE IV

COs	PROGRAM OUTCOMES											
	1	2	3	4	5	6	7	8	9	10	11	12
CO1	√											
CO3	√	√										
CO8	√		√									

Induction Generator as a Wind Power Generator

- Rotating electrical machines are commonly used in wind energy systems and most of these electrical machines can function as either a motor or a generator, depending upon its particular application.

- There is also another more popular type of 3-phase rotational machine that we can use as a wind turbine generator called an Induction Generator.

- Both the synchronous generator and the Induction Generator have similar fixed stator winding arrangement which, when energised by a rotating magnetic field, produces a three-phase (or single phase) voltage output.

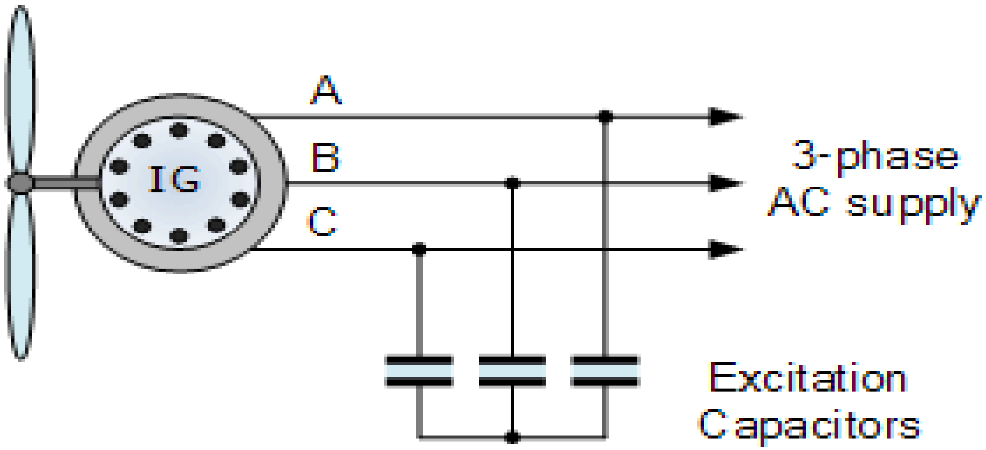
Single Phase Induction Generator

- Induction Generator construction is based on the very common squirrel-cage induction motor type machine as they are cheap, reliable, and readily available in a wide range of electrical sizes from fractional horse power machines to multi-megawatt capacities making them ideal for use in both domestic and commercial renewable energy wind power applications.

- Unlike the previous synchronous generator which has to be “synchronised” with the electrical grid before it can generate power, the induction generator can be connected directly to the utility grid and driven by the turbines rotor blades at variable wind speeds

- For economy and reliability many wind power turbines use induction motors as generator which are driven through a mechanical gearbox to increase their speed of rotation, performance and efficiency.
- However, induction generators require reactive power usually provided by shunt capacitors in the individual wind turbines.
- Induction machines are also known as Asynchronous Machines, that is they rotate below synchronous speed when used as a motor, and above synchronous speed when used as a generator.
- So when rotated faster than its normal operating or no-load speed, an induction generator produces AC electricity.

Capacitor Start Induction Generator



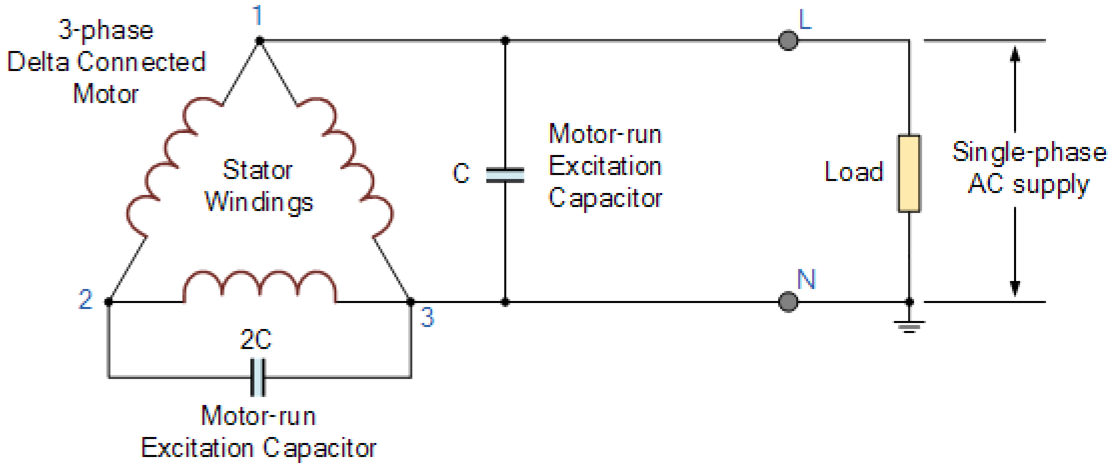
- The excitation capacitors are standard motor-starting capacitors that are used to provide the required reactive power for excitation which would otherwise be supplied by the utility grid.

- The induction generator will self-excite using these external capacitors only if the rotor has sufficient residual magnetism.

- In the self-excited mode, the generator output frequency and voltage are affected by the rotational speed, the turbine load, and the capacitance value in farads of the capacitors.

- Then in order for self-excitation of the generator to occur, there needs to be a minimum rotational speed for the value of capacitance used across the stator windings.

Single-phase Output from a 3-phase Induction Generator



- In the single-phase operation, it is possible to obtain near three phase efficiency producing approximately 80% of the machines maximum rating.
- However, care must be taken when converting a 3-phase supply into a single-phase supply as the single phase line-to-line voltage output will be twice that of the rated winding.
- Induction generators work well with single-phase or three-phase systems that are interconnected to the utility or as a self-excited stand alone generator for small scale wind power applications allowing for variable speed operation.
- However, induction generators require reactive excitation to operate at full power thus they are ideally suited for interconnection to the utility grid as part of an grid-tied wind power system.

Why wind is such a challenge for energy grids

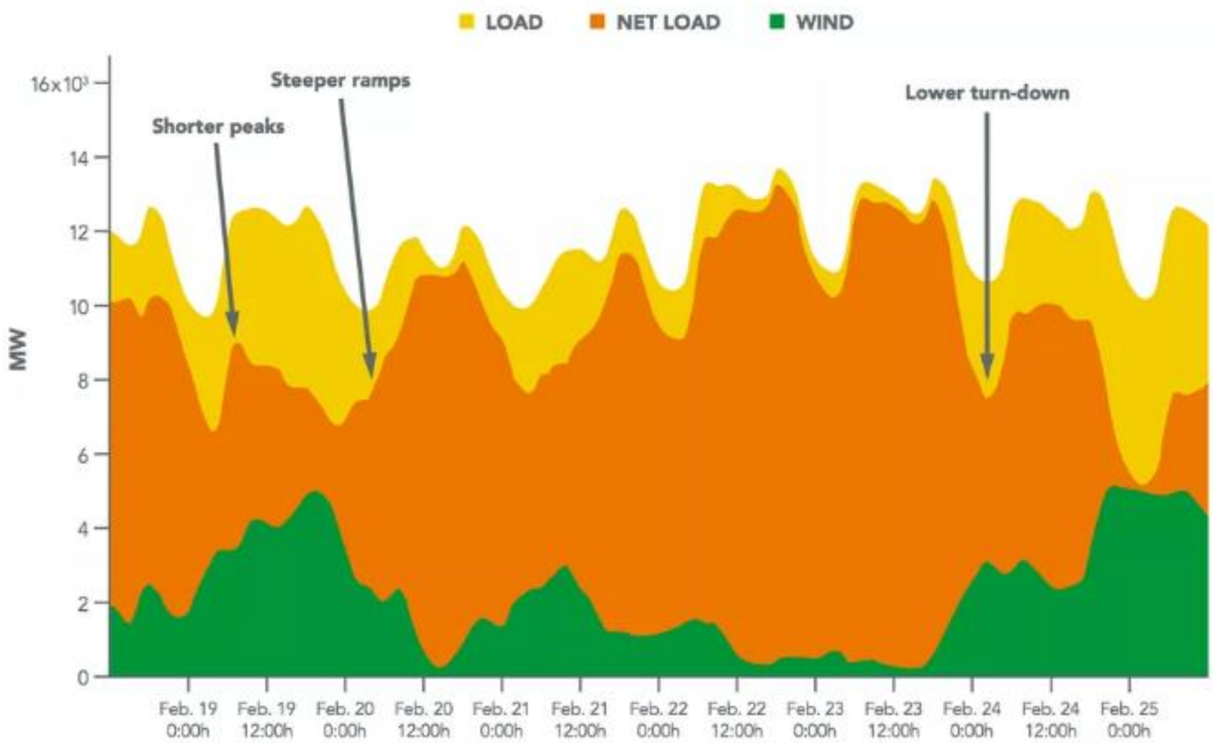
Variability:

- This is the biggest and most vexing.

- Power plants that run on fuel (along with some hydro and geothermal plants) can be ramped up and down on command. They are, in the jargon, "dispatchable.“

- But VRE plants produce power only when the wind is blowing or the sun is shining.

- Grid operators don't control VRE, they accommodate it, which requires some agility.



LOAD
NET LOAD
WIND
16x10³
14
12
10
8
6
4
2
0
MW
Shorter peaks
Steeper ramps
Lower turn-down
Feb. 19 0:00h
Feb. 19 12:00h
Feb. 20 0:00h
Feb. 20 12:00h
Feb. 21 0:00h
Feb. 21 12:00h
Feb. 22 0:00h
Feb. 22 12:00h
Feb. 23 0:00h
Feb. 23 12:00h
Feb. 24 0:00h
Feb. 24 12:00h
Feb. 25 0:00h

Uncertainty: The output of VRE plants cannot be predicted with perfect accuracy in day-ahead and day-of forecasts, so grid operators have to keep excess reserve running just in case.

Location-specificity: Sun and wind are stronger (and thus more economical) in some places than in others — and not always in places that have the necessary transmission infrastructure to get the power to where it's needed.

Nonsynchronous generation: Conventional generators provide voltage support and frequency control to the grid. VRE generators can too, potentially, but it's an additional capital investment.

Low capacity factor:

- VRE plants only run when sun or wind cooperates. According to the Energy Information Administration, in 2014 the average capacity factor — production relative to potential — for utility-scale solar PV was around 28 percent; for wind, 34 percent. (By way of comparison, the average capacity factor of US nuclear power was 92 percent; those plants are almost always producing power.)
- Because of the low capacity factor of VRE, conventional plants are needed to take up the slack, but because of the high output of VRE in peak hours, conventional plants sometimes don't get to run as often as needed to recover costs.

Solutions

Improved planning and coordination: This is the first step, making sure that VRE is matched up with appropriately flexible dispatch able plants and transmission access so that energy can be shared more fluidly within and between grid regions.

Flexible rules and markets: Most grids are physically capable of more flexibility than they exhibit. Changes to the rules and markets that govern how plants are scheduled and dispatched, how reliability is assured, and how customers are billed, says NREL, "can allow access to significant existing flexibility, often at lower economic costs than options requiring new sources of physical flexibility."Recent research from the Regulatory Assistance Project offers an overview of the changes needed in "market rules, market design, and market operations."

Flexible demand and storage:

- To some extent, demand can be managed like supply. "Demand response" programs aggregate customers willing to let their load be ramped up and down or shifted in time.
- The result is equivalent, from the grid operator's perspective, to dispatchable supply.
- There's a whole range of demand-management tools available and more coming online all the time. Similarly, energy storage, by absorbing excess VRE at times when it's cheap and sharing it when it's more valuable, can help even out VRE's variable supply.
- It can even make VRE dispatchable, within limits. (For example, some concentrated solar plants have molten-salt storage, which makes their power available 24 hours a day.)

Flexible conventional generation:

- Though older coal and nuclear plants are fairly inflexible, with extended shut-down, cool-off, and ramp-up times, lots of newer and retrofitted conventional plants are more nimble — and can be made more so by a combination of technology and improved practices.
- Grid planners can favor more flexible non-VRE options like natural gas and small-scale combined heat and power (CHP) plants. Cycling conventional plants up and down more often does come with a cost, but the cost is typically smaller than the fuel savings from increased VRE.

Flexible VRE:

New technology enables wind turbines to "provide the full spectrum of balancing services (synthetic inertial control, primary frequency control, and automatic generation control)," and both wind turbines and solar panels can now offer voltage control.

Interconnected transmission networks:

- This one's pretty simple. Wind and solar resources become less variable if aggregated across a broader region.

- The bigger the geographical area linked up by power lines, the more likely it is that the sun is shining or the wind is blowing somewhere within that area.

- Wind turbines are designed to yield Maximum output at a wind speed of 15M/S if the wind speed is more the excess energy is wasted.

- But the rotor is to be protected from damage .This done by power control mechanism.

The important method use in power control

Pitch Control :-

- The power output of the turbine is constantly checked by an electronic measuring unit.
- When the power output become to high, it a actuate the blade pitch mechanism Which turns the rotor blades out of the wind this reduce the power output.
- When the wind velocity reduce and the power output falls, the blade is turned back to the original position &the power again increases.

Passive Stall control :

- In this control blade fixed at a fixed angle. When the wind speed increases, it creates turbulence on the side opposite to the facing wind reduce the angle of attack.
- This will reduce the lift force developed & hence reduce the power output. It is much sampler method than the pitch control method but it less accurate.

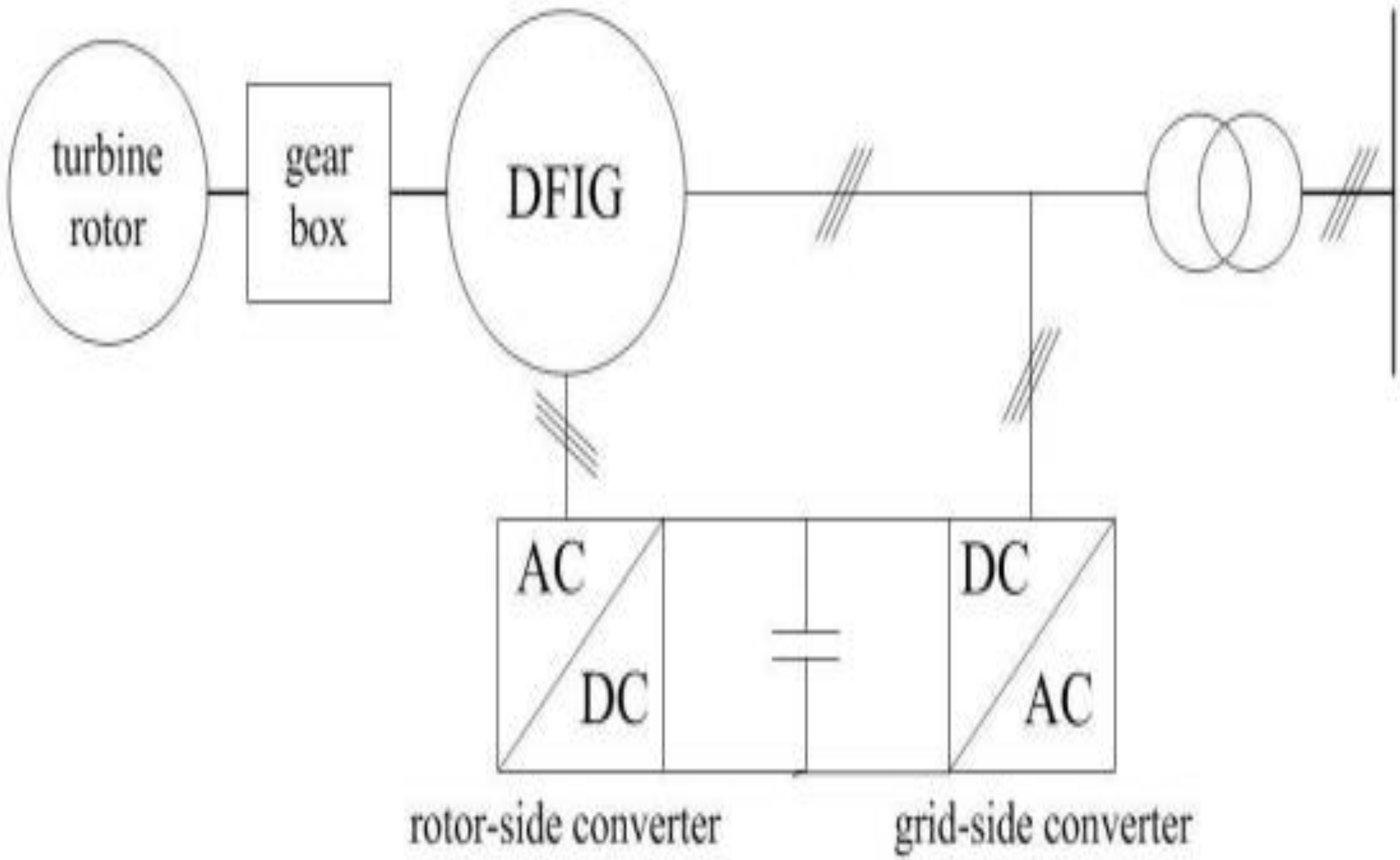
Harmonics in a Wind Power Plant

- The number of wind power plants (WPP) increases world widely and the nominal power of an average wind power plant increases.
- In many countries wind power has already taken an important part in the electrical energy production mix.
- Due to the importance of wind power, manufacturers and transmission system operators (TSO)cannot ignore the effects of wind power plants on the power quality and power system stability.
- Wind power plants introduce a great number of non-linear power electronic devices like full scale frequency converters into the grid.
- A large number of non-linear power electronic devices can have significant effect on the harmonic emissions.
- These harmonics can form a serious threat for power quality . That is why harmonic analysis has to be developed and taken as an integrated part of wind power plant design.

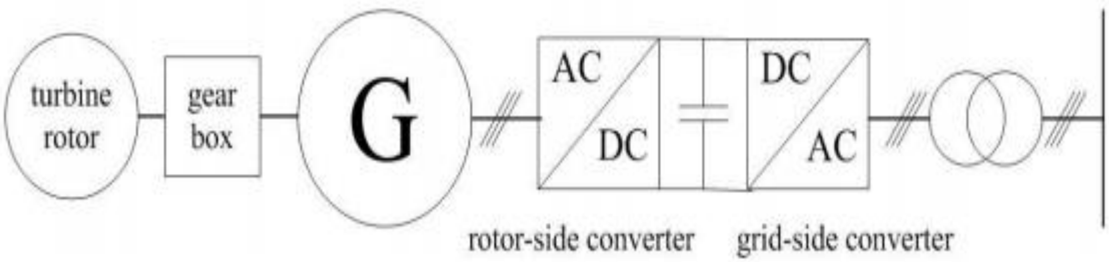
- Emission of harmonics is not the only problem. Another problem occurs when the frequency of a harmonic current coincides with a resonance frequency.
- Optimal circumstances for a devastating resonance occur if some of the harmonics (or inter harmonics) coincides with the network resonance frequency.
- Harmonics have many kinds of adverse effects in a power network.
- The major part of the components used in power networks is mainly designed for the fundamental frequency.
- Many times, the components operate in conditions that do not form an optimal operating environment, which can have adverse effects on the components. Harmonic emissions are a commonly recognised problem in wind power plants

Power Converters in Wind Turbines

- Nowadays new wind turbines are variable speed wind turbines that are connected either partly or totally to the internal medium voltage network of a wind power plant through a power electronic converter.
- In the both types, the power converter actually has two parts, the rotor side converter and the grid side converter that are jointed together by parallel capacitance.
- This kind of converter is called back-to-back Converter. Now, two most common types of wind turbines are presented.
- The first one is called doubly fed induction generator (DFIG).


turbine rotor
gear box
DFIG
AC
DC
DC
AC
rotor-side converter
grid-side converter

- Double fed induction generator (DFIG) with a rotor, a gear box and a converter. The generator is connected to three phase AC grid. Three stripes signify a three phase current and voltage.
- Another type of wind turbines is the full scale converter, where all the power from the generator and flows through the converter. The generator can be either an induction generator or a synchronous generator.
- In the latter case the generator is usually a permanent magnet synchronous generator that is the most widely used type of synchronous generators.
- Permanent magnet synchronous generator becomes more and more feasible option along the development of the technology.
- The arrangement of using a synchronous generator with a full scale converter provides a lot of flexibility in the operation as it can support the network offering reactive power even if there was not wind at all.



- A full scale converter configuration with a turbine rotor, a gear box, a generator (G) and a back-to-back converter.
- The generator is connected to three phase AC grid. Three stripes signify a three phase current and voltage.
- The harmonic emissions of wind turbines can be classified as characteristic and noncharacteristic harmonics.
- The characteristic harmonics depend on the converter topology and switching strategy used during an ideal operation (with no disturbances).

Power Factor: Improvement, Formula & Definition

- In general power is the capacity to do work. In electrical domain, electrical power is the amount of electrical energy that can be transferred to some other form (heat, light etc) per unit time. Mathematically it is the product of voltage drop across the element and current flowing through it. Considering first the DC circuits, having only DC voltage sources, the inductors and capacitors behave as short circuit and open circuit respectively in steady state.
- Hence the entire circuit behaves as resistive circuit and the entire electrical power is dissipated in the form of heat. Here the voltage and current are in same phase and the total electrical power is given by:

$$\text{Electrical power} = \text{Voltage across the element} \times \text{Current through the element.}$$

$$\text{Its unit is Watt} = \text{Joule}/\text{sec.}$$

- The inductor stores electrical energy in the form of magnetic energy and capacitor stores electrical energy in the form of electrostatic energy. Neither of them dissipates it.
- Further, there is a phase shift between voltage and current.
- Hence when we consider the entire circuit consisting of a resistor, inductor, and capacitor, there exists some phase difference between the source voltage and current.
- The cosine of this phase difference is called electrical power factor. This factor ($-1 < \cos\phi < 1$) represents the fraction of the total power that is used to do the useful work.
- The other fraction of electrical power is stored in the form of magnetic energy or electrostatic energy in the inductor and capacitor respectively.

Power Factor Improvement

- The term power factor comes into the picture in AC circuits only. Mathematically it is the cosine of the phase difference between the source voltage and current.
- It refers to the fraction of total power (apparent power) which is utilized to do the useful work called active power.

$$\cos\phi = \frac{Active\ power}{Apparent\ power}$$

Need for Power Factor Improvement

- Real power is given by P = VIcosϕ. The electrical current is inversely proportional to cosϕ for transferring a given amount of power at a certain voltage.
- Hence higher the pf lower will be the current flowing.
- A small current flow requires a less cross-sectional area of conductors, and thus it saves conductors and money.
- From the above relation, we see having poor power factor increases the current flowing in a conductor and thus copper loss increases.
- A large voltage drop occurs in the alternator, electrical transformer and transmission and distribution lines – which gives very poor voltage regulation.

The KVA rating of machines is also reduced by having higher power factor, as per the formula:

$$KVA = \frac{KW}{\cos\phi}$$

There are three main ways to improve power factor:

- Capacitor Banks
- Synchronous Condensers
- Phase Advancers

- **Capacitor Banks**
- Improving power factor means reducing the phase difference between voltage and current.
- Since the majority of loads are of inductive nature, they require some amount of reactive power for them to function.
- A capacitor or bank of capacitors installed parallel to the load provides this reactive power.
- They act as a source of local reactive power, and thus less reactive power flows through the line.
- Capacitor banks reduce the phase difference between the voltage and current.

Phase Advancers

- This is an AC exciter mainly used to improve the PF of an induction motor.
- They are mounted on the shaft of the motor and are connected to the rotor circuit of the motor.
- It improves the power factor by providing the exciting ampere turns to produce the required flux at the given slip frequency.
- Further, if ampere-turns increase, it can be made to operate at leading power factor.

Power Factor Calculation

- In power factor calculation, we measure the source voltage and current drawn using a voltmeter and ammeter respectively.
- A wattmeter is used to get the active power.

Now, we know $P = VI\cos\varphi$ watt

$$From\ this\ \cos\phi = \frac{P}{VI}\ or\ \frac{Wattmeter\ reading}{Voltmeter\ reading \times\ Ammeter\ reading}$$

Hence, we can get the electrical power factor

Now we can calculate the reactive power $Q = VI\sin\varphi$ VAR

This reactive power can now be supplied from the capacitor installed in parallel with the load in local.

The reactive power of a capacitor can be calculated using the following formula:

$$Q = \frac{V^2}{X_C} \Rightarrow C = \frac{Q}{2\pi f V^2}\ farad$$

MODULE-V
POWER QUALITY ISSUES IN INTEGRATION OF RENEWABLE ENERGY RESOURCES

MODULE V - SYLLABUS

Stand alone and Grid connected systems, Power Quality issues, Impact of power quality problems on DG, Mitigation of power quality problems, and Role of custom power devices in Distributed Generation.

COURSE OUTCOMES MAPPED WITH MODULE V

CO	Course Outcomes	Blooms Taxonomy
CO 9	**Identify** the power quality issues and mitigation techniques used in standalone and grid connected systems for ensuring the quality of power.	Apply
CO 10	**Outline** the control and protection of renewable energy systems using custom power devices for stable operation of power systems.	Understand

PROGRAM OUTCOMES MAPPED WITH MODULE V

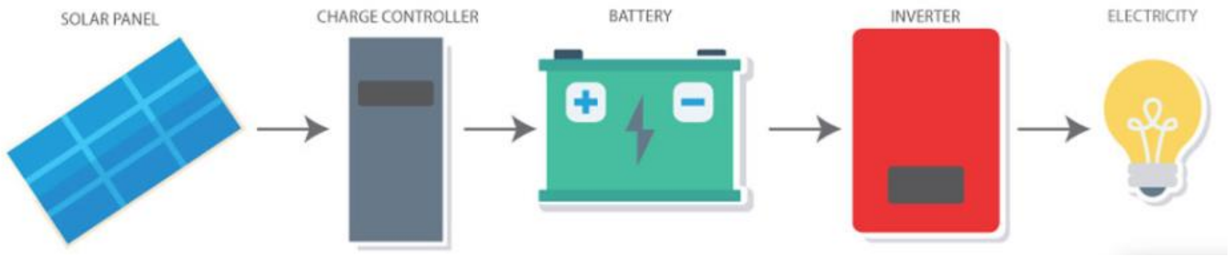
PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
PO 3	**Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

MAPPING OF COs AND POS FOR MODULE V

COs	PROGRAM OUTCOMES											
	1	2	3	4	5	6	7	8	9	10	11	12
CO9	√	√										
CO10	√	√										

Grid connect solar power

- A grid connect system is one that works in with the local utility grid so that when your solar panels produce more solar electricity than your house is using the surplus power is fed into the grid.
- With a grid connect solar power system when your house requires more power than what your solar panels are producing then the balance of your electricity is supplied by the utility grid.
- So for example if your electrical loads in your house were consuming 20 amps of power and your solar power was only generating 12 amps then you would be drawing 8 amps from the grid.
- Obviously at night all of your electrical needs are supplied by the grid because with a grid connect system you do not store the power you generate during the day.



Stand alone solar power

A stand alone solar system the solar panels are not connected to a grid but instead are used to charge a bank of batteries. These batteries store the power produced by the solar panels and then your electrical loads draw their electricity from these batteries. Stand alone solar power systems have been used for a long time in areas where no public grid is available. However, the real growth in solar power systems in the last 5 years has been in grid connect systems. Why is this? Because most people live in areas that are connected to a public grid and stand-alone systems are much, much more expensive than grid connect systems because batteries are very expensive. It is my hope that in the future we will see a fall in battery prices and that stand alone systems will be used more. However, batteries will need to become a lot cheaper for this to happen.

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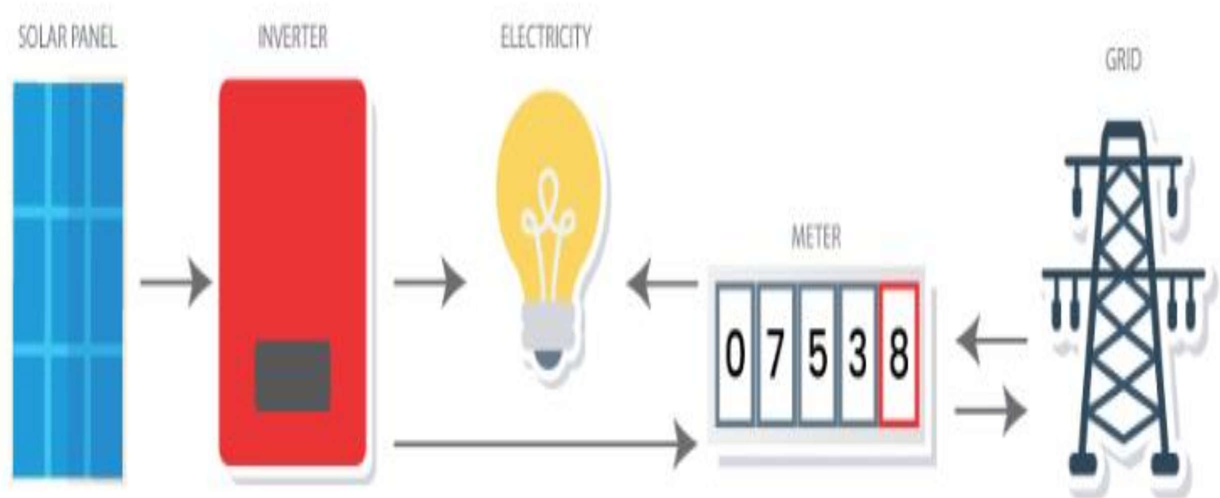


- With a stand alone solar system the solar panels are not connected to a grid but instead are used to charge a bank of batteries.
- These batteries store the power produced by the solar panels and then your electrical loads draw their electricity from these batteries.

- Stand alone solar power systems have been used for a long time in areas where no public grid is available.
- However, the real growth in solar power systems in the last 5 years has been in grid connect systems. Why is this? Because most people live in areas that are connected to a public grid and stand-alone systems are much, much more expensive than grid connect systems because batteries are very expensive.
- It is my hope that in the future we will see a fall in battery prices and that stand alone systems will be used more.
- However, batteries will need to become a lot cheaper for this to happen.

Power Quality issues

- The integration of renewable sources within the existing power system affects its traditional principles of operation.
- The renewable energy sources (RES) can be used in small, decentralized power plants or in large ones, they can be built in small capacities and can be used in different locations.
- In isolated areas where the cost of the extension of the power systems (from utilities point of view) or the cost for interconnection with the grid (from customer’s point of view) are very high with respect to the cost of the RES system, these renewable sources are suitable.
- The RES systems are appropriate for a large series of applications, such as stand-alone systems for isolated buildings or large interconnected networks. The modularity of these systems makes possible the extension in the case of a load growth.

- The increasing penetration rate of RES in the power systems is raising technical problems, as voltage regulation, network protection coordination, loss of mains detection, and RES operation following disturbances on the distribution network.
- The utilization of these alternative sources presents advantages and disadvantages.
- The impact of the wind turbines and photovoltaic systems on network operation and power quality (harmonics, and voltage fluctuations) is highly important.
- The capability of the power system to absorb the power quality disturbances is depending on the fault level at the point of common coupling. In weak networks or in power systems with a high wind generation penetration, the integration of these sources can be limited by the flicker level that must not exceed the standardized limits.
- The wind generators and PV systems interconnected to the main grid with the help of power electronics converters can cause important current harmonics.

- **Power Quality Issues Affected by Distributed Generation | Electricity**
- **Voltage Regulation:**
- This is often the most limiting factor for how much Distributed Generation can be accommodated on a distribution feeder without making changes.
- It may initially seem that Distributed Generation should be able to improve the voltage regulation on a feeder.
- Generator controls are much faster and smoother than conventional tap-changing transformers and switched capacitor banks.
- With careful engineering, this can be accomplished with sufficiently large Distributed Generation.

- However, there are many problems associated with voltage regulation.
- In cases where the Distributed Generation is located relatively far from the substation for the size of Distributed Generation.
- Voltage regulation issues are often the most limiting for being able to accommodate the Distributed Generation without changes to the utility system.

Sustained Interruptions:

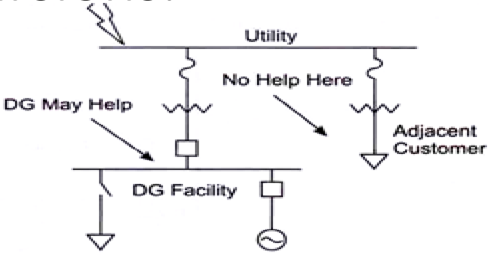
- This is the traditional reliability area.
- Many generators are designed to provide backup power to the load in case of power interruption.
- However, Distributed Generation has the potential to increase the number of interruptions in some cases.
- Much of the Distributed Generation that is already in place was installed as backup generation.
- The most common technology used for backup generation is diesel gensets.
- The bulk of the capacity of this form of DG can be realized simply by transferring the load to the backup system

Harmonics:

- There are harmonics concerns with both rotating machines and inverters, although concern with inverters is less with modern technologies.
- There are many who still associate Distributed Generation with bad experiences with harmonics from electronic power converters.
- If thyristor-based, line-commutated inverters were still the norm, this would be a large problem.
- Fortunately, the technologies requiring inverters have adopted the switching inverters.
- This has eliminated the bulk of the harmonics problems from these technologies.

Voltage Sags:

- The most common power quality problem is a voltage sag, but the ability of Distributed Generation to help alleviate sags is very dependent on the type of generation technology and the interconnection location.
- . During a voltage sag, DG might act to counter the sag. Large rotating machines can help support the voltage magnitudes and phase relationships.
- Although not a normal feature, it is conceivable to control an inverter to counteract voltage excursions.



- The Distributed Generation influence on sags at its own load bus is aided by the impedance of the service transformer, which provides some isolation from the source of the sag on the utility system.
- However, this impedance hinders the ability of the Distributed Generation to provide any relief to other loads on the same feeder.
- Distributed Generation larger than 1 M W will often be required to have its own service transformer.
- The point of common coupling with any load is the primary distribution system.
- Therefore, it is not likely that Distributed Generation connected in this manner will have any impact on the voltage sag characteristic seen by other loads served from the feeder.

- **Power Quality Issues and its Mitigation Techniques**
- Electrical energy is the most efficient and popular form of energy and the modern society is heavily dependent on the electric supply.
- The life cannot be imagined without the supply of electricity.
- At the same time the quality and continuity of the electric power supplied is also very important for the efficient functioning of the end user equipment.
- Most of the commercial and industrial loads demand high quality uninterrupted power.
- Thus maintaining the qualitative power is of utmost important.
- The quality of the power is affected if there is any deviation in the voltage and frequency values at which the power is being supplied.


EVERY ENDING
IS REALLY JUST A
NEW BEGINNING