RENEWABLE AND DISTRIBUTED ENERGY TECHNOLOGIES

PREPARED BY

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RENEWABLE AND DISTRIBUTED ENERGY TECHNOLOGIES (PROFESSIONAL ELECTIVE-III)

Lecture – Tutorial:	3-1 Hours	**Internal Marks:**	30
Credits:	3	**External Marks:**	70

Course Objectives:

- To understand the basic concepts on wind energy systems with concept on aerodynamics, horizontal and vertical axis wind turbines.
- To understand the various relations between speed, power and energy in the wind systems.
- It provides the knowledge in fundamentals of solar energy systems, various components of solar thermal systems, applications in the relevant fields and design of PV systems.
- To understand the Hydel system components and their design concepts.
- To get an idea on different other sources like tidal, geothermal and gas based units.
- To understand the use of various renewable sources as distributed generators

Course Outcomes

Upon successful completion of the course, the student will be able to:

CO1	Illustrate basic concepts of renewable and distributed sources
CO2	Demonstrate the components of wind energy conversion systems.
CO3	Model PV systems and analyse MPPT Techniques
CO4	Illustrate the concept of Energy Production from Hydro - Tidal and Geothermal.
CO5	Distinguish between standalone and grid connected DG systems
CO6	Design hybrid renewable energy systems.

Contribution of Course Outcomes towards achievement of Program Outcomes (1 – Low, 2- Medium, 3 – High)

	PO 1	**PO 2**	**PO 3**	**PO 4**	**PO 5**	**PO 6**	**PO 7**	**PO 8**	**PO 9**	**PO 10**	**PO 11**	**PO 12**
CO1	**3**	**2**									**1**	
CO2	**3**	**3**									**1**	
CO3	**3**	**3**									**1**	
CO4	**3**	**2**										
CO5	**3**	**2**										
CO6	**3**	**2**										

UNIT I

Brief idea on renewable and distributed sources - their usefulness and advantages;

Wind Energy Systems: Estimates of wind energy potential - wind maps - Instrumentation for wind velocity measurements - Aerodynamic and mechanical aspects of wind machine design - Conversion to electrical energy - Aspects of location of wind farms.

UNIT II

Wind speed and energy - Speed and power relations - Power extraction from wind - Tip speed ratio (TSR) - Functional structure of wind energy conversion systems - Pitch and speed control - Power- speed-TSR characteristics - Fixed speed and variable speed wind turbine control - Power optimization - Electrical generators - Self-Excited and Doubly-Fed Induction Generators operation and control.

UNIT III

Solar PV Systems: Present and new technological developments in photovoltaic - estimation of solar irradiance - components of solar energy systems - solar-thermal system applications to power generation - heating - Types of PV systems - Modelling of PV cell - current-voltage and power-voltage characteristics - Effects of temperature - Solar array simulator - Sun tracking - Peak power operations - PV system - MPPT techniques - Effects of partial shading on the characteristic curves and associated MPPT techniques - Solar park design outline.

UNIT IV

Hydel Power: Water power estimates - use of hydrographs - hydraulic turbine - characteristics and part load performance - design of wheels - draft tubes and penstocks - plant layouts; Brief idea of other sources viz. - tidal - geothermal - gas-based - etc.

UNIT V

Requirements of hybrid/combined use of different renewable and distributed sources - Need of energy storage; Control of frequency and voltage of distributed generation in Stand- alone and Grid-connected mode - use of energy storage and power electronics interfaces for the connection to grid and loads - Design and optimization of size of renewable sources and storages.

TEXT BOOKS:

1. Math J. Bollen - Fainan Hassan 'Integration of Distributed Generation in the Power System' - IEEE Press - 2011.
2. Loi Lei Lai and Tze Fun Chan 'Distributed Generation: Induction and Permanent Magnet Generators' - Wiley-IEEE Press - 2007.
3. Studies' Craig Anderson and Rudolf I. Howard 'Wind and Hydropower Integration: Concepts - Considerations and Case - Nova Publisher - 2012.
4. Amanda E. Niemi and Cory M. Fincher 'Hydropower from Small and Low-Head Hydro Technologies' - Nova Publisher - 2011.
6. D. Yogi Goswami - Frank Kreith and Jan F. Kreider 'Principles of Solar Engineering' - Taylor & Francis 2000.
7. G. N. Tiwari 'Solar Energy Technology' - Nova Science Publishers - 2005.

REFERENCE BOOKS:

1. Math J. Bollen - Fainan Hassan 'Integration of Distributed Generation in the Power System' - IEEE Press - 2011.
2. S. Heier and R. Waddington 'Grid Intergration of Wind Energy Conversion Systems' – Wiley - 2006.

UNIT-1

Renewable and Distributed sources

Renewable and Distributed Energy Sources – A Detailed Overview

1. Renewable Energy Sources

Renewable energy comes from natural sources that replenish themselves over time. These sources are essential for reducing dependence on fossil fuels, minimizing carbon emissions, and ensuring sustainable energy production.

1.1 Solar Energy
Utilizes sunlight to generate electricity through photovoltaic (PV) cells or solar thermal systems. Types

of Solar Power:

Photovoltaic (PV) Systems: Convert sunlight directly into electricity using semiconductor materials (e.g., silicon).

Concentrated Solar Power (CSP): Uses mirrors or lenses to concentrate sunlight, generating heat that drives a steam turbine.

Advantages: Abundant, low maintenance, and decreasing installation costs.

Challenges: Energy production depends on sunlight availability; storage is required for nighttime use.

1.2 Wind Energy

Converts the kinetic energy of wind into mechanical power using wind turbines.

Types of Wind Power:

Onshore Wind Farms: Located on land, relatively easy to install and maintain.

Offshore Wind Farms: Placed in water bodies where wind speeds are higher, producing more energy.

Advantages: Clean energy source, cost-competitive with fossil fuels.

Challenges: Requires consistent wind speeds and large land areas; noise and aesthetic concerns.

1.3 Hydropower

Uses the energy of moving water (rivers, dams) to generate electricity.

Types of Hydropower:

Large Hydropower: Uses dams to store water and release it to generate electricity.

Small and Micro Hydropower: Suitable for localized power generation.

Run-of-River Systems: Use natural river flow without significant storage.

Advantages: Reliable, efficient, and long lifespan.

Challenges: Environmental impact on aquatic ecosystems and displacement of communities.

1.4 Biomass and Biogas Energy

Biomass includes organic materials (wood, crop waste, animal waste) burned for energy. Biogas is produced through anaerobic digestion of organic matter, generating methane-rich gas.

Advantages: Uses waste products, reduces landfill accumulation, and provides steady energy supply.

Challenges: Requires sustainable sourcing to prevent deforestation and land use conflicts.

1.5 Geothermal Energy

Uses heat from the Earth's crust for power generation or direct heating.

Types of Geothermal Power Plants:

Dry Steam Plants: Directly use steam from underground reservoirs. Flash

Steam Plants: Convert high-pressure hot water into steam.

Binary Cycle Plants: Transfer geothermal heat to a secondary fluid with a lower boiling point.

Advantages: Consistent energy supply, low emissions.

Challenges: Limited to regions with high geothermal activity, high upfront costs.

1.6 Tidal and Wave Energy

Tidal Energy: Uses the movement of ocean tides to generate electricity.

Wave Energy: Captures the energy of surface waves to drive turbines.

Advantages: Predictable and renewable.

Challenges: High initial investment and limited suitable locations.

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2. Distributed Energy Sources (DES)

Distributed energy refers to small-scale, decentralized energy generation systems located close to consumers. These systems improve grid reliability, reduce transmission losses, and support renewable integration.

2.1 Solar PV Systems (Rooftop Solar)

Small-scale solar installations on homes, businesses, and industrial buildings. Often paired with battery storage for reliability.

2.2 Micro Wind Turbines

Small wind turbines (typically <100 kW) used for local power generation. Ideal for remote areas and farms with sufficient wind speeds.

2.3 Small Hydropower Plants

Hydropower systems (<10 MW) used for local electricity supply. Useful in rural areas with rivers and streams.

2.4 Biogas and Biomass Power Plants

Small-scale facilities producing energy from organic waste.

Often used in agricultural and rural communities.

2.5 Fuel Cells and Combined Heat and Power (CHP) Systems

Fuel Cells: Convert hydrogen into electricity through an electrochemical reaction.

CHP Systems: Simultaneously generate electricity and useful heat, improving efficiency.

2.6 Battery Energy Storage Systems (BESS)

Used to store energy from renewables and supply power when demand is high.

Common types: Lithium-ion, lead-acid, flow batteries.

WIND ENERGY SYSTEMS:

Wind Energy Basics

Wind energy is a form of solar energy. Wind is caused by the uneven heating of the atmosphere by the sun, variations in the earth's surface, and rotation of the earth. Mountains, bodies of water and vegetation influence wind flow patterns. Wind speeds vary based on geography, topography and season. As a result, there are some locations better suited for wind energy generation.

Wind power is the conversion of wind energy into electricity or mechanical energy using wind turbines. Wind turbines convert the kinetic energy in the wind into mechanical power. A generator can convert mechanical power into electricity. Mechanical power can also be utilized directly for specific tasks such as pumping water.

The mechanism used to convert air motion into electricity is referred to as a turbine. The power in the wind is extracted by allowing it to blow past moving blades that exert torque on a rotor. The rotor turns the drive shaft, which turns an electric generator. The amount of power transferred is dependent on the rotor size and the wind speed. The types of wind power plants based on capacity are

- **Utility-scale wind:** Wind turbines that range in size from 100 kilowatts to several megawatts, where the electricity is delivered to the power grid and distributed to the end user by electric utilities or power system operators.
- **Distributed or "small" wind:** Single small wind turbines below 100 kilowatts that are used to directly power a home, farm or small business and are not connected to the grid.
- **Offshore wind:** Wind turbines that are erected in large bodies of water, usually on the continental shelf. Offshore wind turbines are larger than land-based turbines and can generate more power.

Windmills: People have been using windmills for centuries to grind grain, pump water, and do other work. Windmills generate mechanical energy, but they do not generate electricity.

Wind Turbines: In contrast to windmills, modern wind turbines are highly evolved machines with more than 8,000 parts that harness wind's kinetic energy and convert it into electricity.

Wind farm: Oftentimes a large number of wind turbines are built close together, which is referred to as a wind project or wind farm. A wind farm functions as a single power plant and sends electricity to the grid.

Power in the Wind

Windmills have been in use since 2000 B.C. and were first developed in Persia and China. Ancient mariners sailed to distant lands by making use of winds. Farmers used wind power to pump water and for grinding grains. Today the most popular use of wind energy is converting it to electrical energy to meet the critical energy needs of the planet.

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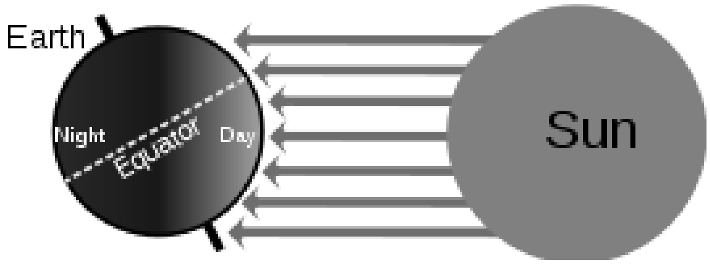
Wind results from the movement of air due to atmospheric pressure gradients. Wind flows from regions of higher pressure to regions of lower pressure. The larger the atmospheric pressure gradient, the higher the wind speed and thus, the greater the wind power that can be captured from the wind by means of wind energy converting machinery. The generation and movement of wind are complicated due to a number of factors. Among them, the most important factors are uneven solar heating, the Coriolis effect due to the earth‘s self-rotation, and local geographical conditions.

Uneven solar heating

The unevenness of the solar radiation can be attributed to four reasons.

First, the earth is a sphere revolving around the sun in the same plane as its equator. Because the surface of the earth is perpendicular to the path of the sunrays at the equator but parallel to the sunrays at the poles, the equator receives the greatest amount of energy per unit area, with energy dropping off toward the poles. Due to the spatial uneven heating on the earth, it forms a temperature gradient from the equator to the poles and a pressure gradient from the poles to the equator. Thus, hot air with lower air density at the equator rises up to the high atmosphere and moves towards the poles and cold air with higher density flows from the poles towards the equator along the earth‘s surface. Without considering the earth‘s self-rotation and the rotation-induced Coriolis force, the air circulation at each hemisphere forms a single cell, defined as the meridional circulation.

Fig. 1. Uneven solar heating



Second, the earth‘s self-rotating axis has a tilt of about 23.5° with respect to its ecliptic plane. It is the tilt of the earth‘s axis during the revolution around the sun that results in cyclic uneven heating, causing the yearly cycle of seasonal weather changes.

Third, the earth‘s surface is covered with different types of materials such as vegetation, rock, sand, water, ice/snow, etc., Each of these materials has different reflecting and absorbing rates to solar radiation, leading to high temperature on some areas (e.g. deserts) and low temperature on others (e.g. iced lakes), even at the same latitudes.

The fourth reason for uneven heating of solar radiation is due to the earth‘s topographic surface. There are a large number of mountains, valleys, hills, etc. on the earth, resulting in different solar radiation on the sunny and shady sides.

Coriolis effect

The earth‘s self-rotation is another important factor to affect wind direction and speed. The Coriolis force, which is generated from the earth's self-rotation, deflects the direction of atmospheric movements. In the north atmosphere wind is deflected to the right and in the south atmosphere to the left. The Coriolis force depends on the earth‘s latitude; it is zero at the equator and reaches maximum values at the poles. In addition, the amount of deflection on wind also depends on the wind speed; slowly blowing wind is deflected only a small amount, while stronger wind is deflected more.

In large-scale atmospheric movements, the combination of the pressure gradient due to the uneven solar radiation and the Coriolis force due to the earth‘s self rotation causes the single meridional cell to break up into three convectional cells in each hemisphere: the Hadley cell, the Ferrel cell, and the Polar cell as shown in Fig.2. Each cell has its own characteristic circulation pattern. In the Northern Hemisphere, the Hadley cell circulation lies between the equator and north latitude 30°, dominating tropical and sub-tropical climates. The hot air rises at the equator and flows toward the North Pole in the upper atmosphere. This moving air is deflected by Coriolis force to create the northeast trade winds. At approximately north latitude 30°, Coriolis force becomes so strong to balance the pressure gradient force. As a result, the winds are defected to the west.

The air accumulated at the upper atmosphere forms the subtropical high-pressure belt and thus sinks back to the earth's surface, splitting into two components: one returns to the equator to close the loop of the Hadley cell; another moves along the earth's surface toward North Pole to form the Ferrel Cell circulation, which lies between north latitude 30° and 60°. The air circulates towards the North Pole along the earth's surface until it collides with the cold air flowing from the North Pole at approximately north latitude 60°. Under the influence of Coriolis force, the moving air in this zone is deflected to produce westerlies. The Polar cell circulation lies between the North Pole and north latitude 60°. The cold air sinks down at the North Pole and flows along the earth's surface toward the equator. Near north latitude 60°, the Coriolis effect becomes significant to force the airflow to southwest.

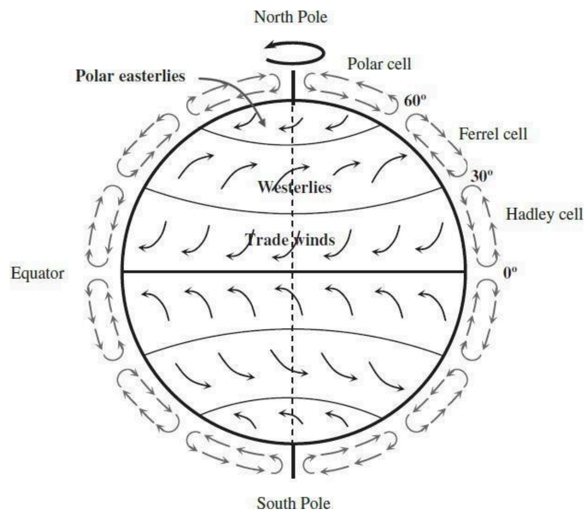


Fig. 2. Idealized atmospheric circulations

Local geography

The roughness on the earth's surface is a result of both natural geography and manmade structures. Frictional drag and obstructions near the earth's surface generally retard with wind speed and induce a phenomenon known as wind shear. The rate at which wind speed increases with height varies on the basis of local conditions of the topography, terrain, and climate, with the greatest rates of increases observed over the roughest terrain. A reliable approximation is that wind speed increases about 10% with each doubling of height. In addition, some special geographic structures can strongly enhance the wind intensity. For instance, wind that blows through mountain passes can form mountain jets with high speeds.

Wind energy characteristics

Wind energy is a special form of kinetic energy in air as it flows. Wind energy can be either converted into electrical energy by power converting machines or directly used for pumping water, sailing ships, or grinding grain. Three key factors affect the amount of energy a turbine can harness from the wind: wind speed, air density, and swept area.

Most of the modern wind turbines have 3 blades which can reach speeds at the tip of over 320 kph (200 mph).

Wind power

Kinetic energy exists whenever an object of a given mass is in motion with a translational or rotational speed. When air is in motion, the kinetic energy in moving air can be determined as

$$E_k = \frac{1}{2} m \bar{u}^2 \quad (1)$$

where m is the air mass and $\bar{u}$ is the mean wind speed over a suitable time period. The wind power can be obtained by differentiating the kinetic energy in wind with respect to time, i.e.:

$$P_w = \frac{dE_k}{dt} = \frac{1}{2} \dot{m} \bar{u}^2 \quad (2)$$

However, only a small portion of wind power can be converted into electrical power. When wind passes through a wind turbine and drives blades to rotate, the corresponding wind mass flowrate is

$$\dot{m} = \rho A u \qquad (3)$$

where ρ is the air density and A is the swept area of blades, as shown in Fig. 3 . Substituting (3) into (2), the available power in wind P_w can be expressed as

$$P_w = \frac{1}{2} \rho A u^3 \qquad (4)$$

An examination of eqn (4) reveals that in order to obtain a higher wind power, it requires a higher wind speed, a longer length of blades for gaining a larger swept area, and a higher air density. Because the wind power output is proportional to the cubic power of the mean wind speed, a small variation in wind speed can result in a large change in wind power.

Blade swept area

As shown in Fig. 3, the blade swept area can be calculated from the formula:

$$A = \pi \left[(l+r)^2 - r^2 \right] = \pi l \,(l+2r) \qquad (5)$$

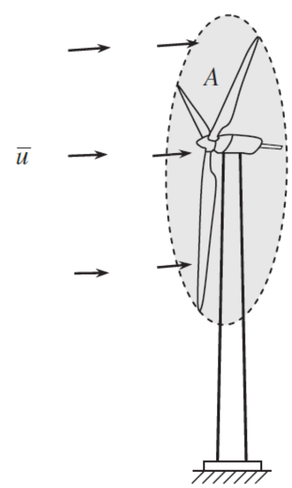


Fig.3. Swept area of wind turbine blades

where l is the length of wind blades and r is the radius of the hub. Thus, by doubling the length of wind blades, the swept area can be increased by the factor up to 4. When l >> 2 r, $A \approx \pi l^2$.

Air density

Another important parameter that directly affects the wind power generation is the density of air, which can be calculated from the equation of state:

$$\rho = \frac{p}{RT} \qquad (6)$$

where p is the local air pressure, R is the gas constant (287 J/kg-K for air), and T is the local air temperature in K.

The hydrostatic equation states that whenever there is no vertical motion, the difference in pressure between two heights is caused by the mass of the air layer:

$$dp = -\rho g \, dz \qquad (7)$$

where g is the acceleration of gravity. Combining eqns (6) and (7), yields

$$\frac{dp}{p} = -\frac{g}{RT} dz \qquad (8)$$

The acceleration of gravity g decreases with the height above the earth's surface z:

$$g = g_0\left(1 - \frac{4z}{D}\right) \tag{9}$$

where g_0 is the acceleration of gravity at the ground and D is the diameter of the earth. However, for the acceleration of gravity g, the variation in height can be ignored because D is much larger than 4z.

In addition, temperature is inversely proportional to the height. Assume that $dT/dz = c$, it can be derived that

$$p = p_0 \left(\frac{T}{T_0} \right)^{-g/cR} \tag{10}$$

where p_0 and T_0 are the air pressure and temperature at the ground, respectively.
Combining eqns (6) and (10), it gives

$$\rho = \rho_0 \left(\frac{T}{T_0} \right)^{-(g/cR+1)} = \rho_0 \left(1 + \frac{cz}{T_0} \right)^{-(g/cR+1)} \tag{11}$$

This equation indicates that the density of air decreases nonlinearly with the height above the sea level.

The largest wind turbine in the world is located in US in Hawaii. It stands 20 stories tall and has blades the length of a football field.

Wind power density

Wind Power Density (WPD) is a quantitative measure of wind energy available at any location. It is the mean annual power available per square meter of swept area of a turbine, and is calculated for different heights above ground. Some of the wind resource assessments utilize 50m towers with sensors installed at intermediate levels (10 m, 20 m, etc.). For large-scale wind plants, class rating of 4 or higher is preferred. Calculation of wind power density includes the effect of wind velocity and air density.

Wind power parameters

Power coefficient

The conversion of wind energy to electrical energy involves primarily two stages: in the first stage, kinetic energy in wind is converted into mechanical energy to drive the shaft of a wind generator.
The power coefficient C_p deals with the converting efficiency in the first stage, defined as the ratio of the actually captured mechanical power by blades to the available power in wind:

$$C_p = \frac{P_{me,out}}{P_W} = \frac{P_{me,out}}{(1/2)\rho A u^3} \tag{12}$$

Because there are various aerodynamic losses in wind turbine systems, for instance, blade-tip, blade-root, profile, and wake rotation losses, etc., the real power coefficient C_p is much lower than its theoretical limit, usually ranging from 30 to 45%.

Total power conversion coefficient and effective power output

In the second stage, mechanical energy captured by wind blades is further converted into electrical energy via wind generators. In this stage, the converting efficiency is determined by several parameters

- Gearbox efficiency η_{gear} – The power losses in a gearbox can be classified as load-dependent and no-load power losses. The load-dependent losses consist of gear tooth friction and bearing losses and no-load losses consist of oil churning, windage, and shaft seal losses. The planetary gearboxes, which are widely used in wind turbines, have higher power transmission efficiencies over traditional gearboxes.
- Generator efficiency η_{gen} – It is related to all electrical and mechanical losses in a wind generator, such as copper, iron, load, windage, friction, and other miscellaneous losses.

- Electric efficiency η_{ele} – It encompasses all combined electric power losses in the converter, switches, controls, and cables.

Therefore, the total power conversion efficiency from wind to electricity η_t is the production of these parameters, i.e.:

$$\eta_t = C_p \, \eta_{gear} \, \eta_{gen} \, \eta_{ele} \tag{13}$$

The effective power output from a wind turbine to feed into a grid becomes

$$P_{eff} = C_p \, \eta_{gear} \, \eta_{gen} \, \eta_{ele} P_w = \eta_t P_w = \frac{1}{2}\left(\eta_t \rho A u^3\right) \tag{14}$$

Lanchester–Betz limit

The Betz limit is the theoretical maximum efficiency for a wind turbine, conjectured by German physicist Albert Betz in 1919. Betz concluded that this value is 59.3%, meaning that atmost only 59.3% of the kinetic energy from wind can be used to spin the turbine and generate electricity. In reality, turbines cannot reach the Betz limit, and common efficiencies are in the 35-45% range. If a wind turbine was 100% efficient, then all of the wind would have to stop completely upon contact with the turbine which is not practically possible.

Wind Speed – Power curve

Wind speed largely determines the amount of electricity generated by a turbine. Higher wind speeds generate more power because stronger winds allow the blades to rotate faster. Faster rotation translates to more mechanical power and more electrical power from the generator. The relationship between wind speed and power for a typical wind turbine is shown in Fig 2.

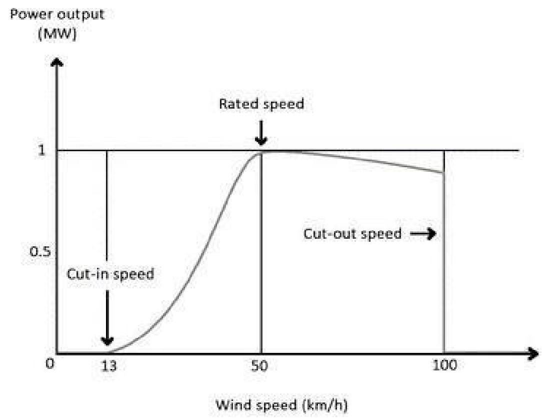


Fig.4 Wind power curve

Turbines are designed to operate within a specific range of wind speeds. The limits of the range are known as the cut-in speed and cut-out speed. The cut-in speed is the point at which the wind turbine is able to generate power. Between the cut-in speed and the rated speed, where the maximum output is reached, the power output will increase cubically with wind speed. For example, if wind speed doubles, the power output will increase 8 times. This cubic relationship is what makes wind speed such an important factor for wind power. This cubic dependence does cut out at the rated wind speed. This leads to the relatively flat part of the curve in Fig. 4, so the cubic dependence is during the speeds below 15 m/s (54 kph).

The cut-out speed is the point at which the turbine must be shut down to avoid damage to the equipment. The cut-in and cut-out speeds are related to the turbine design and size and are decided on prior to construction.

Tip Speed Ratio

The Tip Speed Ratio (often known as the TSR) is of vital importance in the design of wind turbine generators. If the rotor of the wind turbine turns too slowly, most of the wind will pass undisturbed through the gap between the rotor blades. Alternatively if the rotor turns too quickly, the blurring blades will appear like a solid wall to the wind. Therefore, wind turbines are designed with optimal tip speed ratios to extract as much power out of the wind as possible. The tip speed ratio is given by dividing the speed of the tips of the turbine blades by the speed of the wind – for example if a 20 mph wind is blowing on a wind turbine and the tips of its blades are rotating at 80 mph, then the tip speed ration is 80/20 = 4.

Force on a wind turbine

Airflow over any surface creates two types of aerodynamic forces— drag forces, in the direction of the airflow, and lift forces, perpendicular to the airflow. Either or both of these can be used to generate the forces needed to rotate the blades of a wind turbine.

Drag-based wind turbine

In drag-based wind turbines, the force of the wind pushes against a surface, like an open sail. In fact, the earliest wind turbines, dating back to ancient Persia, used this approach. The Savonius rotor is a simple drag-based windmill that you can make at home. It works because the drag of the open, or concave, face of the cylinder is greater than the drag on the closed or convex section.

Lift-based Wind Turbines

More energy can be extracted from wind using lift rather than drag, but this requires specially shaped airfoil surfaces, like those used on airplane wings. The airfoil shape is designed to create a differential pressure between the upper and lower surfaces, leading to a net force in the direction perpendicular to the wind direction. Rotors of this type must be carefully oriented (the orientation is referred to as the rotor pitch), to maintain their ability to harness the power of the wind as wind speed changes.

Types of Wind Power Plants (WPPs)

A wind power plant is simply a collection of wind turbines in one area. There are several different types of wind power plants. The following classification is based on their construction, size and usage.

Remote Wind Power Plants

Areas which are remote but are blessed with good wind speeds and frequency need a wind turbine which is maintenance free or low-maintenance for long periods of time (just imagine a service technician rushing across mountains and valleys on foot or bullock-cart to repair a turbine time and again). This means that they should have the capability of standing against all odds of climate even if they are relatively smaller in size than their conventional counterparts. These types of turbines are known as remote wind power turbines and are specifically designed with these objectives in view.

Cumulative installed capacity of wind power (as on 31.10.2019) in India is 37,090.03 MW.

Hybrid Wind Power Plants

Wind is not fully reliable so we cannot depend on wind alone for generation of power. The best bet would be to combine a wind power plant with some other renewable source of energy, like solar energy. That would be certainly a better idea and you can imagine that when there is a lot of heat, the solar generators would do their job and when the sky is overcast and winds are blowing, the wind power plants would take over. Such an arrangement is known as hybrid arrangement and is useful in regions where there is a lot of heat and wind.

Grid Connected Wind Power Plants

This concept is similar to a hybrid system. The wind power plant is used in conjunction with a main grid which supplies most of the power. The main purpose of the wind turbines is to supplement the energy supply for the grid, whereas the main function in the hybrid system is to complement the energy supply, hence the minor difference in the set up.

Wind Farms

As the name itself suggests, a wind farm is a collection of wind turbines which collectively power a given area or utility harnessing the wind force in a collective manner thereby amplifying the effect of a single unit.

These configurations are used at various locations depending on the conditions of the region and the presence of other sources of electrical supply. An optimum mix would consist of an ingenious combination of the various sources in the best possible manner.

Types of wind turbines

Wind turbines can be separated into two basic types determined by which way the turbine spins. Wind turbines that rotate around a horizontal axis are more common (like a wind mill), while vertical axis wind turbines are less frequently used (Savonius and Darrieus are the most common in the group).

1. Horizontal Axis Wind Turbines (HAWT)

Horizontal axis wind turbines (HAWT) are the common style that most of us think of a wind turbine. A HAWT has a similar design to a windmill, it has blades that look like a propeller that spin on the horizontal axis

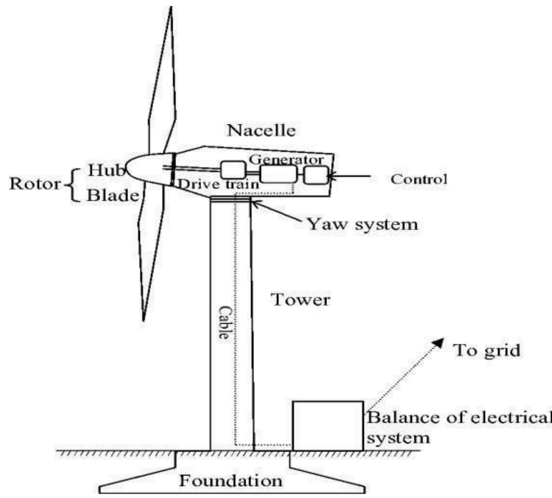


Fig. 5. Horizontal Axis Wind Turbines

Horizontal axis wind turbines have the main rotor shaft and electrical generator at the top of a tower, and they must be pointed into the wind. Small turbine are pointed by a simple wind vane placed square with the rotor (blades), while large turbines generally use a wind sensor coupled with a servo motor to turn the turbine into the wind. Most large wind turbines have a gearbox, which turns the slow rotation of the rotor into a faster rotation that is more suitable to drive an electrical generator.

Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Wind turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount.

Downwind machines have been built, despite the problem of turbulence, because they don‘t need an additional mechanism for keeping them in line with the wind. Additionally, in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since turbulence leads to fatigue failures and reliability is so important, most HAWTs are upwind machines.

Important point to remember recording HAWT are

- Lift is the main force
- Much lower cyclic stress
- 95% of the existing turbines are HAWTs
- Nacelle is placed at the top of the tower
- Yaw mechanism is required

HAWT Advantage

- The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up the wind speed can increase by 20% and the power output by 34%.
- High efficiency, since the blades always move perpendicular to the wind, receiving power through the whole rotation.

HAWT Disadvantages

- Massive tower construction is required to support the heavy blades, gearbox, and generator.
- Components of horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position.
- Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
- Download variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower‘s wind shadow (for this reason, the majority of HAWTs use an upwind design, with the rotor facing the wind in front of the tower).
- HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

- HAWTs generally require a braking or yawing device in high winds to stop the turbine from spinning and destroying or damaging itself.

2. Vertical Axis Wind Turbines (VAWT)

Vertical wind turbines (VAWTs), have the main rotor shaft arranged vertically .The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This makes them suitable in places where the wind direction is highly variable or has turbulent winds. With a vertical axis, the generator and other primary components can be placed near the ground, so the tower does not need to support it, also makes maintenance easier. The main drawback of a VAWT is that, it generally creates drag when rotating into the wind.

It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten its service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and this can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

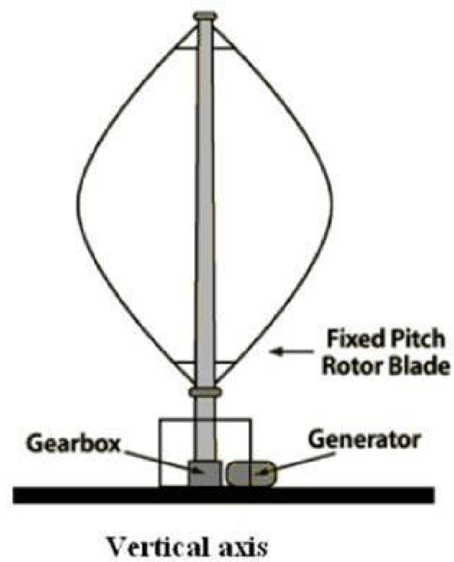


Fig. 6. Vertical Axis Wind Turbines –Darrieus type

Important points to remember for VAWT:

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

VAWT Advantages

- No yaw mechanisms is needed
- A VAWT can be located nearer the ground, making it easier to maintain the moving parts.
- VAWTs have lower wind startup speeds than the typical HAWTs.
- VAWTs may be built at locations where taller structures are prohibited.
- VAWTs situated close to the ground can take advantage of locations where rooftops, means hilltops, ridgelines, and passes funnel the wind and increase wind velocity.

VAWT Disadvantage

- In contrast to HAWT, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to the wind leads to inherently lower efficiency.

- Most VAWTs have an average decreased efficiency from a common HAWT, mainly because of the additional drag that they have as their blades rotate into the wind. Versions that reduce drag produce more energy, especially those that funnel wind into the collector area.
- Having rotors located close to the ground where wind speeds are lower and do not take advantage of higher wind speeds above.
- Because VAWTs are not commonly deployed due mainly to the serious disadvantage mentioned above, they appear novel to those not familiar with the wind industry. This has often made them the subject of wild claims and investment scams over the last 50 years.

Tamil Nadu with 9231.77 MW of installed wind capacity is well ahead of the rest and second positioned Gujarat which has 7203.77 MW of wind generation capacity.

VAWT Subtypes

Darrieus Wind Turbine

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‖ as shown in fig. 6. It is named after the French engineer Georges Darrieus who patented the design in 1931. (It was manufactured by the US company FLoWind which went bankrupt in 1997). The Darrieus turbine is characterized by its C-shaped rotor blades which give it its eggbeater appearance. It is normally built with two or three blades.

Darrieus wind turbines are commonly called ―Eggbeater‖ turbines, because they look like a giant eggbeater. They have good efficiency, but produce large torque ripple and cyclic stress on the tower, which contributes to poor reliability. Also, they generally require some external power source, or an additional savonius rotor, to start turning, because the starting torque is very low. The torque ripple is reduced by using three or more blades which results in a higher solidity for the rotor. Solidity is measured by blade area over the rotor area. Newer Darrieus type turbines are not help up by guy-wires but have an external superstructure connected to the top bearing.

The tip speed ratio (TSR) indicates the rotating velocity of the turbines to the velocity of the wind. In this case, the TSR has a higher value than 1, meaning that the velocity rotation here is greater than the velocity of wind and generates less torque. This makes Darrieus turbines excellent electricity generators. The turbine blades have to be reinforced in order to sustain the centrifugal forces generated during rotation, but the generator itself accepts a lower amount of force than the Savorius type. A drawback to the Darrieus wind turbines is the fact that they cannot start rotation on their own. A small motor, or another Savonius turbine, maybe needed to initiate rotation.

Advantages

- The rotor shaft is vertical. Therefore it is possible to place the load, like a generator or a centrifugal pump at ground level. As the generator housing is not rotating, the cable to the load is not twisted and no brushes are requires for large twisting angles.
- The rotor can take wind from every direction.
- The visual acceptation for placing of the windmill on a building might be larger than for an horizontal axis windmill.
- Easily integrates into buildings.

Disadvantages

- Difficult start unlike the Savonius wind turbine.
- Low efficiency.

Savonius wind turbine

The Savonius wind turbine is a type of vertical-axis wind turbine. It is one of the simplest wind turbine designs. It consists of two to three ―scoops‖ that employ a drag action to convert wind energy into torque to drive a turbine. When looked at from above in cross-section, a two scoop Savonius turbine looks like an S-shape. Due to the curvature of the scoops, the turbine encounters less drag when moving against the wind than with it, and this causes the spin in any wind regardless of facing.

Drag type wind turbines such as the Savonius turbine are less efficient at using the wind's energy than lift-type wind turbines, which are the ones commonly used in wind farms. A Savonius is a drag type turbine, they are commonly used in cases of high reliability in many things such as ventilation and anemometers. Because they are a drag type turbine they are less efficiency than the common HAWT. Savonius are excellent in areas of turbulent wind and self starting.

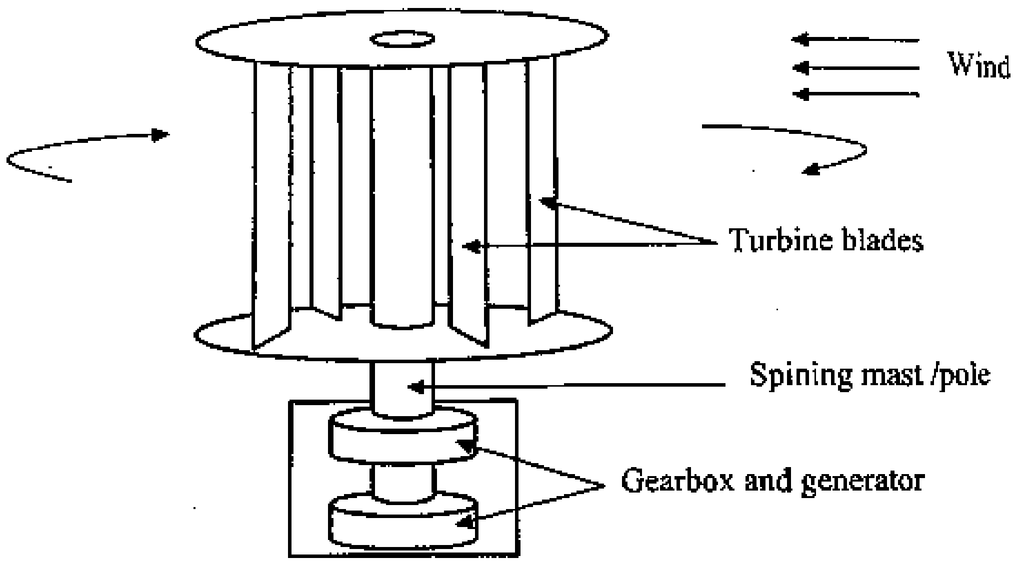


Fig. 7. Savonius wind turbine

Advantages

- Having a vertical axis, the Savonius turbine continues to work effectively even if the wind changes direction.
- Because the Savonius design works well even at low wind speeds, there's no need for a tower or other expensive structure to hold it in place, greatly reducing the initial setup cost.
- The device is quiet, easy to build, and relatively small.
- Because the turbine is close to the ground, maintenance is easy.

Disadvantages

- The scoop system used to capture the wind's energy is half as efficient as a conventional turbine, resulting in less power generation.

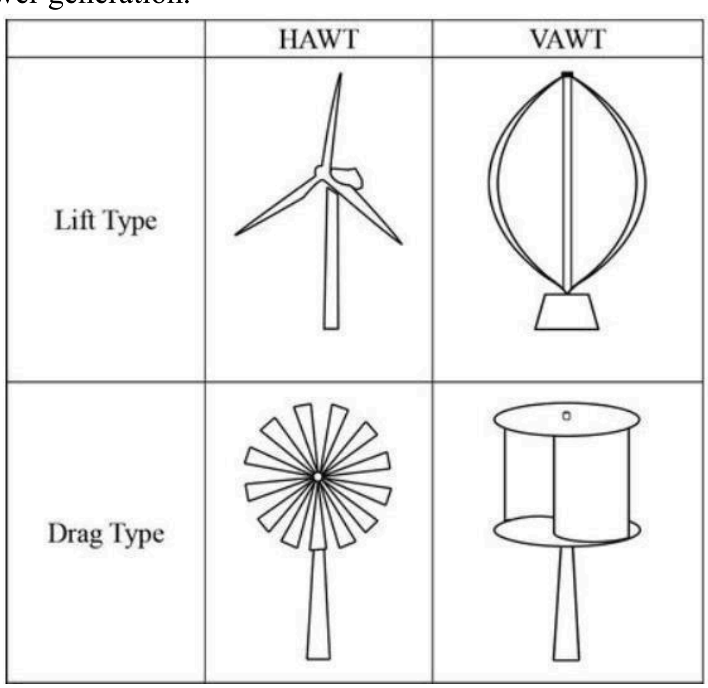


Fig.8. Types of wind turbines

Classification of Wind Energy Conversion Systems

(1) Based on axis
   (a) Horizontal axis machines
   (b) Vertical axis machines

(2) According to size
   (a) Small size machines (upto 2k W)
   (b) Medium size machines (2 to 100k W)
   (c) Large size machines (100k W and above)
      i. Single generator at single site
      ii. Multiple generators

(3) Types of output
   (a) DC output
      i. DC generator
      ii. Alternator rectifier
   (b) AC output
      i. Variable frequency, variable or constant voltage AC.
      ii. Constant frequency, variable or constant voltage AC

(4) According to the rotational speed of the area turbines
   (1) Constant speed and variable pitch blades
   (2) Nearly constant speed with fixed pitch blades
   (3) Variable speed with fixed pitch blades
      (a) Field modulated system
      (b) Double output indication generator
      (c) AC-DC-AC link
      (d) AC commentator generator
   (4) Variable speed constant frequency generating system.

(5) As per utilization of output
   (a) Battery storage
   (b) Direct conversion to an electro magnetic energy converter
   (c) Thermal potential
   (d) Inter convention with conventional electric utility guides

Mupandal wind farm in Tamilnadu with 3000 turbines and total nominal power of 1,500,000 kW is India's largest Onshore wind farm

Components of WPPs

There are three categories of components: mechanical, electrical, and control. The following is a brief description of the main components:

- **The tower** is the physical structure that holds the wind turbine. It supports the rotor, nacelle, blades, and other wind turbine equipment. Typical commercial wind towers are usually 50–120 m long and they are constructed from concrete or reinforced steel.
- **Blades** are physical structures, which are aerodynamically optimized to help capture the maximum power from the wind in normal operation with a wind speed in the range of about 3–15 m/s. Each blade is usually 20m or more in length, depending on the power level.
- **The nacelle** is the enclosure of the wind turbine generator, gearbox and internal equipment. It protects the turbine's internal components from the surrounding environment.
- **The rotor** is the rotating part of the wind turbine. It transfers the energy in the wind to the shaft. The rotor hub holds the wind turbine blades while connected to the gearbox via the low-speed shaft.
- **Pitch** is the mechanism of adjusting the angle of attack of the rotor blades. Blades are turned in their longitudinal axis to change the angle of attack according to the wind directions.
- **The shaft** is divided into two types: low and high speed. The low-speed shaft transfers mechanical energy from the rotor to the gearbox, while the high-speed shaft transfers mechanical energy from gearbox to generator.

- **Yaw** is the horizontal moving part of the turbine. It turns clockwise or anticlockwise to face the wind. The yaw has two main parts: the yaw motor and the yaw drive. The yaw drive keeps the rotor facing the wind when the wind direction varies. The yaw motor is used to move the yaw.
- **The brake** is a mechanical part connected to the high-speed shaft in order to reduce the rotational speed or stop the wind turbine over speeding or during emergency conditions.
- **Gearbox** is a mechanical component that is used to increase or decrease the rotational speed. In wind turbines, the gearbox is used to control the rotational speed of the generator.
- **The generator** is the component that converts the mechanical energy from the rotor to electrical energy. The most common electrical generators used in wind turbines are induction generators (IGs), doubly fed induction generators (DFIGs), and permanent magnet synchronous generators (PMSGs).
- **The controller** is the brain of the wind turbine. It monitors constantly the condition of the wind turbine and controls the pitch and yaw systems to extract optimum power from the wind.
- **Anemometer** is a type of sensor that is used to measure the wind speed. The wind speed information may be necessary for maximum power tracking and protection in emergency cases.
- **The wind vane** is a type of sensor that is used to measure the wind direction. The wind direction information is important for the yaw control system to operate.

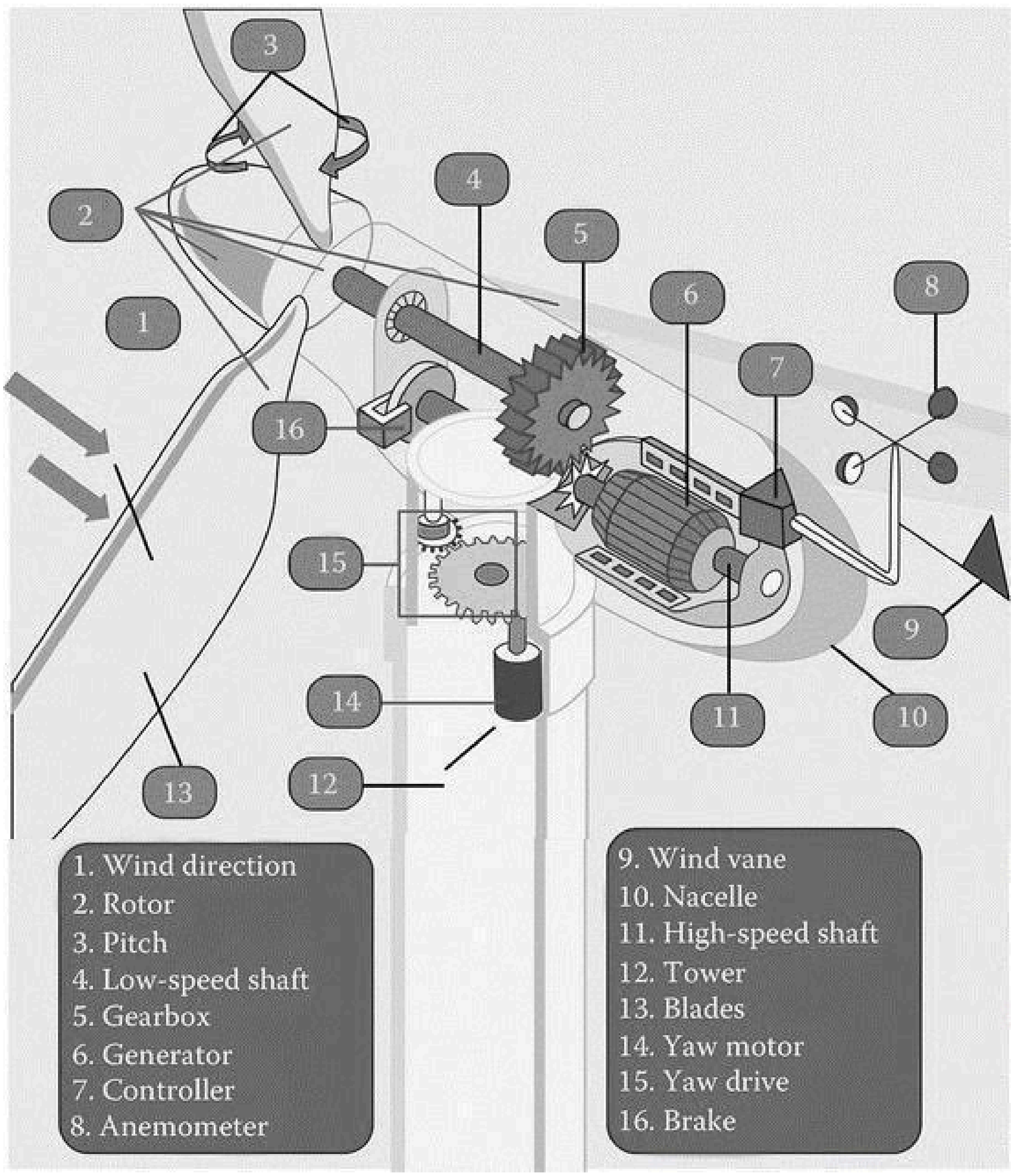


Fig. 9. Components of wind turbine

Working of WPPs (Refer Fig.10 with the following serial no)

1. Wind (moving air that contains kinetic energy) blows toward the turbine's rotor blades.
2. The rotors spin around, capturing some of the kinetic energy from the wind, and turning the central drive shaft that supports them. Although the outer edges of the rotor blades move very fast, the central axle (drive shaft) turns quite slowly.
3. In most large modern turbines, the rotor blades can swivel on the hub at the front so they meet the wind at the best angle (or "pitch") for harvesting energy. This is called the pitch control mechanism. On big turbines, small electric motors or hydraulic rams swivel the blades back and forth under precise electronic control. On smaller turbines, the pitch control is often completely mechanical. However, many turbines have fixed rotors and no pitch control at all.
4. Inside the nacelle (the main body of the turbine sitting on top of the tower and behind the blades), the gearbox converts the low-speed rotation of the drive shaft (perhaps, 16 revolutions per minute, rpm) into high-speed (perhaps, 1600 rpm) rotation fast enough to drive the generator efficiently.
5. The generator, immediately behind the gearbox, takes kinetic energy from the spinning drive shaft and turns it into electrical energy. Running at maximum capacity, a typical 2MW turbine generator will produce 2 million watts of power at about 700 volts.
6. Anemometers (automatic speed measuring devices) and wind vanes on the back of the nacelle provide measurements of the wind speed and direction.
7. Using these measurements, the entire top part of the turbine (the rotors and nacelle) can be rotated by a yaw motor, mounted between the nacelle and the tower, so it faces directly into the oncoming wind and captures the maximum amount of energy. If it is too windy or turbulent, brakes are applied to stop the rotors from turning (for safety reasons). The brakes are also applied during routine maintenance.
8. The electric current produced by the generator flows through a cable running down through the inside of the turbine tower.
9. A step-up transformer converts the electricity to about 50 times higher voltage so it can be transmitted efficiently to the power grid (or to nearby buildings or communities). If the electricity is flowing to the grid, it is converted to an even higher voltage by a substation nearby.
10. The consumer enjoy clean, green energy: the turbine has produced no greenhouse gas emissions or pollution as it operates.
11. Wind carries on blowing past the turbine, but with less speed and energy and more turbulence (since the turbine has disrupted its flow).

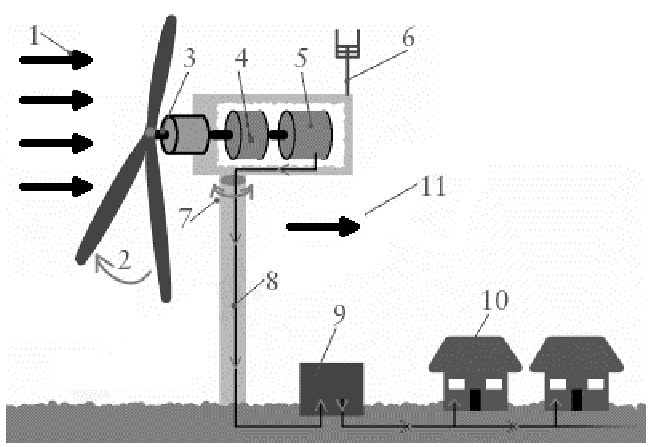


Fig. 10. Working of wind power plant

Pitch control and yaw control

Suzlon Energy Limited, Regen Powertech private limited, Inox Wind limited, Orient Green Power Limited, Vestas India, Enercon India Pvt limited, Gamesa wind turbines private limited.

Different control methods are used either to optimize or limit power output. You can control a turbine by controlling the generator speed, blade angle adjustment and rotation of the entire wind turbine. Blade angle adjustment and turbine rotation are also known as pitch and yaw control, respectively.

The purpose of **pitch control** is to maintain the optimum blade angle to achieve certain rotor speeds or power output. You can use pitch adjustment to stall and furl, two methods of pitch control. By stalling a wind turbine, you increase the angle of attack, which causes the flat side of the blade to face further into the wind. Furling decreases the angle of attack, causing the edge of the blade to face the oncoming wind. Pitch angle adjustment is the most effective way to limit output power by changing aerodynamic force on the blade at high wind speeds. This maintains the turbine‘s safety in the event of high winds, loss of electrical load, or other catastrophic events.

Fig. 11. Pitch control

Yaw refers to the rotation of the entire wind turbine in the horizontal axis. Yaw control ensures that the turbine is constantly facing into the wind to maximize the effective rotor area and, as a result, power. Because wind direction can vary quickly, the turbine may misalign with the oncoming wind and cause power output losses.

Fig. 12. Yaw control

Stall control

(Passive) stall controlled wind turbines have the rotor blades bolted onto the hub at a fixed angle. The geometry of the rotor blade profile, however has been aerodynamically designed to ensure that the moment the wind speed becomes too high, it creates turbulence on the side of the rotor blade which is not facing the wind. This stall prevents the lifting force of the rotor blade from acting on the rotor. In other words, as the actual wind speed in the area increases, the angle of attack of the rotor blade will increase, until at some point it starts to stall.

If you look closely at a rotor blade for a stall controlled wind turbine you will notice that the blade is twisted slightly as you move along its longitudinal axis. This is partly done in order to ensure that the rotor blade stalls gradually rather than abruptly when the wind speed reaches its critical value (other reasons for twisting the blade are mentioned in the previous section on aerodynamics).

The basic advantage of stall control is that one avoids moving parts in the rotor itself, and a complex control system. On the other hand, stall control represents a very complex aerodynamic design problem, and related design challenges in the structural dynamics of the whole wind turbine, e.g. to avoid stall-induced vibrations. Around two thirds of the wind turbines currently being installed in the world are stall controlled machines.

Siting of WPPs

The power available in the wind increases rapidly with the speed, hence wind energy conversion machines should be located preferable in areas where the winds are strong and persistent. Although daily winds at a given site may be highly variable, the monthly and especially annual average are remarkably constant from year to year.

The major contribution to the wind power available at a given site is actually made by winds with speeds above the average. Nevertheless, the most suitable sites for wind turbines would be found in areas where the annual average wind speeds are known to be moderately high or high.

The site choice for a single or a spatial array of WECS is an important matter when wind electrics is looked at from the systems point of view of aero turbine generators feeding power into a conventional electric grid. If the WECS sites are wrongly or poorly chosen the net wind electrics generated energy per year may be sub optimal with resulting high capital cost for the WECS apparatus, high costs for wind generated electric energy, and low Returns on Investment. Even if the WECS is to be a small generator not tied to the electric grid, the siting must be carefully chosen if inordinately long break even times are to be avoided. Technical, economic, environmental, social and other factors are examined before a decision is made to erect a generating plant on a specific site. Some of the main site selection consideration are given below:

1. High annual average wind speed
2. Availability of anemometry data
3. Availability of wind V(t) Curve at the proposed site
4. Wind structure at the proposed site
5. Altitude of the proposed site
6. Terrain and its aerodynamic
7. Local Ecology
8. Distance to road or railways
9. Nearness of site to local centre/users
10. Nature of ground
11. Favourable land cost

1. **High annual average wind speed:** The speed generated by the wind mill depends on cubic values of velocity of wind, the small increases in velocity markedly affect the power in the wind. For example, Doubling the velocity, increases power by a factor of 8. It is obviously desirable to select a site for WECS with high wind velocity. Thus a high average wind velocity is the principle fundamental parameter of concern in initially appraising WESCS site. For more detailed estimate value, one would like to have the average of the velocity cubed.
2. **Availability of anemometry data:** It is another improvement sitting factor. The anemometry data should be available over some time period at the precise spot where any proposed WECS is to be built and that this should be accomplished before a sitting decision is made.
3. **Availability of wind V(t) Curve at the proposed site:** This important curve determines the maximum energy in the wind and hence is the principle initially controlling factor in predicting the electrical output and hence revenue return o the WECS machines.

   It is desirable to have average wind speed ‗V' such that V>=12-16 km/hr (3.5 – 4.5 m/sec) which is about the lower limit at which present large scale WECS generators ‗cut in' i.e., start turning. The V(t) Curve also determines the reliability of the delivered WECS generator power, for if the V(t) curve goes to zero there be no generated power during that time.

   If there are long periods of calm the WECS reliability will be lower than if the calm periods are short. In making such reliability estimates it is desirable to have measured V(t) Curve over about a 5 year period for the highest confidence level in the reliability estimate.
4. **Wind structure at the proposed site:** The ideal case for the WECS would be a site such that the V(t) Curve was flat, i.e., a smooth steady wind that blows all the time; but a typical site is always less than ideal. Wind specially near the ground is turbulent and gusty, and changes rapidly in direction and in velocity. This departure from homogeneous flow is collectively referred to as ―the structure of the wind‖.
5. **Altitude of the proposed site:** It affects the air density and thus the power in the wind and hence the useful WECS electric power output. Also, as is well known, the wind tend to have higher velocities at

higher altitudes. One must be carefully to distinguish altitude from height above ground. They are not the same except for a sea level WECS site.

6. **Terrain and its aerodynamic:** One should know about terrain of the site to be chosen. If the WECS is to be placed near the top but not on the top of a not too blunt hill facing the prevailing wind, then it may be possible to obtain a _speed-up‘ of the wind velocity over what it would otherwise be. Also the wind here may not flow horizontal making it necessary to tip the axis of the rotor so that the aeroturbine is always perpendicular to the actual wind flow.
   It may be possible to make use of hills or mountains which channel the prevailing wind into a pass region, thereby obtaining higher wind power.
7. **Local Ecology:** If the surface is base rock it may mean lower hub height hence lower structure cost. If trees or grass or vegetation are present, all of which tend to destructure the wind, the higher hub heights will be needed resulting in larges system costs that the bare ground case.
8. **Distance to road or railways:** This is another factor the system engineer must consider for heavy machinery, structure, materials, blades and other apparatus will have to be moved into any choosen WECS site.
9. **Nearness of site to local centre/users:** This obvious criterion minimizes transmission line length and hence losses and cost. After applying all the previous string criteria, hopefully as one narrows the proposed WECS sites to one or two they would be relatively near to the user of the generated electric energy.
10. **Nature of ground:** Ground condition should be such that the foundation for a WECS are secured. Ground surface should be stable. Erosion problem should not be there, as it could possibly later wash out the foundation of a WECS, destroying the whole system.
11. **Favourable land cost:** Land cost should be favourable as this along with other siting costs, enters into the total WECS system cost.
12. **Other conditions such as icing problem, salt spray or blowing dust should not present at the site, as they** may affect aeroturbine blades or environmental is generally adverse to machinery and electrical apparatus.

Grid integration issues of WPPs.

The electrical grid is the electrical power system network comprised of the generating plant, the transmission lines, the substation, transformers, the distribution lines and the consumer. Ideally the electric grid is aimed to operate at constant voltage and frequency. However, the grid can take some fluctuation in voltage and electrical equipment is designed for maximum and minimum allowable voltage levels, usually about +/- 10%.

Wind power generation varies depending on how wind fluctuates. However, the variations in output are smoothed when many wind power plants are aggregated over an area in a power system. To deal with uncertainty, wind power output can be forecasted minutes, hours, and even days ahead. Aggregating wind power plants over a wider geographic area will improve the forecast accuracy at all time frames.

Wind power as a generation source has specific characteristics, including variability, geographical distribution, favourable economics. Large-scale integration of both onshore and offshore wind raises challenges for the various stakeholders involved, ranging from generation, transmission and distribution to power trading and consumers.

In order to integrate wind power successfully, a number of issues need to be addressed in the following areas:

- **Variability:** 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 Variable Renewable Energy (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.
- **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.
- **Design and operation of the power system:** Reserve capacities and balance management, short- term forecasting of wind power, demand side management and storage and optimisation of system flexibility;
- **Grid infrastructure issues:** Optimisation of present infrastructure, extensions and reinforcements, offshore grids and improved interconnection;
- **Grid connection of wind power:** Grid codes and power quality and wind power plant capabilities;
- **Market redesign issues:** Market aggregation and adapted market rules increase the market flexibility particularly for cross-border exchange and operating the system closer to the delivery hour;
- **Institutional issues:** Stakeholder incentives, non-discriminatory third party grid access and socialisation of costs

The cost of a single 225 KW or 250 KW which is widely preferred is about Rs. 1 Crore.

Steps to integrate wind power to grid

Despite these issues, there are solutions for integrating solar and wind into the grid

- **Improved planning and coordination:** This is the first step, making sure that VRE is matched up with appropriately flexible dispatchable 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(National Renewable Energy Laboratory), ―can allow access to significant existing flexibility, often at lower economic costs than options requiring new sources of physical flexibility." This is the low-hanging fruit of grid flexibility. Recent research from the Regulatory Assistance Project offers an overview of the changes needed in "market rules, market design, and market operations." A new Department of Energy study describes utility best practices in "time-of-use pricing," which varies the price of electricity throughout the day to encourage demand shifting. In New York, utility regulations are being fundamentally rewritten to optimize the management of distributed energy resources (DERs).
- **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 is 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 is cheap and sharing it when it is more valuable, can help even out VRE's variable supply. It can even make VRE dispatchable, within limits.
- **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:** 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.

Grid Integration of wind farms and Power Quality Issues

The issue of power quality is of great importance to the wind turbines. The critical power quality issues related to integration of wind farms are discussed below.

1. **Issue of voltage variation:** If a large proportion of the grid load is supplied by wind turbines, the output variations due to wind speed changes can cause voltage variation, flicker effects in normal operation. The voltage variation can occur in specific situation, as a result of load changes, and power produce from turbine.
2. **Issue of voltage dips:** It is a sudden reduction in the voltage to a value between 1% & 90 % of the nominal value after a short period of time, conventionally 1ms to 1min. This problem is considered in the power quality and wind turbine generating system operation and computed according to the rule given in IEC 61400-3-7 standard, ―Assessment of emission limit for fluctuating load‖.
3. **Switching operation of wind turbine on the grid:** Switching operations of wind turbine generating system can cause voltage fluctuations and thus voltage sag, voltage swell that may cause significant voltage variation. The acceptances of switching operation depend not only on grid voltage but also on how often this may occur. The maximum number of above specified switching operation within 10- minute period and 2-hr period are defined in IEC 61400-3-7 Standard.
4. **Harmonics:** The harmonics voltage and current should be limited to acceptable level at the point of wind turbine connection in the system. This fact has lead to more stringent requirements regarding power quality, such as Standard IEC 61000-3-2 or IEEE-519.
5. **Flickers:** Flicker is the one of the important power quality aspects in wind turbine generating system. Flicker has widely been considered as a serious drawback and may limit for the maximum amount of wind power generation that can be connected to the grid. Flicker is induced by voltage fluctuations, which are caused by load flow changes in the grid. The flicker emission produced by grid-connected variable-speed wind turbines with full-scale back-to-back converters during continuous operation and mainly caused by fluctuations in the output power due to wind speed variations, the wind shear, and the tower shadow effects.
6. **Reactive power:** Traditional wind turbines are equipped with induction generators. Induction generator is preferred because they are inexpensive, rugged and requires little maintenance. Unfortunately induction generators require reactive power from the grid to operate. The interactions between wind turbine and power system network are important aspect of wind generation system.
7. **Location of wind turbine:** The way of connecting wind turbine into the electric power system highly influences the impact of the wind turbine generating system on the power quality. As a rule, the impact on power quality at the consumer‘s terminal for the wind turbine generating system (WTGS) located close to the load is higher than WTGS connected away, that is connected to H.V. or EHV system.
8. **Low voltage ride through capability:** The impact of the wind generation on the power system will no longer be negligible if high penetration levels are going to be reached. The extent to which wind power can be integrated into the power system without affecting the overall stable operation depends on the technology available to mitigate the possible negative impacts such as loss of generation for frequency support, voltage flicker, voltage and power variation due to the variable speed of the wind and the risk of instability due to lower degree of controllability.
9. **IEC recommendation:** For consistent and replicable documentation of power quality characteristic of wind turbine, the international Electro-technical Commission IEC-61400-21 was developed and today, most of the large wind turbine manufactures provide power quality characteristic data accordingly. IEC 61400-21 describe the procedures for determine the power quality characteristics of wind turbines.

Grid code for wind farms

Parameter	Allowable limit
Voltage Rise	< 2%
Voltage dips	≤ 3 %
Flicker	≤ 0.4, for average time of 2 hours
Grid frequency	47.5-51.5 Hz

Unit – 2
Wind Speed and Energy

2.0 Power contained in wind: Power contained in wind is given by the kinetic energy of the flowing air mass per unit time. That is,

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

Kinetic Energy= $\frac{1}{2}(m v^2)$ joules (1-1)

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

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

(1-2)

If we let P = mechanical power in the moving air ρ= air density, kg/m^3

A = area swept by the rotor blades, m^2 V = velocity of the air, m/s

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

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

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

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

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

2.0 Thermodynamics of Wind Energy:

It is easy to appreciate the fact that though kinetic in nature, wind is low-quality energy. It is basically a relatively unidirectional motion of air molecules, in that not all the molecules move in the same direction. There is random and disorderly thermal motion of the molecules in all directions. Only the algebraic summation yields a resultant value in one direction. Naturally, the order or organization of this form of energy is low in comparison with the motion of a shaft, where all the molecules share a common motion. Our objective in wind energy conversion is to transform this energy into the rotation of a shaft or the flow of electrons. Only then it becomes useful to mankind.

The second law of thermodynamics states that whenever there is a transformation from low-quality energy to high-quality energy it is impossible to achieve 100 per cent efficiency even in theory. There is always a theoretical maximum limit on the efficiency. In the case of conversion of heat energy into mechanical energy, the limit is given by **$(1 - T_2/T_1)$** where **T_1** and **T_2** are the temperatures of the source and the sink, respectively, expressed in absolute scale. Similarly, in the case of conversion of wind energy into the mechanical energy of a rotating shaft , there must be some theoretical upper limit on the efficiency of the conversion. What is that upper limit? We will discuss this limit in the following section.

2.0 Efficiency limit for wind energy conversion:

(Power Extracted from the Wind) (This is from Mukund)

The actual power extracted by the rotor blades is the difference between the upstream and the downstream wind powers. That is, using Equation 4-2:

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

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

The air velocity is discontinuous from V to V_o at the "plane" of the rotor blades in the macroscopic sense *(we leave the aerodynamics of the blades which is beyond* *our scope)*. The mass flow rate of air through the rotating blades is, therefore, derived by multiplying the density with the average velocity. That is:

$$mass\ flow\ rate = \rho \cdot A \cdot \frac{V + V_o}{2} \tag{1.6}$$

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

$$P_o = \frac{1}{2}\left[\rho \cdot A \cdot \frac{(V + V_o)}{2}\right] \cdot \left(V^2 - V_o^2\right) \tag{1.7}$$

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

$$P_o = \frac{1}{2}\rho \cdot A \cdot V^3 \frac{\left(1 + \frac{V_o}{V}\right)\left[1 - \left(\frac{V_o}{V}\right)^2\right]}{2} \tag{1.8}$$

T[illegible]sed as a fraction of the upstream wind power as follows:

$$P_o = \frac{1}{2}\rho \cdot A \cdot V^3 \cdot C_p \tag{1.9}$$

Where

$$C_p = \frac{\left(1 + \frac{V_o}{V}\right)\left[1 - \left(\frac{V_o}{V}\right)^2\right]}{2} \tag{1.10}$$

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

For a given upstream wind speed, the value of C_p depends on the ratio of the downstream to the upstream wind speeds, that is (V_o/V). The plot of power coefficient versus (V_o/V) shows that C_p is a single, maximum-value function (Figure 4-3). It has the maximum value of 0.59 when the (V_o/V) is one-third. The maximum power is extracted from the wind at that speed ratio, when the downstream wind speed equals one-third of the upstream speed. Under this condition:

$$P_{max} = \frac{1}{2}\rho \cdot A \cdot V^3 \cdot 0.59 \tag{1.11}$$

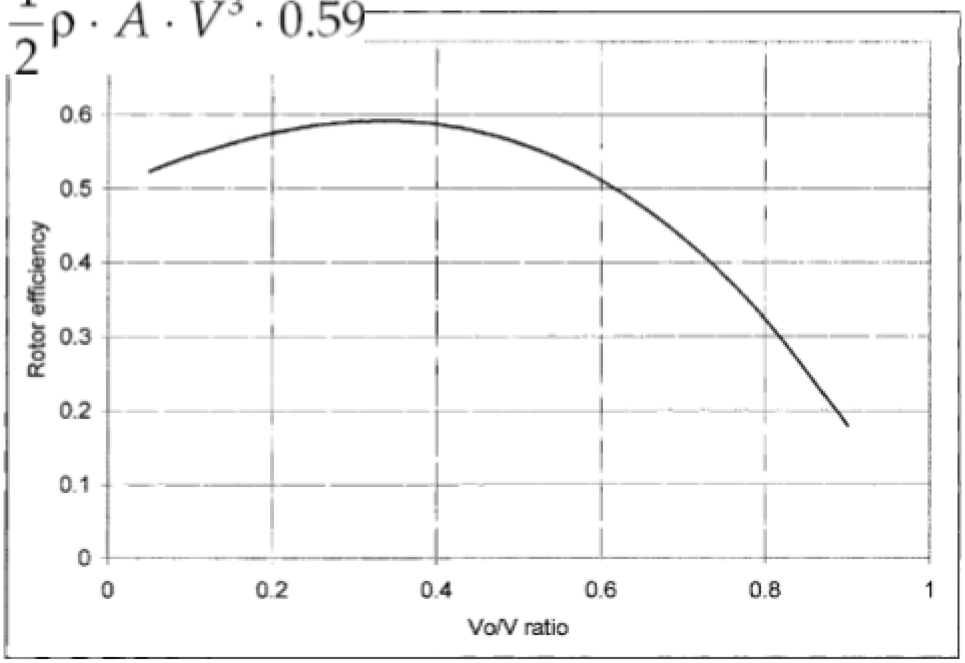


Figure 1-3: Rotor efficiency versus V_o/V ratio has single maximum. Rotor efficiency is the fraction of available wind power extracted by the rotor and fed to the electrical generator.

The theoretical maximum value of C_p is 0.59. This limit is called '***Betz Limit***'. In practical designs, the maximum achievable C_p is below 0.5 for high-speed, two- blade turbines, and between 0.2 and 0.4 for slow speed turbines with more blades as shown in the figure below. (Figure 1-2).

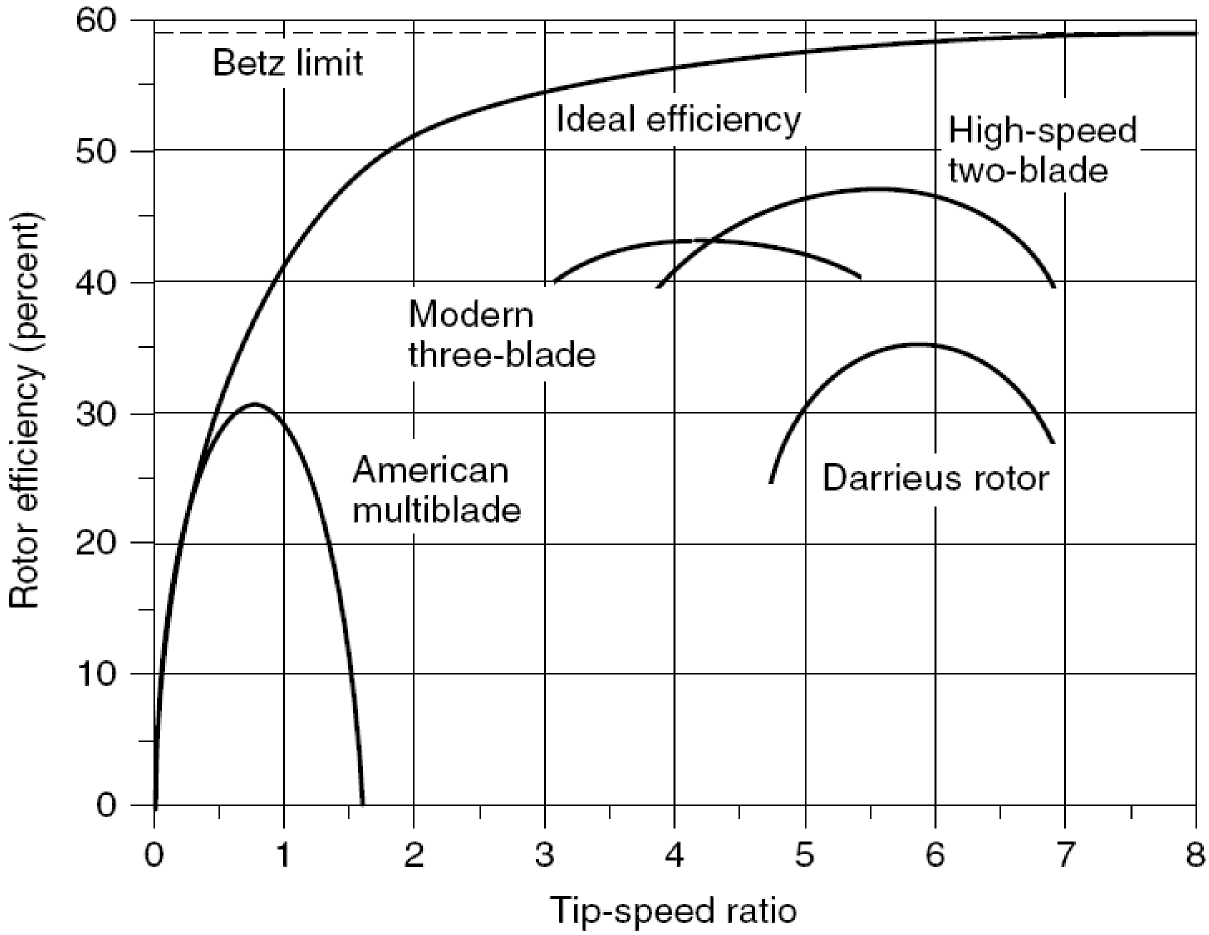


Figure 1-2: Rotor efficiency versus tip speed ratio for rotors with different number of blades. Two-blade rotors have the highest efficiency.

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

$$P_{max} = \frac{1}{4} \cdot \rho \cdot V^3 \text{ watts per } m^2 \text{ of swept area.} \tag{1.12}$$

Tip speed ratio:

The tip speed ratio (TSR) of a wind turbine is defined as $\lambda = (2\pi RN)/V$ where λ is the TSR (non dimensional, R is the radius of the swept area (in meters), N is the rotational speed in revolutions per second and V is the wind speed without rotor interruption in meters/second).

The TSRs of Savonius rotor and multiblade water pumping windmills are generally low. In high speed horizontal axis rotors and Darrieus rotors, the outer tip actually turns much faster than the wind speed owing to the aerodynamic shape. Consequently, the TSR can be as high as 9. It can be said that high solidity rotors have in general low TSRs and vice versa.

Power Coefficient:

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

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

2.0 Design of the wind turbine rotor:

The design of the wind turbine rotor is basically aerodynamics related and its study is beyond our scope. However a basic knowledge of the underlying basic principles of a WT Rotor design is essential even for an Electrical engineer. Hence we will study them briefly in this topic.

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

2.0.1 Design of the Blade profile:

From the basic principles of Aerodynamics, efficient design of a blade maximizes the lift and minimizes the drag. Minimization of Drag means that the aerofoil should face the relative wind in such a direction that the smallest possible area is exposed to the wind drag. The angle of relative wind is determined by the relative magnitudes of ‘u’ and ‘v’. The wind velocity is constant throughout the rotor area but the blade velocity increases from the inner edge to the tip. So neither the magnitude nor the angle of the relative wind is constant throughout the length of the blade.

From this observation a few qualitative conclusions about the desirable features of a wind turbine blade can be drawn.

First as the aerofoil has to face the relative wind at all points, it should have a varying pitch angle along the blade. In other words, it should have a twist.

Second, as the lift force developed at the blade tip is higher than that at the inner edge due to the difference in the magnitude of ‘w’, the tip tries to move faster than the central parts. This produces a stress that may cause blade failure. Moreover, the tension developed at the inner side due to centrifugal force is more than that at the tip.

Both these problems can be remedied by designing a tapering blade so that the blade area at the tip is less than that at the inner edge. To achieve perfect balance of all these forces at all parts of the blade , it may sometimes be desirable to have a varying aerofoil section along the blade .However some of these features are too expensive to implement , and a compromise is often struck between efficiency and production cost.

Diameter of the Rotor:

The diameter of the rotor is determined from the operating wind speed and the rated power output. The generated power is given by: v $\eta_m \rho$ $\eta_e \rho$ $C_p V3$

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

Where η_m is the efficiency of the mechanical transmission and η_e is the efficiency of electrical generation. If the rated P (W), V (m/s) , and C_p are known ,the diameter in meters can be found out.

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

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

$= 0.20D^2V^3$ for fast rotors

Choice of the number of blades :

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

Let 't_a' be the time taken by one blade to ove into the position previously occupied by the preceding blade. For a 'n' bladed rotor roating at an angular velocity of 'ω'

$t_a = 2\pi/n\omega$ 1.36

Let t_b be the time taken by the distributed wind , caused by the interference of a blade , to move away and normal air to be re-established. It depends on the wind speed 'v' and the length of the strongly perturbed air stream, say 'd'. This length stretching both upward and downward depends on the size and shape of the blades.

$t_b = d/v$ 1.37

For maximum power extraction , t_a and t_b should be more or less equal. Then from the above equations 1.36 and 1.37 we have

$2\pi/n\omega = d/v$ or $\omega/v = 2\pi/nd$

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

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

Choice of the Pitch angle :

The pitch angle is given by $\alpha = I - i$. As I varies along the length of blade , α should also vary to ensure an optimal angle of incidence at all points of the blade. Thus the desirable twist along the blade can be calculated easily.

The pitch angle should be such that tan ε or C_D/C_L is minimum at all points of the rotor. Some authors recommend the use of the Eiffel polar plot for this purpose. In this method , the tangent to the Effel polar plot gives the minumum C_D/C_L.However for the tangent to represent tan ε , both C_D and C_L should be drawn to the same scale. This becomes very inconvenient, since for most aerofoils
, C_L is about two orders of magnitude higher than C_D.It is more convenient to plot the curve for C_D/C_Lversus i. Its minimum point will then represent the optimal value of the incidence angle.

This method yields a twisted blade i.e. one that has dfferent pitch angles at different distances from the axis. If the constraints in the production method do not permit a twist , the optimal value of α can be chosen for a suitable point on the blade, say r= 0.8R, and the same picth angle maintained through out the blade.

The Tower:

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

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

The Transmission System and the GearBox:

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

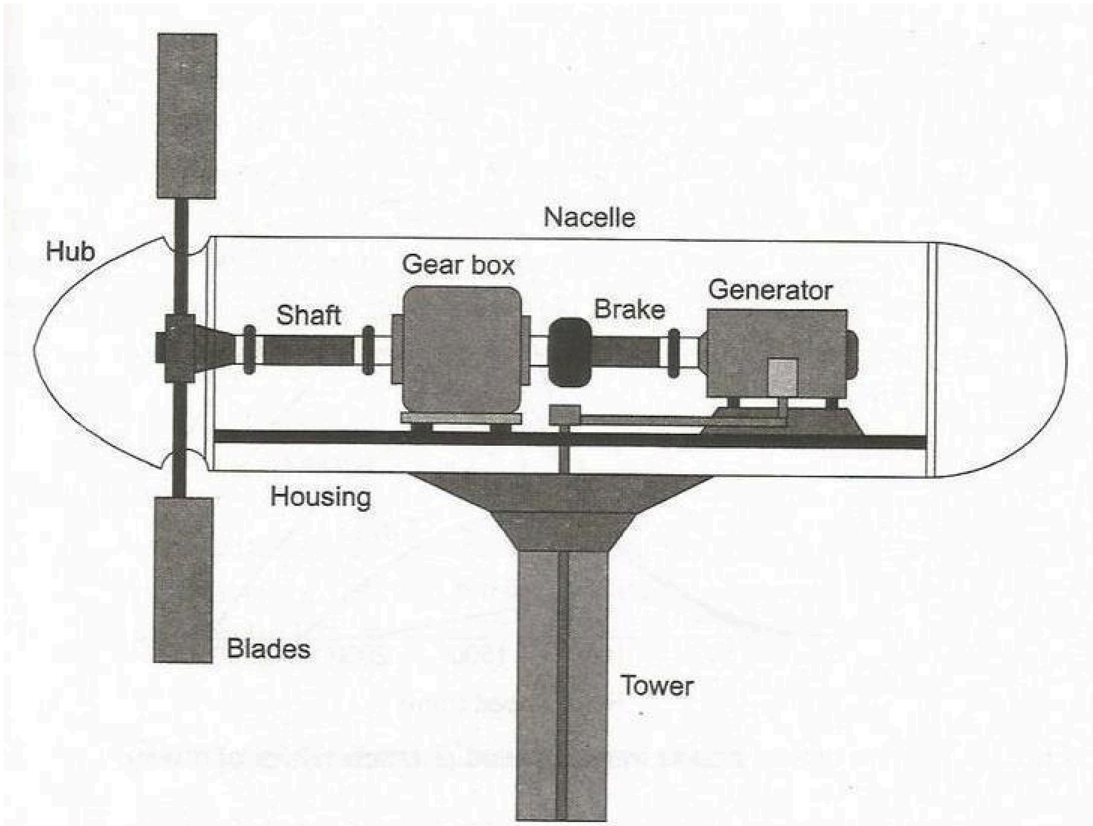


Figure : The Shaft ,Gearbox,Generator and Brake inside the Nacelle (Nacelle and the important subsystems inside)

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

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

Power –Speed Characteristics :

The wind turbine power curves shown in the figure below (1-17) illustrate how the mechanical power that can be extracted from the wind depends on the rotor speed. For each wind speed there is an optimum turbine speed at which the extracted wind power at the shaft reaches its maximum.

Such a family of wind turbine power curves can be represented by a single dimensionless characteristic curve , namely , the C_P-λ curve as shown in the figure below (1-12) where the power coefficient is plotted against the TSR. For a given turbine , the power coefficient depends not only on the TSR but also on the blade pitch angle. Figure 1-18 shows the typical variation of the power coefficent with
respect to the TSR λ with blade pitch control.

From equations 1-1 and 1-19 , the mechanical power transmitted to the shaft is given by:

$$P_m = \frac{1}{2}\rho C_p A V_\infty^3 \qquad (1.40)$$

Where C_P is a function of the TSR λ and the pitch angle α. For a wind turbine with a radius R, equation 1-40 can be expressed as

$$P_m = \frac{1}{2}\rho C_p \pi R^2 V_\infty^3 \qquad (1.41)$$

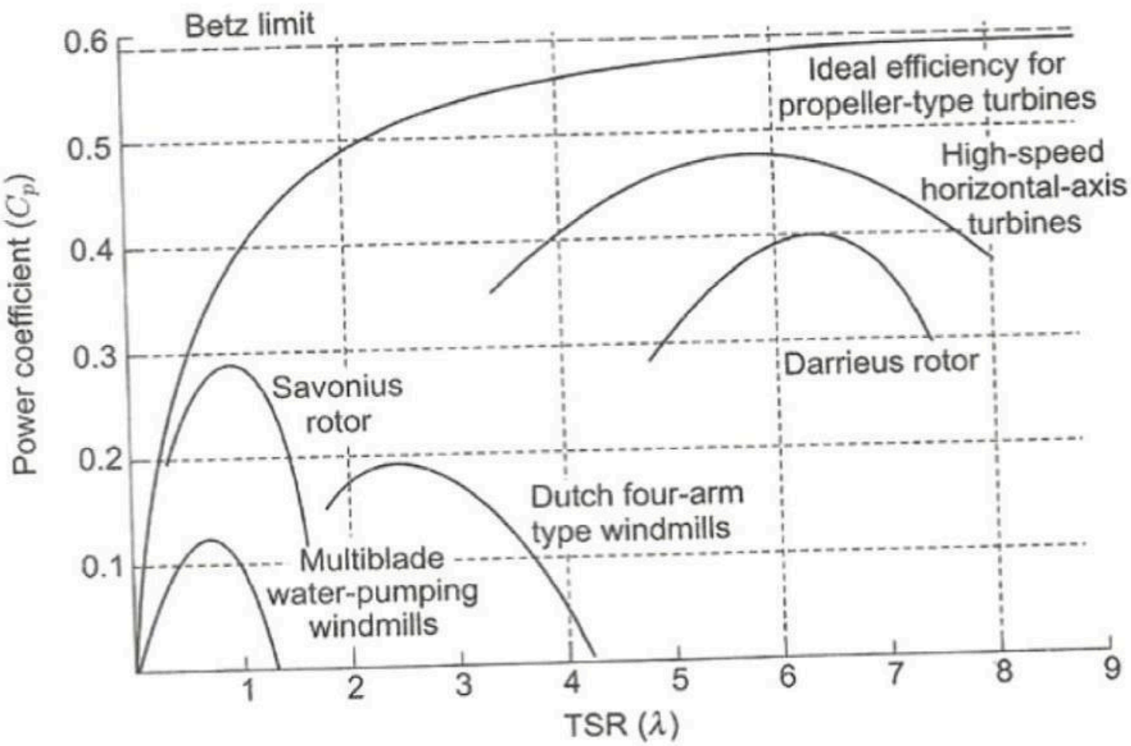


Figure (1-12): Curves of C_P vs TSR for various types of wind mills

For a given wind speed , the power extracted from the wind is maximised if C_P is maximised. The optimum value of C_P, say C_{Popt},always occurs at a definite value of λ say($= \lambda_{opt}$). This means that for varying wind speed, the rotor speed should be adjusted proportionally to adhere this value of λ ($= \lambda_{opt}$) for maximum mechanical output power from the turbine. Using the relation $\lambda = \omega R/V$ in equation (1-41) , the maximum value of the shaft mechanical power for any wind speed can be expressed as :

$$P_{\max} = \frac{1}{2}\, C_{p,\text{opt}} \pi \left(\frac{R^5}{\lambda_{\text{opt}}^3}\right) \omega^3 \qquad (1\text{-}42)$$

Thus the maximum mechanical power that can be extracted from wind is proportional to the cube of the rotor speed i.e.$P_{max} \propto \omega^3$. This is shown in figure 1- 17.

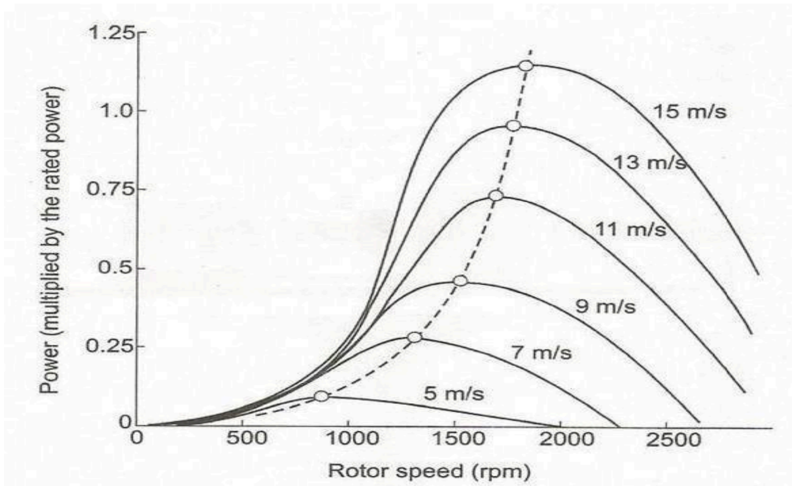


Figure : (1-17) Typical power vs speed characteristics of a wind turbine

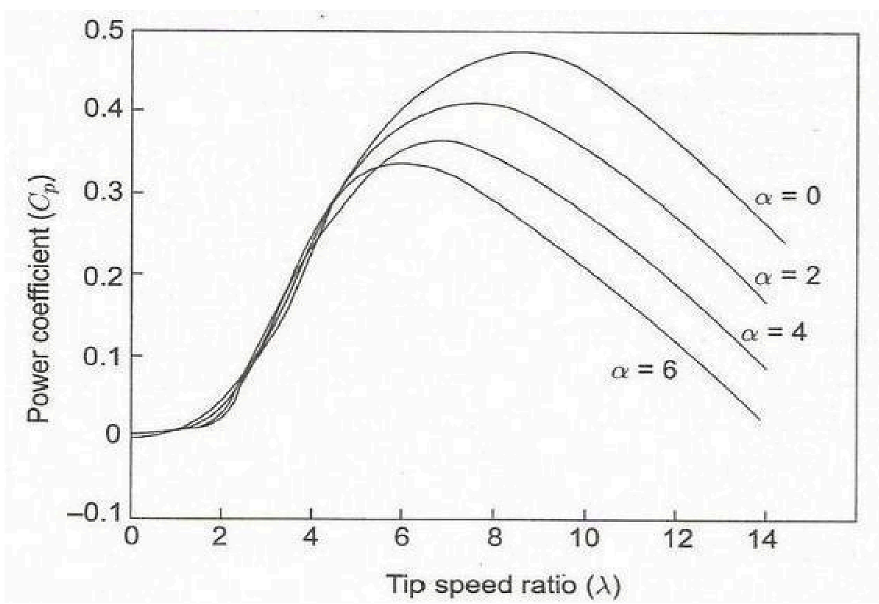


Figure: Typical curves of Power coefficient vs TSR for various Pitch angles

Torque –Speed Characteristics :

Studying the Torque versus rotational characteristics of any prime mover is very important for properly matching the load and ensuring stable operation of the electrical generator.The typical torque-speed characteristics of the two blade propellor type wind turbine, the Darrieus rotor and the Savonius rotor are shown in the figure below (1-19). The profiles of the torque –speed characteristic curves shown in this figure follow from the power curves, since Torque and power are related as follows:

$T_m = P_m/\omega$

From equation 1-42 , at the optimum operating point ($C_{p,opt}$, λ_{opt}), the relation between aerodynamic torque and rotational speed is:

$$T_m = \frac{1}{2}\rho C_{p,\text{opt}}\pi\left(\frac{R^5}{\lambda_{\text{opt}}^3}\right)\omega^2 \qquad \text{1-44}$$

It is seen that at the optimum operating point on the C_P-λ curve, the torque is quadratically related to the rotational speed.

The curves in figure 1-19 show that for the propellor turbine and the Darrieus rotor, for any wind speed , the torque reaches a maximum value at a specific rotational speed and this maximum shaft torque varies approximately as the square of the rotational speed. In the case of electricity production the load torque depends on the electrical loading and by properly choosing the load (or power electronics interface) the torque can be made to vary as the square of the rotational speed.

The choice of the constant of proportionality of the load is very important (see fig1-20) At the optimal value,the load curve follows the maximum shaft power. But at a higher value the load torque may exceed the turbine torque for most speeds.

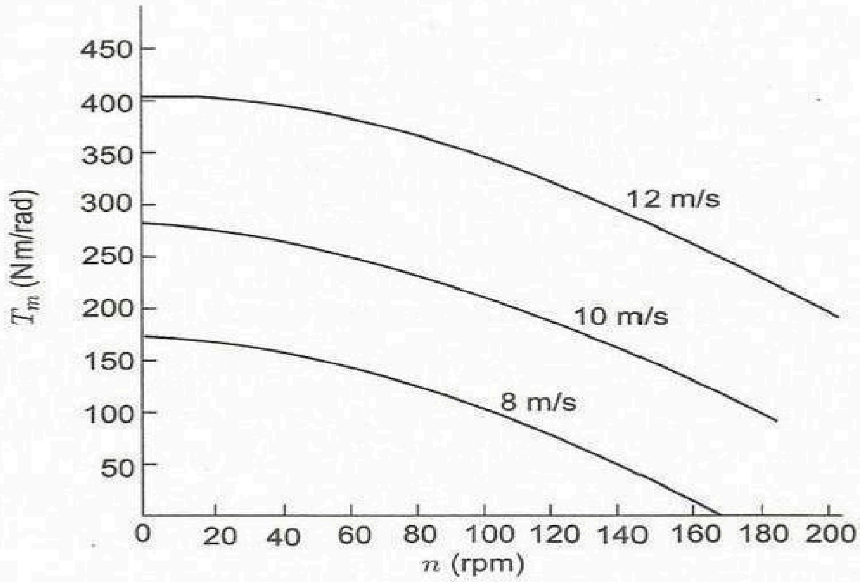
Consequently the machine would fail to speed up above a very low value. If the constant K is lower than the optimumvalue the machine may overspeed at the rated wind speed activating the speed limiting mechanism. Thus the proportionality constant of the load needs to be selected from a rather narrow range , about 10-20% of the optimum power curve. Note that the point of maximum torque is not the same as that of maximum power.

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

In terms of the power coefficient $C_P(\lambda,\alpha)$, the aerodynamic torque becomes :

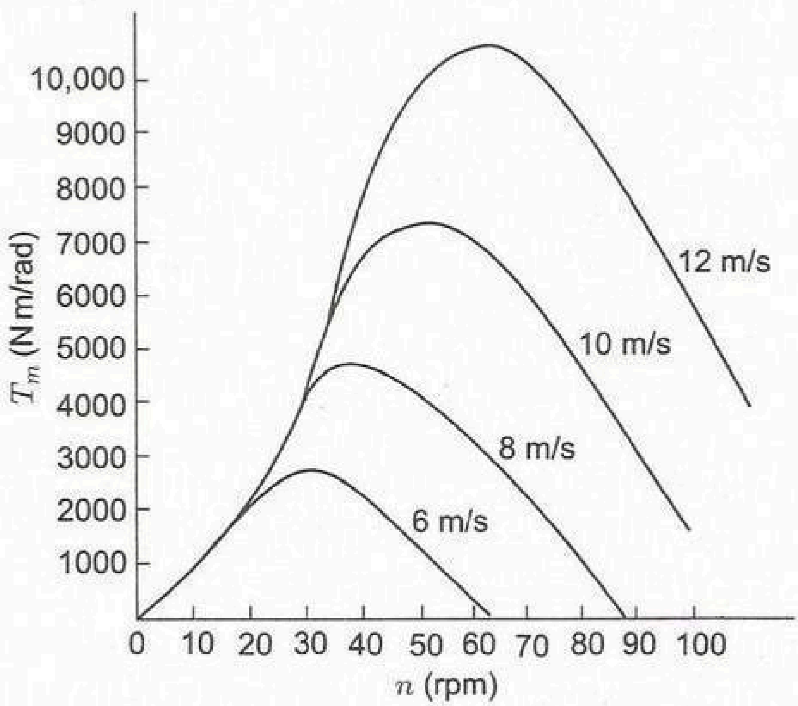
$$T_m = \frac{1}{2}\rho C_T \pi R^3 V_\infty^2 \qquad \text{1-45}$$

Where $C_T = C_P/\lambda$ is called the ***Torque Coefficient***



450
400
350
300
250
200
150
100
50
T_m (Nm/rad)
12 m/s
10 m/s
8 m/s
0 20 40 60 80 100 120 140 160 180 200
n (rpm)

(a)



10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
T_m (N m/rad)
12 m/s
10 m/s
8 m/s
6 m/s
0 10 20 30 40 50 60 70 80 90 100
n (rpm)

(b)

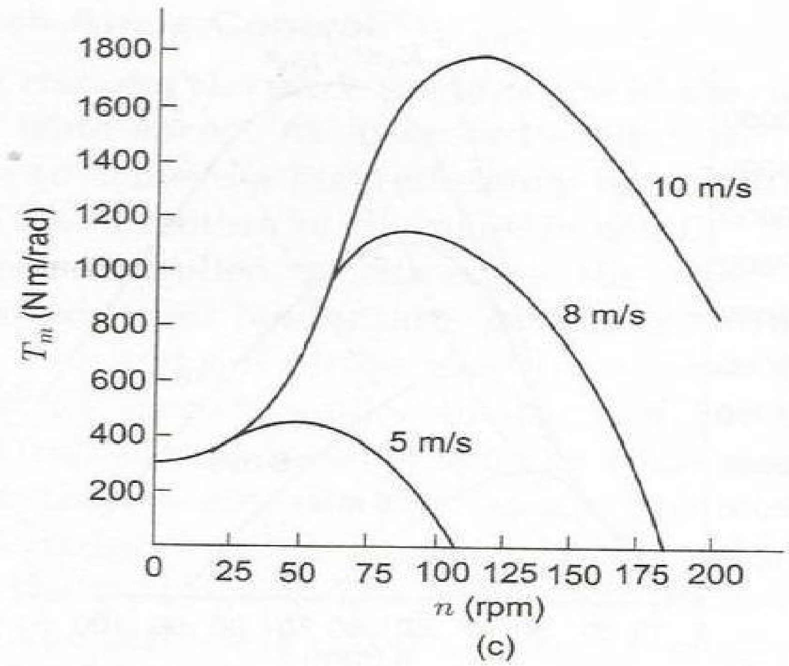


Fig. 1.19 The torque–speed characteristics of various types of wind machines: (a) the Savonius rotor, (b) the Darrieus rotor, (c) the two-blade propeller-type rotor

Wind Turbine Control systems:

1.12 Wind Turbine Control Systems

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

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

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

1.12.1 Pitch Angle Control

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

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

The Pitch angle control principle is explained in the figure below (1.21). The input variable to the pitch controller is the error signal arising from the difference between the output electrical power and the reference power. The pitch controller operates the blade actuator to alter the pitch angle. During operation below the rated speed, the control system endeavors to pitch the blade at an angle that maximizes the rotor efficiency. The generator must be able to absorb the mechanical power output and deliver to the load. Hence, the generator output power needs to be simultaneously adjusted.

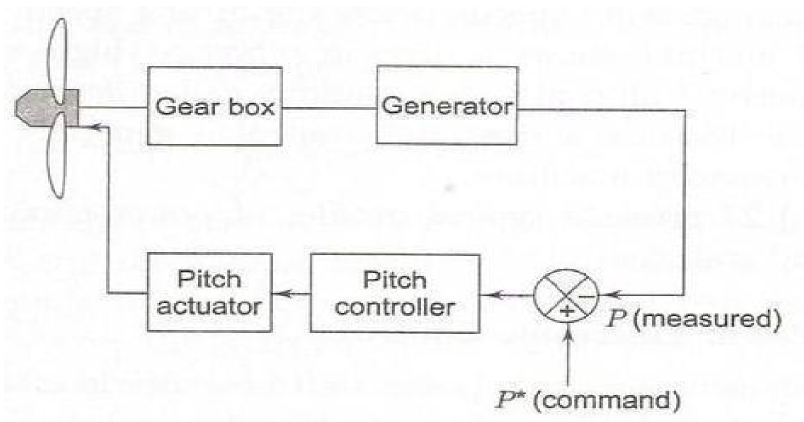


Fig. 1.21 The feedback loop for pitch angle control

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

1.12.2 Stall

Control

Passive stall

control

Generally stall control to limit the power output at high winds is appiled to constant-pitch turbines driving induction generators connected to the network. The rotor speed is fixed by the network, allowing only 1-4% variation. As the wind speed increases, the angle of attack also increases for a blade running at a near constant speed. Beyond a particular angle of attack, the lift force decreases, causing the rotor efficeincy to drop. This is an intrinsic property and dispenses with the need for a complex control system and moving parts. The lift force can be furthur reduced to restrict the power output at high winds by properly shaping the rotor blade profile to create turbulence on the rotor blade side not facing the wind.

Active stall control

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

Figure below (1.22) presents typical profiles of power curve for pitch control and stall control.

1.12.3 Power Electronic Control

In a system incorporating a power electronic interface between the generator and the load (or the grid), the electrical power delivered by the generator to the load can be dynamically controlled.

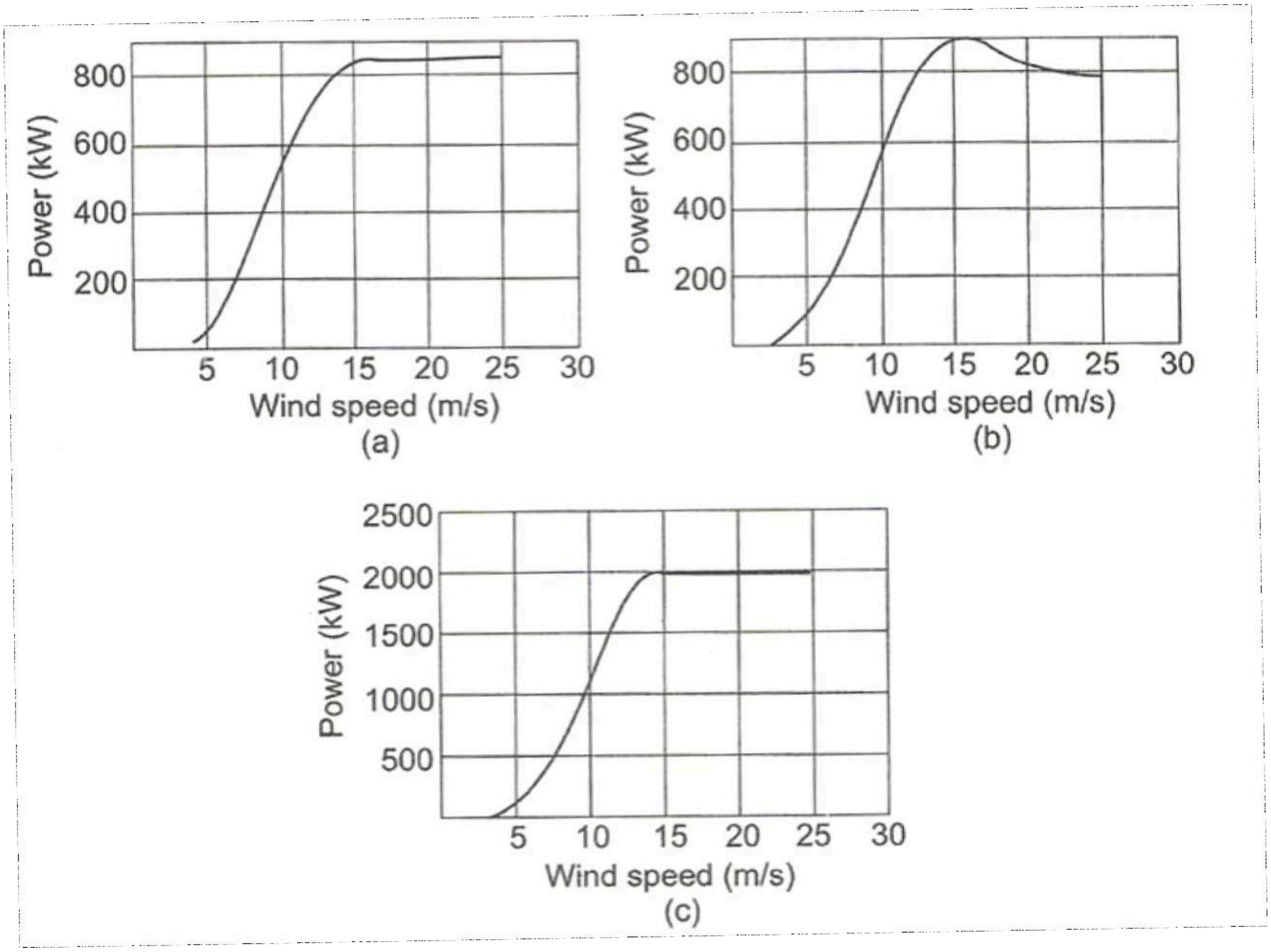


Fig. 1.22 Typical power profile: (a) pitch control (b) passive stall control (c) active stall control

The instantaneous difference between mechanical power and electrical power changes the rotor speed following the equation.

$$J\frac{dw}{dt} = \frac{Pm - Pe}{\omega} \qquad (1.46)$$

Where J is the polar moment of inertia of the rotor, ω is the angular speed of the rotor, P_m is the mechanical power produced by the turbine, and P_e is the electrical power delivered to the load. Integrating Eqn (1.46), we get

$$\frac{1}{2} J (\omega_2^2 - \omega_1^2) = \int_{t_1}^{t_2} (P_m - P_e)\,dt$$

The advantage of this method of speed control is that it does not involve any mechanical action and is smooth in operation. A disadvantage is that fast variation of speed requires a large difference between the input power and output power, which scales as the moment of inertia of the rotor. This results in a large torque and hence increases stress on the blades. Moreover, continuous control of the rotor speed by this method implies continuous fluctuation of the power output to the grid, which is usually undesirable for the power system.

1.12.4 Yaw Control

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

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

1.13 Control Strategy

For every wind turbine, there are five different ranges of wind speed, which require different speed control strategies (Fig. 1.23).

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

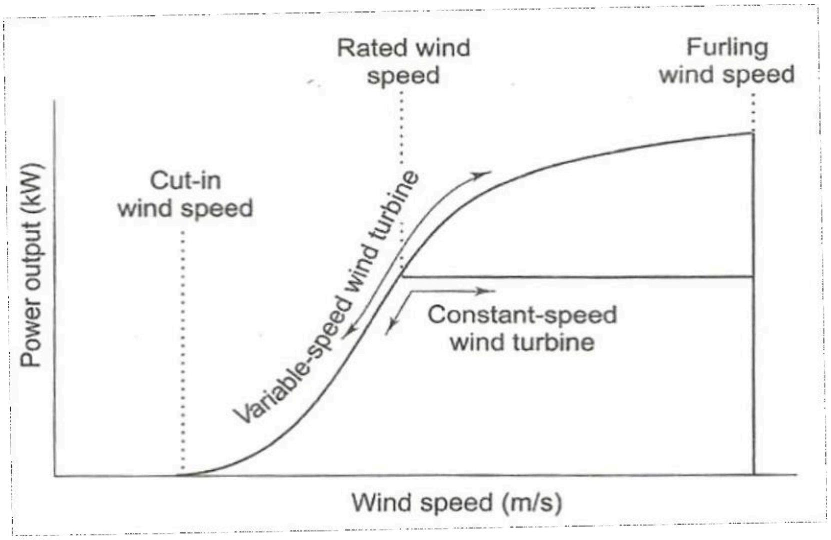


Fig. 1.23 Typical Power versus wind speed characteristics of variable speed wind machines

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

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

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

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

However, constant-speed generation systems cannot maximize the extraction of the power contained in wind. We can see from Fig.1.12 that the power coefficient reaches a maximum at a specific value of TSR for evey type of wind turbine. Therefore, to extract the maximum amount of power from the wind, the turbine should opearate at a constant TSR, which means that the rotational speed should be proportional to the wind speed. Hence the extraction of maximum power requires a variable-speed generation system with the speed control aimed at keeping a constant TSR.

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

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

The control scheme generally takes two possible forms. In the first case, the value of the TSR for maximum C_p is stored in a microprocessor. The operating TSR is obtained from the measured values of the wind speed and rotational speed. An error signal is generated whenever the operating TSR deviates from the optimum TSR. If the current value of the TSR deviates from the optimum TSR, the power electronic converted increases the power output so that the rotational speed is reduced to the desired value. The oppsite action is performed if the optimal value exceeds the current TSR.

This scheme has a few disdavantages. First, the wind speed measured in the neighbourhood of a wind turbine (or a wind farm) is not a reliable indicator of V_∞ because of the shadowing effects. Second, it is difficult to determine the value of TSR for maximum C_p. Third, this value changes during the lifetime of a wind turbine due to the changes in the smoothness of the blade surface, necessitating alterations in the refrence setting.

A second control scheme is devised to continousaly track the maximum power point (MPP) using the property that the C_P versus TSR curve has a single smooth maximum point. This means that if we operate ata the maximum point, small fluctuations in the rotational speed do not significantly change the power output, i.e., the MPP is characterized by $dP/d\omega = 0$. To implement this scheme, the speed is varied in small steps, the power output is measured, and $\Delta P/\Delta\omega$ is evaluated. If this ratio is positive, more mechanical power can be obtained by increasing the speed. Hence the electrical power output is decreased temporarily by power electronic control so that the speed increases. This increases the mechanical power, and the electrical power output is again raised to a higher value. The process continues untill the optimum speed is reached, when mechanical power becomes insensitive to speed fluctuations. When the wind speed changes, this mechanism readjusts the speed at the optimum value.

While controlling the rotaional speed, it should be remembered that a large difference between mechanical power and electrical power results in large torque and, hence, a large stress on the rotor components (especially on the joints between the blades and the shaft). To avoid fatigue and failure, it is necessary to limit the acceleration and deceleration rates to values dictated by the structual strength of the mechanical parts.

The use of brakes

In the event of load tripping or accidental disconnection of the electrical load, the rotor speed may increase dangerously. This may even lead to the mechanical destruction of the rotor. Moreover, at very high wind speeds, the electrical power throughput has to be kept within limits to protect the generator and the power electronic converter. This can be done by reducing the rotational speed. However, this speed control cannot be achived by power electronic control as discussed above, because that would call for an increase in the electrical power output which is exactly the opposite of what was desired.

UNIT – 3 SOLAR

PV SYSTEMS

Introduction

The basic principle behind both solar panel – solar photovoltaic (PV) and solar thermal – is the same. They absorb raw energy from the sun and use it to create usable energy. In solar PV systems this is through the creation of electricity, whereas thermal systems are used directly for heating water or air. The amount of solar radiation on the earth surface can be instrumentally measured using Pyrheliometer, Pyranometer, Photoelectric sunshine recorder and many instruments. Solar thermal power plants collect and concentrate sunlight to produce the high temperature heat needed to generate electricity. Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. A photovoltaic module consists of multiple PV cells connected in series to provide a higher voltage output. A photovoltaic array is a system composed of multiple PV modules. They can be connected in one or more series circuits, which are connected to a combiner box to provide a single direct-current output.

Solar Radiation

Solar radiation, often called the solar resource, is a general term for the electromagnetic radiation emitted by the sun. The sun emits electromagnetic radiations as a black body having a surface temperature of about 6000 K. This is because of the nuclear reaction running in it, where the sun is converting hydrogen into helium. The radius of the sun amounts to 1.39×10^9 m. The total radiation power received from the sun on a unit area perpendicular to the sun rays at the mean earth sun distance, termed an astronomical unit, is called the solar constant (SC), where 1 astronomical unit = 1AU = 1.496×10^{11}m.

The solar radiation intensity at other distances is expressed in terms of SC with SC = 1.353 kW/m^2. Like a black body radiation, the sun‘s radiation covers a wide spectrum of wavelengths from deep ultraviolet to far infrared. The power spectral distribution of the sunlight is shown in Fig. 1. The vertical axis represents the spectral irradiance I(λ) while the horizontal axis represents the wavelength in mm. The irradiance I(λ) is equal to the incident solar power/m^2/δλ = [W/m^2/mm], where δλ is the respective wavelength range in μm. It is clear from this figure that the maximum spectral irradiance lies at λ = 0.5μm. The spectral irradiance decreases because of the presence of air in the atmosphere. The air molecules scatter and absorb the solar radiation. There are multiple absorption bands for O_2, H_2O, and CO_2. It is important to notice that the solar irradiance resembles the black body radiation at ~ 6000 K represented by the dashed line.

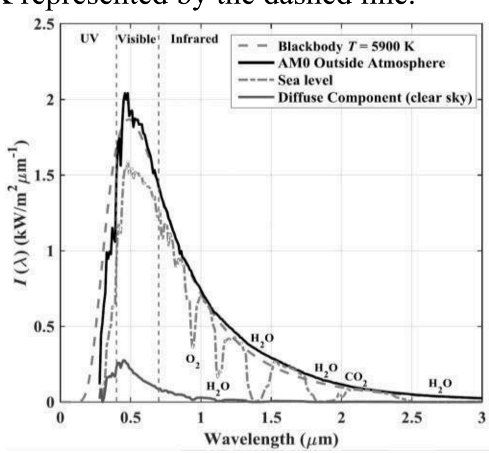


Fig.1. The power spectral distribution of the sunlight

The solar power intensity without the effect of the atmosphere or ground surface is called the Air Mass Zero where one AM0 = 1 SC = 135.3 mW/cm^2. The solar power intensity after crossing one air mass perpendicular to the earth is called the air mass 1, AM1. It represents the area under the spectral irradiance curve and amounts to 92.5 mW/cm^2. If θ is the angle of incidence with normal to the earth surface, then the optical path in units of the air mass will be larger. The air mass AM = 1/(cos θ).

As the solar radiation passes through the atmosphere, it gets absorbed, scattered, reflected, or transmitted. All these processes result in reduction of the energy flux density. Actually, the solar flux density is reduced by about 30% compared to extraterrestrial radiation flux on a sunny day and is reduced by as much as 90% on a cloudy day. The following main losses should be noted:

- ❖ absorbed by particles and molecules in the atmosphere - 10-30%
- ❖ reflected and scattered back to space - 2-11%
- ❖ scattered to earth (direct radiation becomes diffuse) - 5-26%

- As a result, the direct radiation reaching the earth surface (or a device installed on the earth surface) never exceeds 83% of the original extraterrestrial energy flux. This radiation that comes directly from the solar disk is defined as beam radiation.
- The scattered and reflected radiation that is sent to the earth surface from all directions (reflected from other bodies, molecules, particles, droplets, etc.) is defined as diffuse radiation. The sum of the beam and diffuse components is defined as total (or global) radiation. The beam radiation can be concentrated, while the diffuse radiation, in many cases, cannot be concentrated.
- Short-wave radiation, in the wavelength range from 0.3 to 3 μm, comes directly from the sun. It includes both beam and diffuse components.
- Long-wave radiation, with wavelength 3 μm or longer, originates from the sources at near-ambient temperatures - atmosphere, earth surface, light collectors, other bodies.
- The solar radiation reaching the earth is highly variable and depends on the state of the atmosphere at a specific locality. Two atmospheric processes can significantly affect the incident irradiation: scattering and absorption.

Scattering is caused by interaction of the radiation with molecules, water and dust particles in the air. The amount of light scattered depends on the number of particles in the atmosphere, particle size and the total air mass the radiation comes through.

Absorption occurs upon interaction of the radiation with certain molecules, such as ozone (absorption of short-wave radiation - ultraviolet), water vapour, and carbon dioxide (absorption of long- wave radiation - infrared).

Due to these processes, out of the whole spectrum of solar radiation, only a small portion reaches the earth surface. Thus most of x-rays and other short-wave radiation is absorbed by atmospheric components in the ionosphere, ultraviolet is absorbed by ozone and not-so abundant long-wave radiation is absorbed by CO_2. As a result, the main wavelength range to be considered for solar applications is from 0.29 to 2.5 μm.

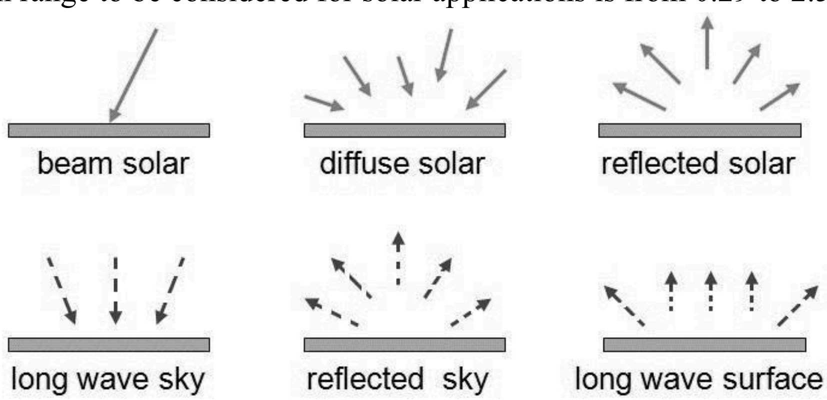


Fig.2.Different types of radiation at the earth surface: — short wave; - - long wave

India's solar installed capacity reached 34.404 GW as of 29 February 2020.

Insolation is the incident solar radiation onto some object. Specifically, it is a measure of the solar energy that is incident on a specified area over a set period of time. Generally insolation is expressed in two ways. One unit is kilowatt-hours per square meter (kWh/m^2) per day which represents the average amount of energy hitting an area each day. Another form is watts per square meter (W/m^2) which represents the average amount of power hitting an area over an entire year.

It is important to have values for insolation at certain positions on the Earth as these figures are used to help determine the size and output of solar power systems. Values for insolation can help to determine the expected output for solar panels and determine where on Earth solar panels would be most effective.

Radiation Measurement

The amount of solar radiation on the earth surface can be instrumentally measured, and precise measurements are important for providing background solar data for solar energy conversion applications. There are two important types of instruments to measure solar radiation:

1) Pyrheliometer 2) Pyranometer

Pyrheliometer is a device used for measuring direct beam radiation at normal incidence. Its outer structure looks like a long tube, projecting the image of a telescope and we have to point the lens to the sun to measure the radiance.

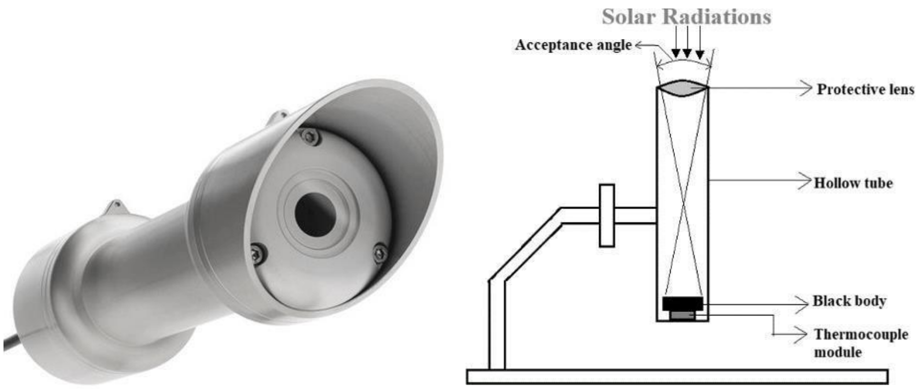


Fig. 3. Construction of Pyrheliometer

The lens is pointed towards the sun and the radiation will pass through the lens, tube and at the end falls on to the black object present at the bottom. A simpler diagram is shown in the Fig.4

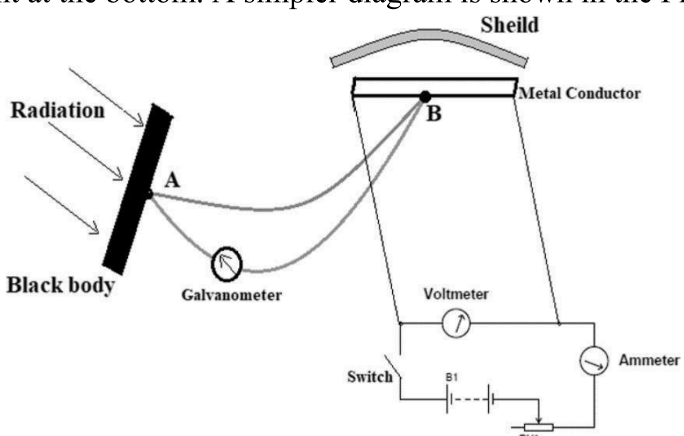


Fig.4. Simple diagram of Pyrheliometer

In the circuit, it can be seen that the black body absorbs the radiation falling from the lens and a perfect black body completely absorbs any radiation falling on it, so the radiation falling into the tube gets absorbed by the black object entirely. Once the radiation gets absorbed the atoms in the body gets excited because of the increasing temperature of the entire body. This temperature increase will also be experienced by the thermocouple junction ‗A‘. Now with junction ‗A‘ of the thermocouple at high temperature and junction ‗B‘ at low temperature, a current flow takes place in its loop.(Thermocouple action) This current in the loop will also flow through the galvanometer which is in series and thereby causing a deviation in it. This deviation is proportional to current, which in turn is proportional to temperature difference at junctions.

The deviation in the galvanometer can be reduced by adjusting the rheostat to change the current in the Metal conductor. Now by adjusting the rheostat until the galvanometer deviation becomes completely void. Once this happens we can obtain voltage and current readings from the meters and do a simple calculation to determine the heat absorbed by the black body. This calculated value can be used to determine the radiation, as heat generated by the black body is directly proportional to the radiation.

-Top 5 Largest Solar Power Plants in India-

1. Pavagada Solar Park, Karnataka 2. Kurnool Ultra Mega Solar Park, Andhra Pradesh 3. Kamuthi Solar Power Project, Tamil Nadu 4. Bhadla Solar Park, Rajasthan 5. Charanka Solar Park, Gujarat

Pyranometer working and Construction

Pyranometer is a device that can be used to measure both beam radiation and diffused radiation. In other words, it is used to measure total hemispherical radiation (beam plus diffuse on a horizontal surface). The device looks like a saucer which is the best shape suited for its purpose. This device is more popular than the others and most of the solar resource data nowadays are measured using it. The original picture and internal structure of the Pyranometer is shown in Fig.5.

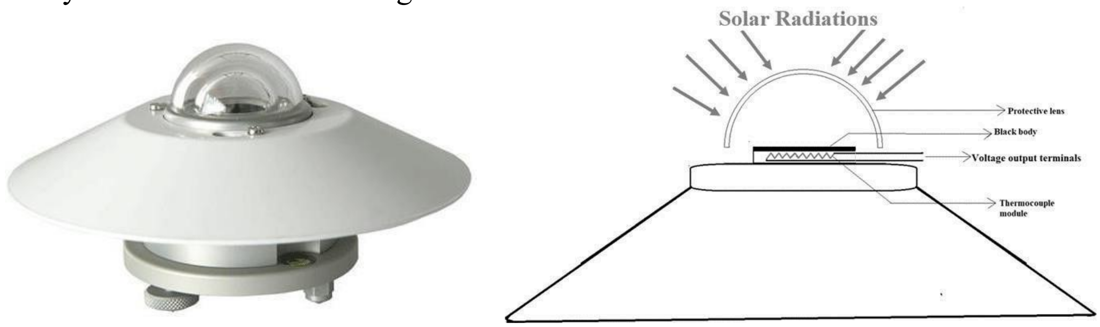


Fig.5. Pyranometer

Here the radiation from the surrounding atmosphere passes through the glass dome and falls onto the blackbody situated at the centre of the instrument. The temperature of the body rises after absorbing all the radiation and this rise will also be experienced by the Thermocouple chain or Thermocouple module present directly beneath the blackbody. So one side of the module will be hot and another will be cold because of the heat sink. The thermocouple module generates a voltage and this can be seen at the output terminals.
This voltage received at the output terminals is directly proportional to temperature difference according to the principle of a thermocouple.

Since we know that the temperature difference is related to radiation absorbed by the black body, we can say the output voltage is linearly proportional to the radiation. Similar to the previous calculation, the value of total radiation can be easily obtained from this voltage value. Also by using the shade and following the same procedure, we can also obtain the diffused radiation. With total radiation and diffused radiation value, beam radiation value can also be calculated.

Quantum Sensors

Quantum sensors are specialized devices which measure the quantity of photosynthetically active radiation, or the portion of the visible spectrum which can be used by photosynthetic organisms, within a band of solar radiation. Specifically, quantum sensors measure the photosynthetic photon flux density (PPFD) of sunlight. This measurement is useful in agriculture for choosing productive farmland locations or maintaining growhouses and is also used in oceanography to calculate the boundaries of an ocean's sunlight zone. (For the latter reason, quantum sensors are often built with waterproof housing.) Quantum sensors typically use photovoltaic technology to generate a potential output.

Fig. 6. Quantum sensors

Solar Thermal Power Plant

Solar thermal power plant is a combination of solar energy and thermal energy. The sun‘s radiations is used as fuel in the power plant. Solar energy is converted into heat or thermal energy which is further converted to mechanical energy using turbine and electrical energy using generators. Further categories are based upon the power cycles i.e. low, medium and high temperature cycles. These cycles are based upon the solar radiations and type of collectors used for collecting the solar radiations. In low temperature cycles the temperature is limited to about 100^0 C in medium temperature, range varies from 150^0 C to 300^0 C whereas in high temperature cycles temperature may go above 300^0 C.

For different temperature cycle different thermodynamic cycles are used in the power plant. Generally, for low and medium temperature ranges, Rankine cycle is preferred whereas for high temperature range Brayton cycle is used. The cycle operation and different components of the solar thermal power plant are discussed here;

- Solar pond
- Solar energy collectors
- Working fluid
- Evaporator Boiler
- Turbine and Generator
- Condenser and Cooling tower

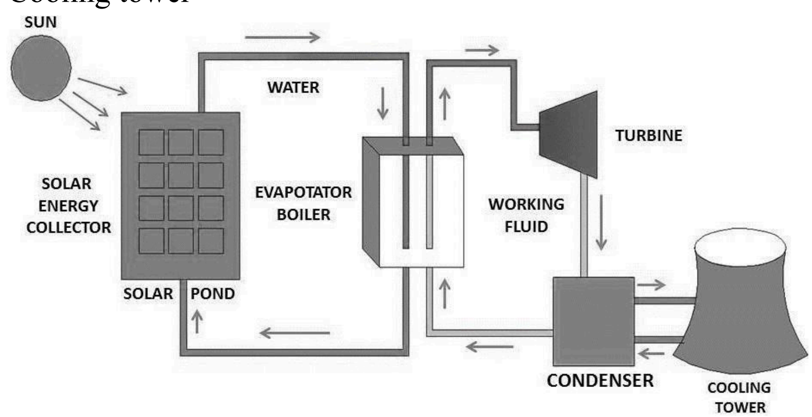


Fig.7. Solar thermal power plant

Solar pond: The solar energy coming from the sun is firstly absorbed by the solar pond. Solar pond is a reservoir of water where sun‘s rays directly focus by using solar energy collectors. After that, solar energy increases the internal energy and raises the temperature of solar pond. The fluid in the solar pond may be directly used as the working fluid if its temperature reaches up to evaporating temperature or other way is to use a secondary fluid known as working fluid. The fluid from the solar pond goes into cyclic process. The detailed operation of solar pond is as follows.

Solar pond, also called solar ‗salt pond‘, is an artificially designed pond, filled with salty water, maintaining a definite concentration gradient. It combines solar energy radiation and sensible heat storage, and as such, it is utilised for collecting and storing solar energy. A solar pond reduces the convective and evaporative heat losses by reversing the temperature gradient with the help of non-uniform vertical concentration of salts.

The vertical configuration of ―salt gradient solar pond‖ normally consists of the following three zones:

1. ―Surface (homogeneous) convective zone (SCZ)‖- It is adjacent to the surface and serves as a buffer zone between environmental fluctuations at the surface and conductive heat transport from the layer below. It is about 10 to 20 cm thick with a low uniform concentration at nearly the ambient air temperature.
2. ―Lower connective zone (LCZ)‖- It is at the bottom of the pond and this is the layer with highest salt concentration, where high temperatures are built up.

3. ―Concentration/Intermediate gradient zone (CGZ)‖- This zone keeps the two convective zones (SCZ and LCZ) apart and gives the solar pond its unique thermal performance. It provides excellent insulation for the storage layer, while transmitting the solar radiation. To maintain a solar pond in this non- equilibrium stationary state it is necessary to replace the amount of salt that is transported by molecular

SCG whilst brine is removed. The brine can be recycled, divided into water and salt (by solar distillation) and returned to the pond.

The major heat loss occurs from the surface of the solar pond. This heat loss can be prevented by spreading a plastic grid over the pond‘s surface to prevent disturbance by the wind. Disturbed water tends to lose heat transfer faster than when calm.

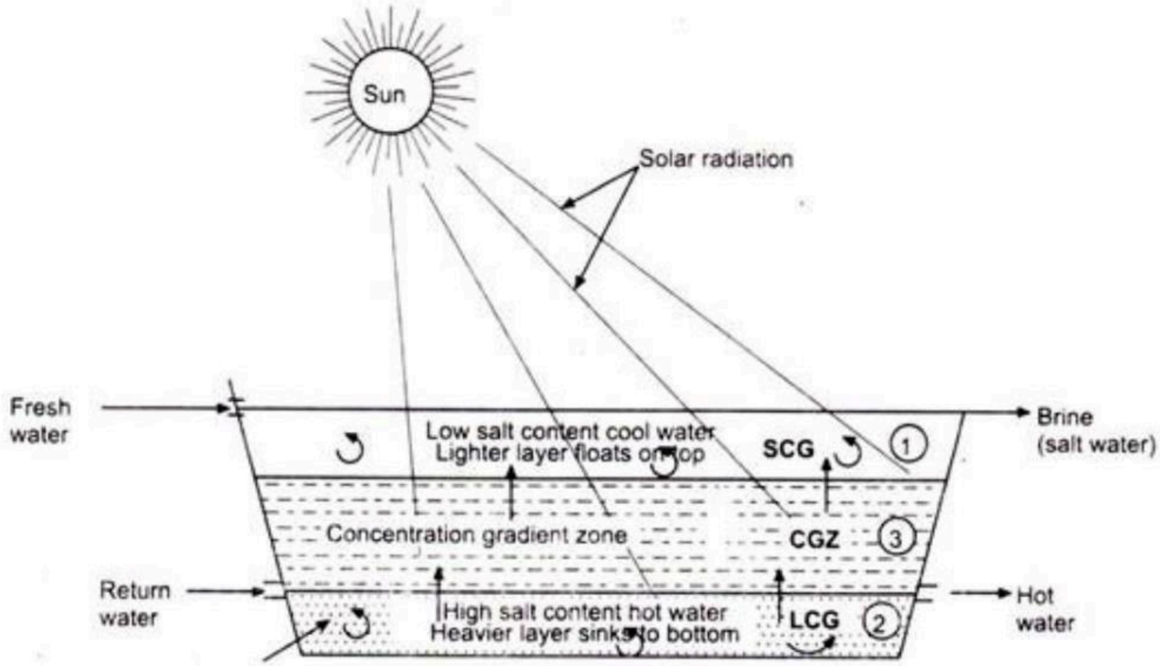


Fig.8. Principle of Solar Pond

Principle of Solar Pond

Due to the excessively high salt concentration of the LCZ, a plastic liner or impermeable soil must be used to prevent infiltration into the nearby ground water or soil. The liner is a factor that increases the cost of a solar pond. A site where the soil is naturally impermeable, such as the base of a natural pond or lake, or can be made impermeable by compaction or other means, will allow considerably lower power costs.

The optical transmission properties and related collection efficiency vary greatly and depend on the following factors:

i. Salt concentration.
ii. The quantity of suspended dust or other particles.
iii. Surface impurities like leaves or debris, biological material like bacteria and algae.
iv. The type of salt.

It becomes obvious that much higher efficiencies and storage can be achieved through the utilization of refined or pure salt whenever possible, as this maximizes optical transmission.

The solar pond is an effective collector of diffuse, as well as direct radiation, and will gather useful heat even on cloudy or overcast days. Under ideal conditions, the pond‘s absorption efficiency can reach 50% of incoming solar radiation, although actual efficiencies average about 20% due to heat losses.

Applications of Solar Ponds:

1. Power generation.
2. Space heating and cooling.
3. Crop drying.
4. Desalination.
5. Process heat.

Limitations of Solar Ponds:

1. Sunny climate is required
2. Need for large land area.
3. Availability of salt.
4. Availability of water.

Solar energy collectors: Solar energy collectors are the device used for collecting the solar radiations and focus the solar radiations at particular location to transfer the heat energy into the solar ponds or fluid. Generally, two types of collectors are used first is non-concentrating or flat plate type solar collector which is used for low temperature cycle and second one is concentrating or focusing type solar collector which are used for medium and high temperature applications. Collectors make the solar energy more useful. Flat plate collectors are very simple, the collecting area is equal to absorbing area where as focusing type collector have several arrangements of mirrors and lenses for proper concentration of sun light. Due to this by using focus type collectors we can capture 100 times solar radiation as compared to flat plate collector keeping the area same. By using focusing type collector we can directly generate medium pressure steam.

Solar collectors are classified as

1. Non concentrating type
   i) Flat-Plate Collectors
   ii) Evacuated-Tube Collector
2. Concentrating type
   i) Parabolic trough collector.
   ii) Power tower receiver.
   iii) Parabolic dish collector.
   iv) Fresnel lens collector.

Flat-Plate Collectors

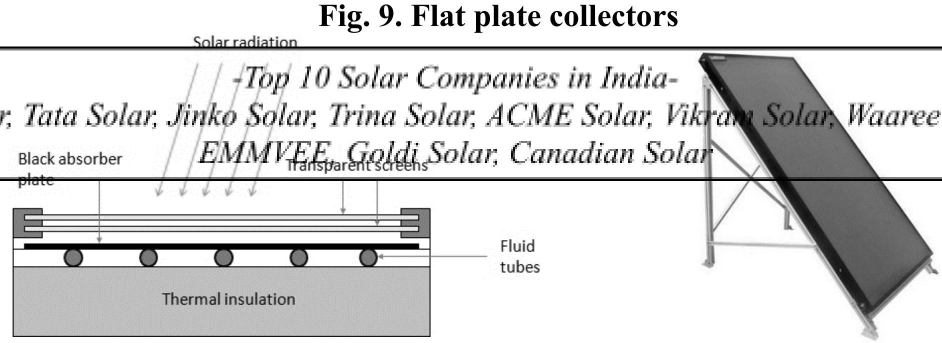
Flat-plate solar collectors are the most common ones. They consist of an absorber, a transparent cover and insulation. The main use of the technology is usually in residential buildings where the demand for hot water is big and affects bills. Commercial application of flat-plate collectors is usually seen in car washes, laundromats, military laundry facilities or restaurants.

The parts of a flat plate collectors are

- 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 solar collectors show a good price-performance ratio and also give a lot of mounting options.

Fig. 9. Flat plate collectors



Evacuated-Tube Collector

This is a type of a vacuum collector. Its absorber strip is placed in an evacuated and pressure proof glass tube. The heat transfer fluid flows directly the absorber into a U-tube or in a tube-in-tube system. The heat pipe collector integrates a special fluid, which evaporates even at low temperatures, thus the steam rises in the individual heat pipes and warms up the fluid in the main pipe, generating heat. Thermodynamic panels are also based on such a refrigerant fluid but are exploiting the heat in the ambient air, and, therefore, are only suitable for hot water.

The technology is very reliable as it has an estimated lifespan of 25 years. The vacuum that surrounds the outside of the tubes greatly reduces the risk of heat loss, therefore efficiency is greater than it is with flat-plate collectors.

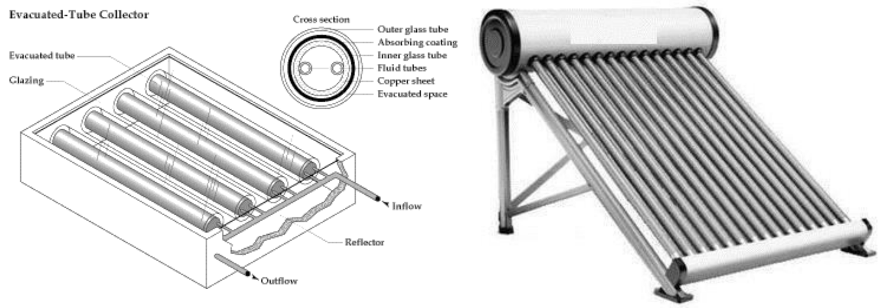


Fig. 10. Evacuated-Tube Collector

Parabolic Trough Collector

- It is a line focusing type collector. In this type of collector, the solar radiations falling on the area of the parabolic reflector are concentrated at the focus of the parabola.
- When the reflector is manufactured in the form of a trough with the parabolic cross-section, the solar radiations gets focused along a line. An absorber pipe is placed along this line and a working fluid (usually synthetic oil or water) flows through it.
- When the focused solar radiations fall on the absorber pipe, it heats the fluid to a high temperature. Then the heat absorbed by the working fluid is transferred to water for producing steam.
- The focus of solar radiations changes with the change in sun‘s elevation. In order to focus the solar radiations on the absorber pipe, either the trough or the collector pipe is rotated continuously about the axis of the absorber pipe.

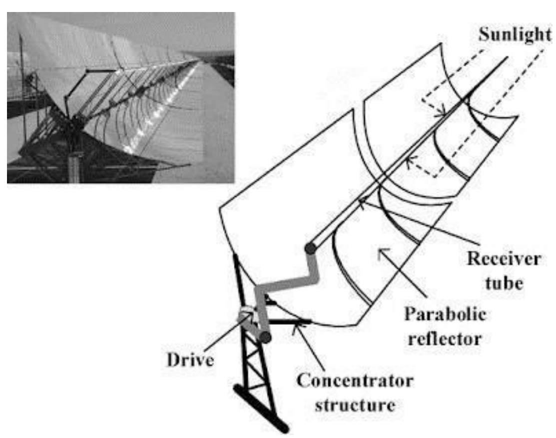


Fig.11. Parabolic Trough Collector

Power Tower Receiver

In this collector, the receiver is located at the top of the tower. It has a large number of independently-moving flat mirrors (heliostats) spread over a large area of ground to focus the reflected solar radiations on the receiver. The heliostats are installed all around the central tower. Each heliostat is rotated into two directions so as to track the sun. The solar radiations reflected from heliostats are absorbed by the receiver mounted on a tower of about 500 m height. The tower supports a bundle of vertical tubes containing the working fluid. The working fluid in the absorber receiver is converted into the high-temperature steam of about 600ºC – 700ºC. This steam is supplied to a conventional steam power plant coupled to an electric generator to generate electric power.

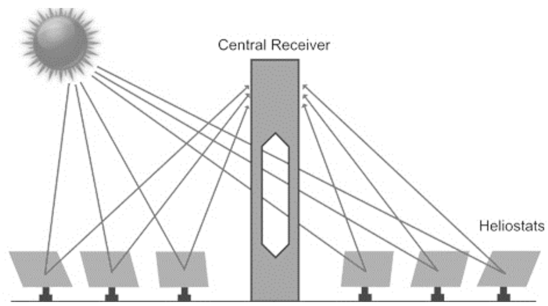
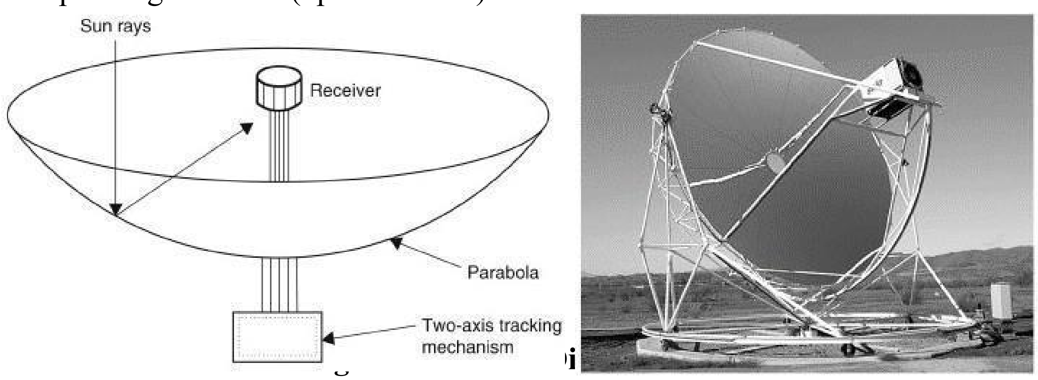


Fig.12. Power tower receiver

Parabolic Dish Collector

- In these collectors, the receiver is placed at the focal point of the concentrator. The solar beam radiations are focused at a point where the receiver (absorber) is placed. The solar radiations are collected in the receiver.
- A small volume of fluid is heated in the receiver to a high temperature. This heat is used to run a prime mover coupled with a generator.
- A typical parabolic dish collector has a dish of 6 m diameter. This collector requires two-axis tracking. It can yield temperatures up to 3000^0 C.
- Due to the limitations of size and the small quantity of fluid, dish type solar collectors are suitable for only small power generation (up to few kW).



Fresnel Lens Concentrating Collector

- In this collector, a Fresnel lens which consists of fine, linear grooves on the surface of refracting material of optical quality on one side and flat on the other side is used.
- The angle of each groove is so designed that the optical behaviour of the Fresnel lens is similar to that of a common lens.
- The solar radiations which fall normally to the lens are refracted by the lens and are focused on a line where the absorber tube (receiver) is placed to absorb solar radiations.

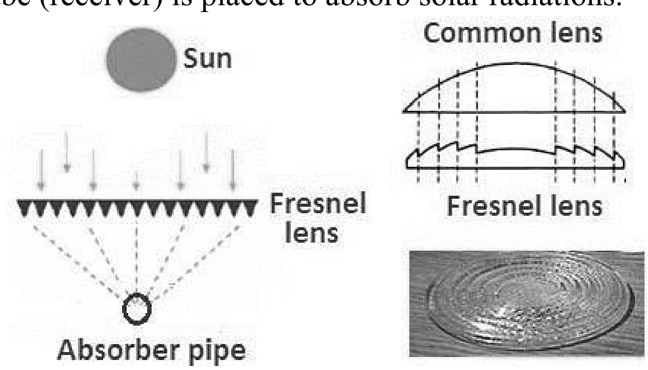


Fig.14. Fresnel Lens Concentrating Collector

Working Fluid: It is the fluid used in the cyclic operation. We use some other fluid as a working fluid because sometimes solar energy is not capable to evaporate the water. We use working fluid which gains energy from the solar pond and evaporate easily or having evaporation temperature less as compare to water. Generally, brine or some organic fluids are used as the working fluid. After evaporation working fluid goes through cyclic operations in turbine and then through condenser it goes again into the evaporator boiler. The cycle is continuously repeated.

Evaporator Boiler: In this device, working fluid is kept and gains latent heat of vaporisation from the sun's radiations or by solar pond. Working fluid is circulating throughout the cycle by evaporating boiler.

Turbine and Generator: Turbine and generators are the essential part of the power generation system. Working fluid goes through the cyclic operation and runs the turbine which is connected to the generator. Generator generates electricity which is transferred to the required location.

Condenser and cooling tower: After turbine, the working fluid goes into the condenser and cooling tower condenses the working fluid and sends back to the evaporator boiler with the help of pump.

Working of solar power plant

The working is very simple almost similar to any thermal power plant. Solar power plant also works on Rankine cycle and Brayton cycle as per the requirements. With the help of construction, we can easily predict the cycle of operation and working. Working fluid gains latent heat of vaporisation from the direct solar radiations or by means of solar ponds in the evaporator boiling and converts it into vapour form. After that it runs the turbine which is connected to the generator. Then the turbine working fluid goes into the condenser and loses heat and again sends back to the evaporator boiler with the help of pump. This whole cycle repeats continuously until the sun remains in the sky and radiation falls on the earth surface.

Advantages:

- Solar power plants work on solar energy which is available in abundant on the earth surface at most of the places.
- Solar power plants produce negligible pollution as compared to thermal power plant.
- The energy produced is renewable energy with negligible cost.
- Quantity of water used in solar power plants is very less as compare to other power plants.

Disadvantages:

- The major drawback is the availability of the sun. Sun's radiation of desired intensity is not available whole day.
- For collecting the sun radiations at useful rate large area is required.
- Initial setup cost of Solar plant is quite high.

It would cost anywhere between Rs 70,000 to Rs 1,20,000 per kW depending on the panels and inverter

Central Receiver Power Plants

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.

Central receiver systems are typically large-scale plants that are usually built to power a steam cycle. The central position of the receiver offers a universal advantage to collect all energy at one location and save on transport networks. Central receiver systems use a field of distributed, circular array of mirrors that is, heliostats which individually track the sun and focus the sunlight on the top of a tower. By concentrating the sunlight 600 – 1000 times, they achieve temperatures from 800°C to well over 1000°C. Solar energy is absorbed by a working fluid and then used to generate steam to power a conventional turbine. The high temperatures available in solar towers can be used not only to drive steam cycles, but also for gas turbines and combined cycle systems. Such systems can achieve up to 35% peak and 25% annual solar electric efficiency when coupled to a combined cycle power plant.

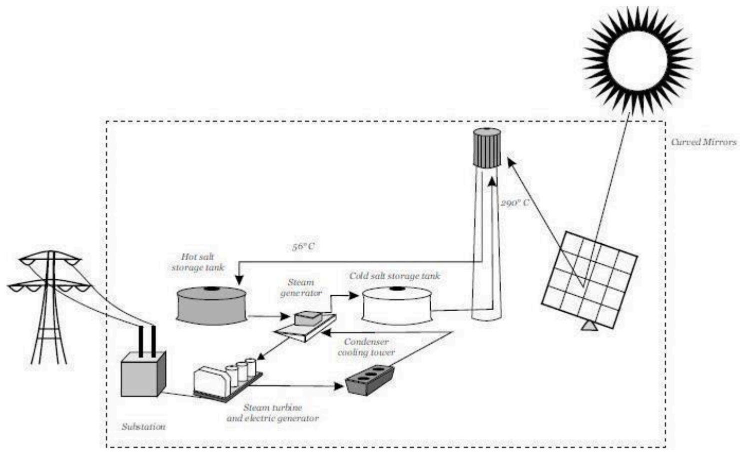


Fig.15. Operation of Central Receiver Power Plants

Major sub-components of central receiver system

- **Heliostat field:** The heliostat field comprises a large heliostat, structure, and control/tracking. The heliostat typically utilizes a mirror, which can be oriented throughout the day to redirect sunlight along a fixed axis toward a stationary target or receiver. The reflecting element of a heliostat is typically a thin, back (second) surface, low-iron glass mirror. This heliostat is composed of several mirror module panels rather than a single large mirror. The thin glass mirrors are supported by a substrate backing to form a slightly concave mirror surface. Individual panels on the heliostat are also canted toward a point on the receiver. The heliostat focal length is approximately equal to the distance from the receiver to the farthest heliostat. Subsequent ―tuning‖ of the closer mirrors is possible.
- **Storage:** Central tower based systems typically use Molten salt, hot concrete storage, phase change materials, saturated steam or pressurized air as storage media.
    - o Nitrate salt mixtures can be used as both a heat transfer fluid and a storage medium at temperatures of up to 565°C. However, most mixtures currently being considered freeze at temperatures around 140 to 220°C and thus must be heated when the system is shutdown. They have a good storage potential because of their high volumetric heat capacity.
    - o Liquid sodium can also be used as both a heat transfer fluid and storage medium, with a maximum operating temperature of 600°C. Because sodium is liquid at this temperature, its vapour pressure is low. However, it solidifies at 98°C thereby requiring heating on shutdown. The cost of sodium-based systems is higher than the nitrate salt systems.
    - o For high-temperature applications such as Brayton cycles, it is proposed to use air or helium as the heat transfer fluid. Operating temperatures of around 850°C at 12 atm pressure are being proposed. Although the cost of these gases would be low, they cannot be used for storage and require very large diameter piping to transport them through the system.
- **Receivers/absorber and power block:** This includes the receivers, absorbers including heat collection elements, and Power Block. The receiver, placed at the top of a tower, is located at a point where reflected energy from the heliostats can be intercepted most efficiently. The receiver absorbs the energy being reflected from the heliostat field and transfers it into a heat transfer fluid. There are two basic types of receivers: external and cavity.
    - o **External Receivers.** These normally consist of panels of many small (20-56 mm) vertical tubes welded side by side to approximate a cylinder. The bottoms and tops of the vertical tubes are connected to headers that supply heat transfer fluid to the bottom of each tube and collect the heated fluid from the top of the tubes.
    - o **Cavity Receivers.** In an attempt to reduce heat loss from the receiver, some designs propose to place the flux absorbing surface inside of an insulated cavity, thereby reducing the convective heat losses from the absorber. The flux from the heliostat field is reflected through an aperture onto absorbing surfaces forming the walls of the cavity. Typical designs have an aperture area of about one-third to one-half of the internal absorbing surface area. Cavity receivers are limited to an acceptance angle of 60 to 120 degrees. Therefore, either multiple cavities are placed adjacent

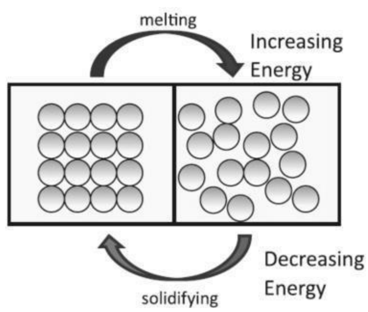
to each other, or the heliostat field is limited to the view of the cavity aperture.

The solar field which consists of solar collectors, balance of system and tracking constitutes 36% of the cost followed by the power block at 24% which comprises the turbine, generator, heat exchangers etc. The receiver is also a major component of this technology comprising 15% of the cost.

Thermal Energy storage system with PCM

Phase change materials (PCMs) are materials that undergo the solid-liquid phase transformation, more commonly known as the melting-solidification cycle, at a temperature within the operating range of a selected thermal application. As a material changes phase from a solid to a liquid, it absorbs energy from its surroundings while remaining at a constant or nearly constant temperature. The energy that is absorbed by the material acts to increase the energy of the constituent atoms or molecules, increasing their vibrational state. At the melt temperature the atomic bonds loosen and the materials transitions from a solid to a liquid.

Solidification is the reverse of this process, during which the material transfers energy to its surroundings and the molecules lose energy and order themselves into their solid phase. This can be seen in Fig. 16.a. The energy that is either absorbed or released during the melting-solidification cycle is known as the latent heat of fusion. Latent heat is unique in that it is heat that is absorbed into a material without the material itself increasing in temperature.



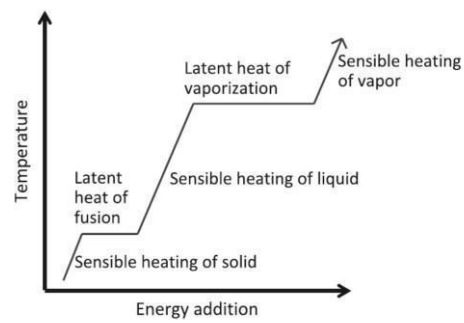


Fig. 16.a. The melting solidification process **b. Standard heating curve**

It is easy to picture this process by considering the melting of an ice cube. You can heat the ice cube by exposing it to ambient room temperature conditions, by heating it with a hair dryer, or by blasting it with a blow torch, but no matter how much heat flux is supplied to it, that ice cube will not increase in temperature until the melting process is complete. The latent heat absorbed during the melting process is referred to as the latent heat of fusion, in order to distinguish it from the other form of latent heat, the latent heat of vaporization, which characterizes the change in phase from a liquid to a gas. In contrast to latent heat, which does not increase the temperature of a material, sensible heat is that heat which does result in a change in temperature within the material.

A standard continuous heating process may begin with a subcooled solid, which is heated to the melting point through sensible heating. As the heating process continues the solid transitions to a liquid through the latent of heat fusion, and sensible heat then increases its temperature to the boiling point. Once the boiling point is reached, the liquid transitions to a vapour through the latent heat of vaporization until the phase change process is complete. Any additional heating is now in the form of sensible heat which acts to superheat the vapour. It can be seen in Fig. 16.b that the latent heat of vaporization is a higher energy process than the latent heat of fusion.

It is true that in general that the boiling/condensation process absorbs/and releases more energy, but the density change from a liquid to a vapour is large, and working with boilers and condensers often requires a significant amount of support equipment which is not always convenient. There are of course many applications for boiling heat transfer, but here we will concentrate on the applications for which a solid- liquid phase change process is most advantageous. The amount of energy absorption or release during the melting-solidification cycle is governed by the value of that material‘s latent heat of fusion. The latent heat of fusion is commonly expressed in units of J/g or kJ/kg. Thus the process is a mass-based process. The amount of energy absorbed by the material during melting depends solely on the mass of material present in the design.

Advantages of PCMs

- The use of PCMs for transient thermal management has the advantage of maintaining a constant system temperature throughout the melt process regardless of applied heat flux.
- PCMs are lightweight, portable and highly reliable depending only on the characteristics of the material itself, and do not depend on an external flow source such as a fan or pump.
- The main options available for thermal energy storage include sensible heat storage and thermochemical storage.
- Latent heat storage has a much higher energy density than sensible heat storage, resulting in less required material mass and/or smaller storage tank volumes.
- Latent heat storage systems are also easier to work with than thermochemical storage.
- The solid-liquid transition results in only a small density change, resulting in smaller system size and less support equipment than when attempting to store thermal energy for long term use through the liquid vapour phase change process.

Limitations

PCMs, however, are far from perfect solutions. The detriment most commonly cited to their greater utilization is that many PCMs do not have high thermal conductivities or diffusivities, preventing rapid system transients.

Application of PCM in Concentrating Solar Power Plants

The use of phase change materials for thermal energy storage (TES) in solar applications can extend the usefulness of the technology so that benefits can be provided even where there is low or no direct insolation. Commercial solar power plants are designed using the concept of Concentrating Solar Power (CSP). In these plants, sunlight is reflected and concentrated using mirrors and then used to heat a carrier fluid. An example of parabolic trough technology is shown in Fig. 17. In this image, the thermal receiver is supported above the concentrating mirrors. The receiver is a black pipe encased in a vacuum tube to reduce convective losses.

A high temperature, high pressure heat transfer fluid (HTF) circulates through the receiver pipes. Depending on the design of the system, the HTF fluid may serve as the heat source in an evaporator, creating steam which powers a stream turbine which drives a generator, or the HTF may directly vaporize as it passes through the solar field and then pass straight through the turbine without an intermediate heat exchanger (known as Direct Steam Generation—DSG). In either design, during periods of high insolation, it is possible to absorb more solar thermal energy into the HTF than is necessary to power the turbine. This ―excess‖ solar thermal energy can be stored using sensible or latent heat in storage tanks as shown in Fig. 17.

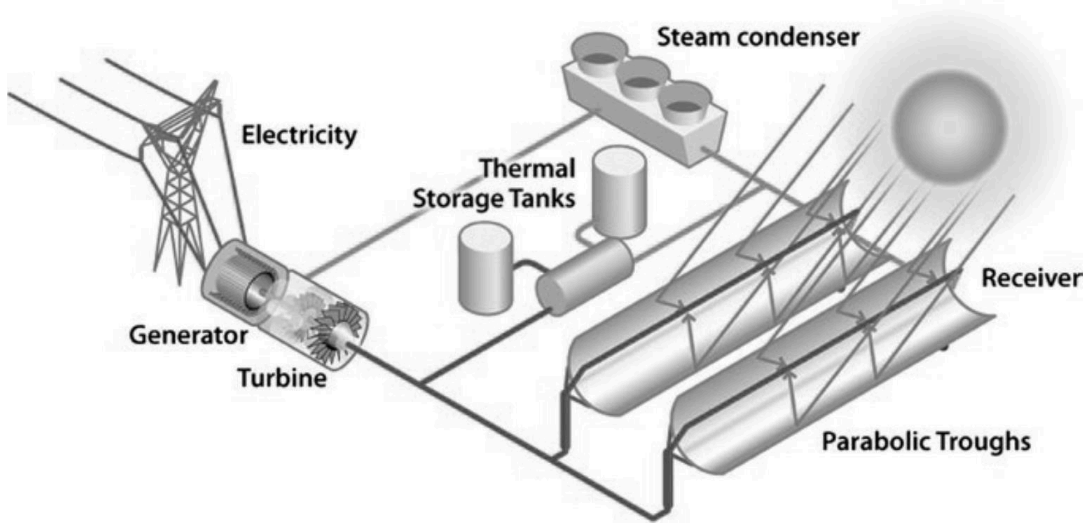


Fig. 17. Direct steam generation concentrating solar power plant with thermal energy storage

In the two-tank molten system a heat exchanger is located between the two tanks with the HTF flowing on one side of the exchanger and the storage medium (molten salt) on the other side. During the energy storage cycle, some of the HTF from the solar is diverted to this exchanger where it transfers energy to the molten salt.

In this case, the salt flow originates in the ―cold‖ tank and flows through the heat exchanger where it absorbs solar thermal energy and then into the ―hot‖ tank where it is stored. During the energy discharge cycle, the HTF and molten salt flow paths are reversed.

The salt gives up its energy to the HTF as it moves from the hot tank through the heat exchanger into the cold tank, and the now hot HTF is used in the power cycle. While these systems have seen success, there is significant cost inherent in using two storage tanks, and the energy density of these storage systems is low as the salt remains in the liquid phase at all times. The use of PCMs in these applications can thus reduce tank number (to one), size and installation costs, creating an economic benefit. Molten salts are commonly used in these applications because of their high operating points. These materials have melting points from around 300 °C to over 800 °C. The HTF in parabolic trough and linear Fresnel system can reach around 300–400 °C in the receiver, while heliostats receivers can operate in excess of 2000 °C. Salts are well suited for these operational ranges, but suffer from a few drawbacks including high corrosiveness and low thermal conductivity. The primary issue with low thermal conductivity is the need for quick charge and discharge of energy as the HTF flows through the storage medium. In a few cases, liquid metal alloys may be used instead of molten salts.

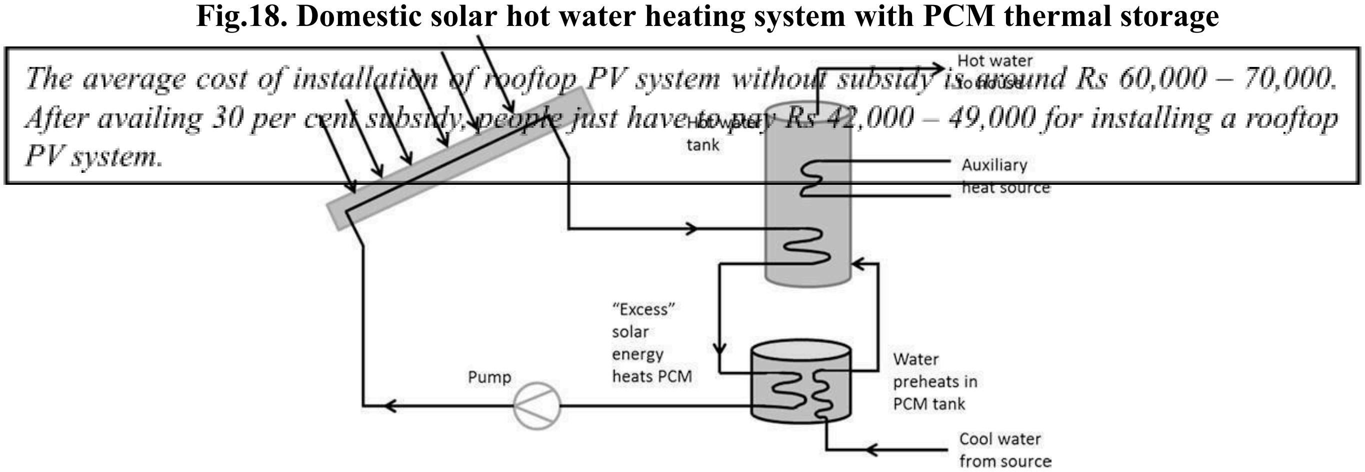
The PCM used in the Rankine cycle system was 60 % $NaNO_3$/40 % KNO_3, known as solar salt while the PCM used with the s-CO2 power cycle was $KCl/MgCl_2$. The typical PCMs used in these applications are inorganic salts which melt in the range from 300–800 °C. These PCMs tend to be corrosive and have low thermal conductivities but it was shown that this can be offset with the use of embedded heat pipes or thermosyphons. In certain applications liquid metals may be used instead.

Domestic Solar Applications

While the large CSP plants certainly have significant technical and economic incentives to implement PCM thermal energy storage systems, smaller scale solar systems can also reap some benefits from TES. For example, solar thermal systems can be used by small businesses and homes for hot water production and for heating systems. A small scale solar hot water system with energy storage can be seen in Fig. 18. These systems feature a flat plate solar collector, typically mounted on the roof, which features a heat transfer fluid passing through the receiver tubes.

The receiver tubes are isolated within an enclosure with a glass cover plate. The enclosure may be evacuated to prevent convective losses. In many ways this is similar to the CSP solar field, but without the concentrators. The lack of concentrators means that the HTF will not reach the high temperatures characteristic of CSP. As such the fluid can‗t be used to create vapour and drive a power system, but is hot enough to provide the heat source for a domestic hot water tank. As with CSP, the effectiveness of the system is limited to daylight hours, but the solar thermal system can be designed to store extra heat using PCM in the storage tanks for the overnight hours, greatly reducing dependence on supplemental natural gas or electrical heating.

Fig.18. Domestic solar hot water heating system with PCM thermal storage



Solar Photovoltaic systems: Basic Principle of SPV conversion

A photovoltaic (PV) cell is an energy harvesting technology that converts solar energy into useful electricity (DC) through a process called the photovoltaic effect. It is made up of semiconductor materials such as silicon, gallium arsenide and cadmium telluride, etc. These cells vary in size ranging from about 0.5 inches to 4 inches. There are different types of PV cells which all use semiconductors to interact with incoming photons from the Sun in order to generate an electric current.

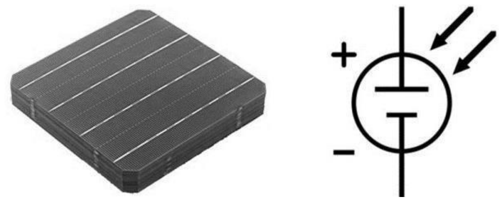


Fig. 19 PV cell and PV Cell symbol

Photovoltaic cell concepts: Cell Layers of a PV Cell

A photovoltaic cell is comprised of many layers of materials, each with a specific purpose. The most important layer of a photovoltaic cell is the specially treated semiconductor layer. It is comprised of two distinct layers of p-type and n-type, and is what actually converts the Sun's energy into useful electricity through a process called the photovoltaic effect. On either side of the semiconductor is a layer of conducting material which "collects" the electricity produced. Note that the backside or shaded side of the cell can afford to be completely covered in the conductor, whereas the front or illuminated side must use the conductors sparingly to avoid blocking too much of the Sun's radiation from reaching the semiconductor.

The final layer which is applied only to the illuminated side of the cell is the anti-reflection coating. Since all semiconductors are naturally reflective, reflection loss can be significant. The solution is to use one or several layers of an anti-reflection coating (similar to those used for eyeglasses and cameras) to reduce the amount of solar radiation that is reflected off the surface of the cell.

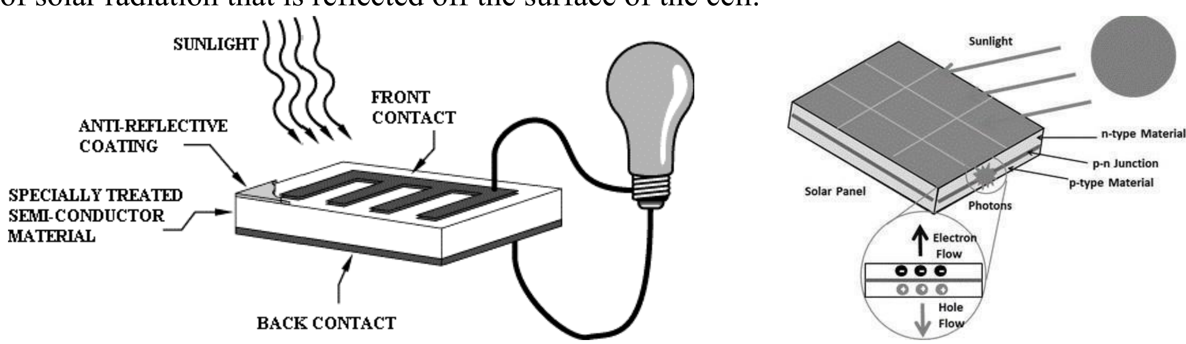


Fig. 20. A diagram showing the photovoltaic effect.

Photovoltaic Effect

The photovoltaic effect is a process that generates voltage or electric current in a photovoltaic cell when it is exposed to sunlight. These solar cells are composed of two different types of semiconductors—a p-type and an n-type that are joined together to create a p-n junction. By joining these two types of semiconductors, an electric field is formed in the region of the junction as electrons move to the positive p-side and holes move to the negative n-side. This field causes negatively charged particles to move in one direction and positively charged particles in the other direction.

Light is composed of photons, which are simply small bundles of electromagnetic radiation or energy. When light of a suitable wavelength is incident on these cells, energy from the photon is transferred to an electron of the semiconducting material, causing it to jump to a higher energy state known as the conduction band. In their excited state in the conduction band, these electrons are free to move through the material, and it is this motion of the electron that creates an electric current in the cell.

- **Cell:** A photovoltaic cell is the most basic unit of a solar PV system - solar cells can be either monocrystalline or polycrystalline, and their key characteristic is that they produce a voltage output when exposed to light. It is important to note that although they are normally called "solar cells", they can respond to any type of light. Each cell produces approximately 1/2 a volt and a solar module can have any number of solar cells.

- **Module:** A photovoltaic module consists of multiple PV cells connected in series to provide a higher voltage output. PV modules are manufactured in standard sizes. A solar module designed for charging a 12 volt battery will typically have 36 solar cells while the typical residential grid connected system uses solar modules with 60 solar cells. For large commercial and utility scale solar systems, solar modules will have typically 72 solar cells. By increasing the number of solar cells the module voltage and wattage increases. The term solar panel is sometimes used interchangeably with solar module. The main difference is that some solar panels models are composed of multiple modules mounted together.
- **Array:** A photovoltaic array is a system composed of multiple PV modules. They can be connected in one or more series circuits, which are connected to a combiner box to provide a single direct- current output. This output can be used to charge batteries, power DC loads, or fed to an inverter to provide an AC voltage for home appliances or exporting to the electric grid.

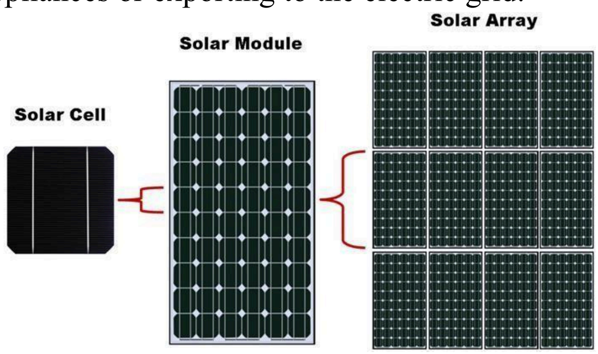


Fig.21. Cell module and array

Operation of PV Systems

Solar cells produce direct current (DC), therefore they are only used for DC equipments. If alternating current (AC) is needed for AC equipment or backup energy is needed, solar photovoltaic systems require other components in addition to solar modules. These components are specially designed to integrate into solar PV system. The components of solar photovoltaic system are shown in the figure.

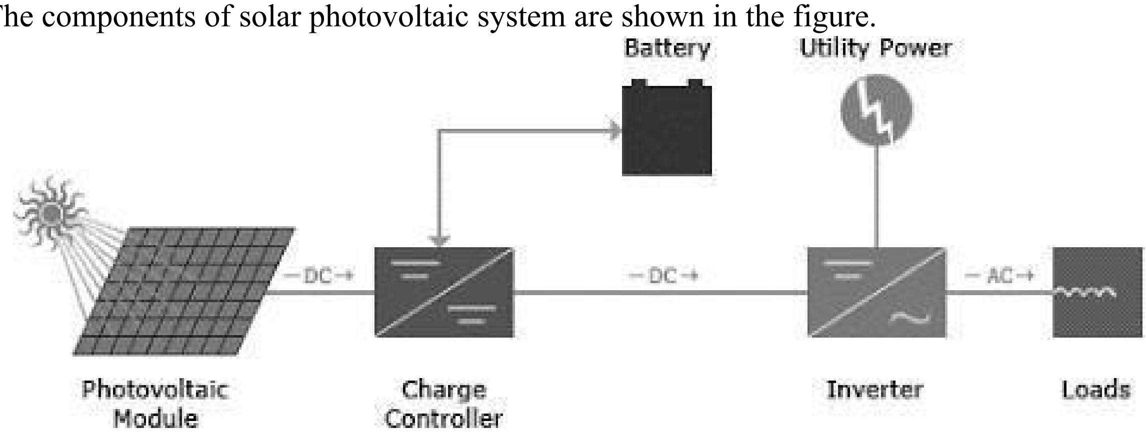


Fig. 22. Components of Photovoltaic system

1. **Solar or Photovoltaic Module** is the essential component of any solar PV system that converts sunlight directly into DC electricity.
2. **Solar Charge Controller** regulates voltage and current from solar arrays, charges the battery, prevents battery from overcharging and also performs controlled over discharges.
3. **Battery** stores the energy produced from solar arrays for using when sunlight is not visible, night time or other purposes.
4. **Inverter** is a critical component of any solar PV system that converts DC power output of solar arrays into AC for AC appliances.
5. **Lightning protection** prevents electrical equipment from damages caused by lightning or induction of high voltage surge. It is required for the large size and critical solar PV systems, which include efficient grounding.

Net metering is a billing mechanism that credits solar energy system owners for the electricity they add to the grid.

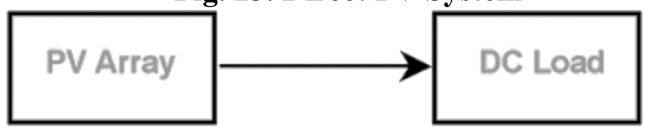
Types of PV Systems

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principle classifications are grid-connected or utility-interactive systems and stand-alone systems. Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems.

PV Direct System

These are the simple most type of solar PV systems, with the fewest components; the Solar Panels and the load. Because they don't have batteries and are not hooked up to the grid, they only power the loads when the sun is shining. They are appropriate for a few applications e.g. water pumping or attic ventilation fan.

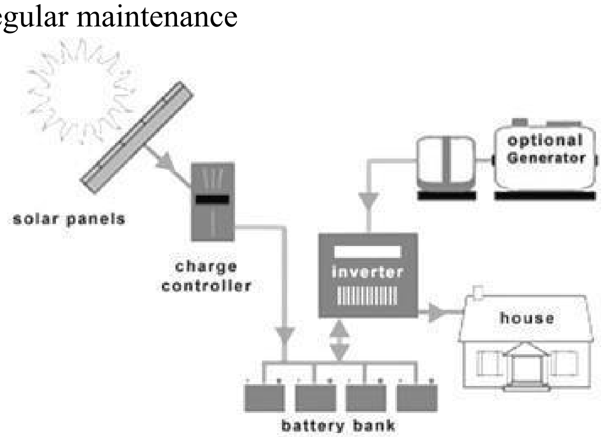
Fig. 23. Direct PV System



Solar Off Grid System

Also referred to as stand-alone systems, it is designed to be independent of the power grid. Batteries are used to store energy when the sun is not available during cloudy days or at night. This type of system will require regular attention to battery electrolyte levels and terminal corrosion.

- Independence from the utility grid
- Not subject to the terms/policies of the utility company
- Rate increases, blackouts, or brownouts do not apply
- In remote areas, it is cost effective than extending a grid
- Encourages energy efficiency
- Batteries require maintenance and has limited life
- More components means more complexity
- Batteries decrease system efficiency
- It is more expensive than a grid-direct system
- When the batteries are fully charged, potential power from the PV array is not utilized
- If the PV system fails, back-up electricity is required to run load
- Most off-grid systems use a backup generator for non-sunny days. They are expensive, noisy, dirty, and require fuel and regular maintenance



Solar Grid Tied System without Battery backup

These are most common type of PV systems. They are also known as on-grid, grid-tied, grid- intertied, or grid-direct systems. They generate solar electricity and route it to the loads and to the grid, offsetting some of electricity usage. System components comprises of the PV array and inverter. Grid- connected system is similar to regular electric powered system except that some or all of the electricity comes from the sun. The drawback of these battery less systems is that they provide no outage protection when the utility grid fails, these systems cannot operate.

- grid-tied-system
- Increased design flexibility because the system does not have to power all of the home‘s loads
- It is less expensive compared to stand-alone or grid-tied with battery backup systems
- It requires the least amount of maintenance
- If the system produces more than the loads need, then the extra energy is exchanged with the grid
- Grid-direct systems have a higher efficiency because batteries are not part of the system
- Higher voltage means smaller wire size
- Electricity costs are fixed for the life of your system
- There is no power to the home when the grid goes down
- Paperwork requirements for interconnection, incentives, and rebates

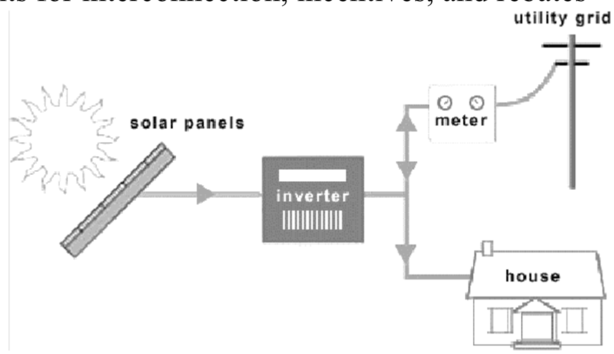


Fig. 25. Grid tied system without battery back up

Solar Grid Tied with Battery Backup System

This type is very similar to an off-grid system in design and components, but adds the utility grid, which reduces the need for the system to provide all the energy all the time.

- grid-tied-with-battery-backup
- Designated loads have power when the grid goes down
- If the system produces more than the home needs, then the extra energy is sold back to the utility- not lost as in a stand-alone systems after the batteries get full on a sunny day
- Batteries require maintenance
- Requires rewiring circuits from main service panel to a separate subpanel
- More components mean more complexity
- Batteries decrease system performance because of their efficiency losses
- More expensive than a grid-direct system
- Typically only provides modest backup – usually not all of the loads are backed up
- Requires paperwork for interconnection, incentives, and rebates

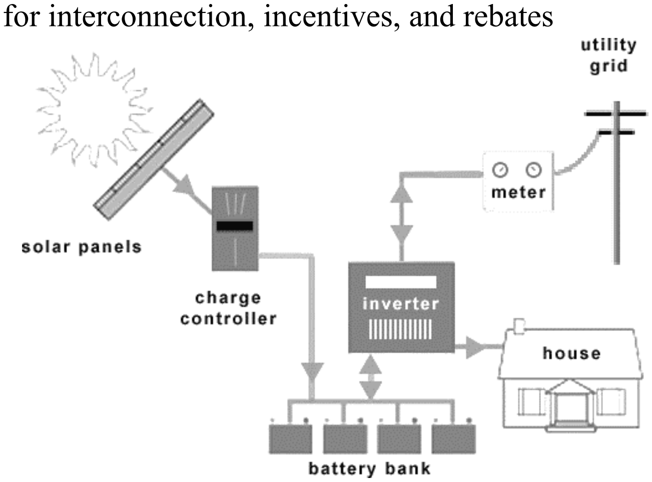


Fig. 26. Gird tied solar system with battery back up

Hybrid system

Hybrid system tries to combine multiple sources of power to maximize availability of power. It may source energy from sun, wind or diesel generator and back it up with battery.

- Multiple sources of generation allows for complementary sources and backup. For instance, when it is sunny out the PV array will charge the battery; if it is cloudy and windy, a wind turbine can charge the batteries.
- Array size and battery bank capacity can typically be reduced and not having to oversize for periods of no sun
- More complex system design and installation
- Multiple power sources can increase upfront expenses
- Wind turbines and generators require regular maintenance.

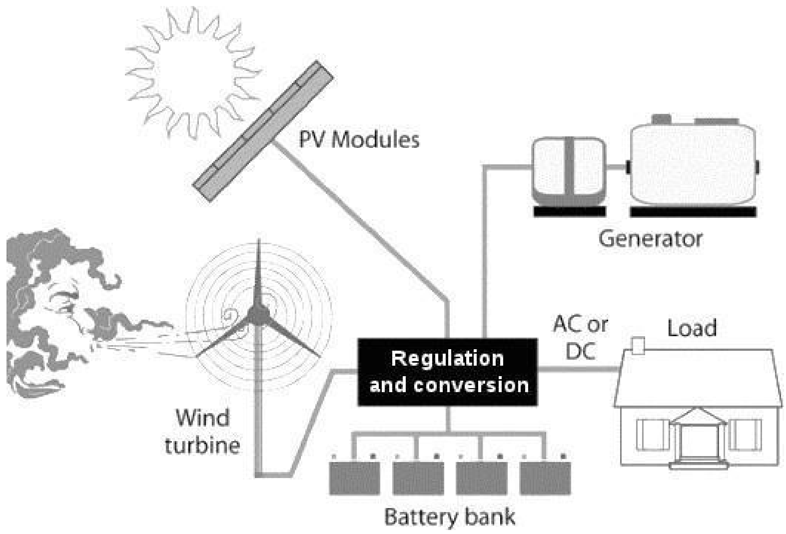


Fig. 27. Hybrid power systems

Types of Solar Cells

There are different types of photovoltaic cells available to buy, but mainly they are manufactured from silicon (Si). The use of silicon in the manufacture of photovoltaic cells produces the stereo typical uniform blue coloured PV cell which we see on roof tops and the sides of buildings.

The two major types of photovoltaic cell materials used are crystalline silicon and thin film deposits, which vary from each other in terms of light absorption efficiency, energy conversion efficiency, manufacturing technology and cost of production. Crystalline silicon PV cells are the most common type of photovoltaic cell in use today and are also one of the earliest successful PV devices.

The three general types of photovoltaic cells made from silicon are:

1. Mono-crystalline Silicon – also known as single-crystal silicon
2. Poly-crystalline Silicon – also known as multi-crystal silicon
3. Thin Film Silicon

Noor Complex is the world's largest concentrated solar power (CSP) plant, located in the Sahara Desert. The project has a 580-megawatt capacity.

Crystalline Silicon (c-Si)

This is the most common technology used to produce photovoltaic cells representing about 90% of the market today. Crystalline photovoltaic cells are made from silicon which is first melted, and then crystallised into ingots or casting‘s of pure silicon. Thin slices of silicon called wafers, are cut from a single crystal of silicon (Mono-crystalline) or from a block of silicon crystals (Poly-crystalline) to make individual cells. The conversion efficiency for these types of photovoltaic cell ranges between 10% and 20%.

Mono-crystalline Silicon is a type of photovoltaic cell material manufactured from a single-crystal silicon structure which is uniform in shape because the entire structure is grown from the same crystal. High purity silicon is melted in a crucible. A single-crystal silicon seed is dipped into this molten silicon and is slowly pulled out from the liquid producing a single-crystal ingot. The ingot is then cut into very thin wafers or slices which are then polished, doped, coated, interconnected and assembled into modules and arrays.

These types of photovoltaic cells are also widely used in photovoltaic panel construction.

Compared to non-crystalline cells, the uniform molecular structure of the silicon wafer makes it ideal for transferring loose electrons through the material resulting in a high energy conversion efficiency. The conversion efficiency for a mono-crystalline cell ranges between 15 to 20%.

Not only are they energy efficient, mono-crystalline photovoltaic cells are highly reliable for outdoor power applications due to their wafer thickness. However, to make an effective PV cell, the silicon has to be ―doped‖ with other elements to make the required N-type and P-type conductive layers.

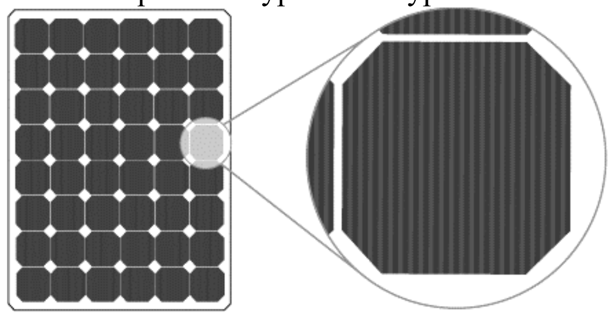


Fig. 28. Monocrystalline solar panels

Poly-crystalline Silicon also known as multi-crystalline silicon, is cast to produce a silicon ingot. The silicon molecular structure consists of several smaller groups or grains of crystals, which introduce boundaries between them. Poly-crystalline PV cells are less energy efficient than the previous mono- crystalline silicon PV cells because these boundaries restrict the flow of electrons through it by encouraging the negative electrons to recombine with the positive holes reducing the power output of the cell.

The result of this means that a poly-crystalline PV cell only has an energy conversion efficiency of between 10 to 14%. However, these types of photovoltaic cell are much less expensive to produce than the equivalent single mono-crystalline silicon due to their lower manufacturing costs.

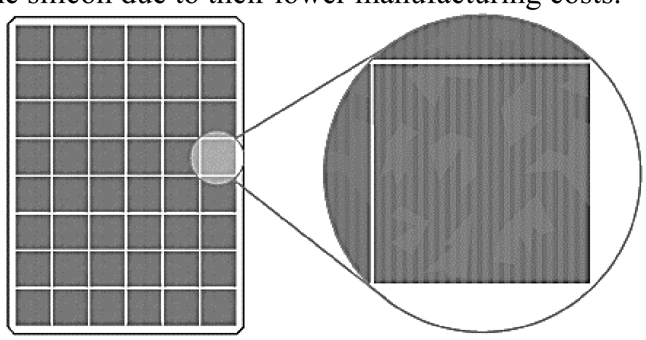


Fig. 29. Polycrystalline solar panels

Thin Film Solar Cell

Thin Film Solar Cells are another type of photovoltaic cell which were originally developed for space applications with a better power-to-size and weight ratio compared to the previous crystalline silicon devices. Thin film photovoltaics are produced by printing or spraying a thin semiconductor layer of PV material onto a glass, metal or plastic foil substrate. By applying these materials in thin layers, the overall thickness of each photovoltaic cell is substantially smaller than an equivalent cut crystalline cell, hence the name ―thin film‖. As the PV materials used in these types of photovoltaic cells are sprayed directly onto a glass or metal substrate, the manufacturing process is therefore faster are cheaper making thin film PV technology more viable for use in a home solar system as their payback time is shorter.

However, although thin film materials have higher light absorption than equivalent crystalline materials, thin film PV cells suffer from poor cell conversion efficiency due to their non-single crystal structure, requiring larger sized cells. Semiconductor materials used for the thin film types of photovoltaic cell include: Cadmium Telluride, Amorphous Silicon and Copper Indium diSelenide or CIS.

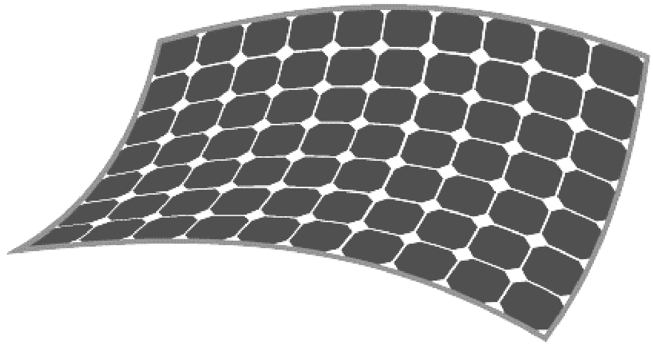


Fig. 30. Thinfilm solar panels

Cadmium Telluride, (CdTe) is a poly-crystalline semiconductor material made from cadmium and tellurium. Thin film cadmium telluride has a high light absorption level so the amount of CdTe required can be quite minimal with less than 1.0 microns of semiconductor material is needed to effectively absorb sunlight for the solar device to perform.

Although the process of spraying or printing the thin film is relatively easy making it cheap to manufacture these types of photovoltaic cell, the main material, cadmium is a toxic heavy metal can pollute the environment if the cell is damaged or broken. Another disadvantage of these types of photovoltaic cells is that the conversion efficiency for a cadmium telluride PV cell can be low at less than 10%.

Amorphous Silicon, (a-Si) is a non-crystalline form of silicon that is widely used in calculators, consumer electronics and solar garden products that require a small current at a low voltage. Of the different types of photovoltaic cell available, amorphous silicon has the highest light absorption of over 40 times higher than crystalline silicon. The advantage of this is that a much thinner layer of amorphous silicon material is required to make a thin film PV cell reducing manufacturing costs and price.

Amorphous silicon cells have various advantages and disadvantages. On the plus side, amorphous silicon can be deposited on a variety of low cost rigid and flexible substrates such as polymers, thin metals and plastics as well as tinted glass for building integration. However, on the minus side, two of the main disadvantages of amorphous silicon (a-Si) is its very low conversion efficiency ranging from between 7 to 9% when new, degrading down within a few months of exposure to sunlight to less than 5%.

Copper Indium diSelenide, (CIS) is another type of poly-crystalline semiconductor material composed of Copper, Indium and Selenium, ($CuInSe2$). Thin film CIS types of photovoltaic cell can produce conversion efficiencies of nearly 10%, almost double that of amorphous silicon without suffering from the same outdoor degradation problems due to their thicker film. Also CIS cells are one of the most light-absorbent semiconductor compounds absorbing up to 90% of the solar spectrum.

Although Copper Indium diSelenide, CIS cells are efficient, the complexity of the formulation of the semiconductor compound makes them difficult to manufacture and expensive. Also, Indium is a relatively expensive material due to its limited availability with manufacturing safety issues a concern as hydrogen selenide is an extremely toxic gas.

Copper Indium Gallium diSelenide, (CIGS) is another type of photovoltaic cell. It is basically a P-type poly-crystalline thin film material based on the previous copper indium diselenide (CIS) semiconductor material. The addition of small amounts of the compound Gallium (Ga) produces a photovoltaic cell with a higher conversion efficiency of around 12% from the same amount of sunlight with an open circuit voltage of about 0.7 volts. This is because Gallium, which is a liquid similar to mercury at room temperatures, increases the light-absorbing band gap of the cell, which matches more closely the solar spectrum, thereby improving its conductivity allowing electrons to freely move through the cell to the electrodes.

Other Types of Photovoltaic Cell

Apart from the commonly used types of photovoltaic cell mentioned above, and which account for about 95%

of the commercial market, other types of photovoltaic cell currently being developed include:

Multijunction PV Cells – These are types of photovoltaic cell designed to maximise the overall conversion efficiency of the cell by creating a multi-layered design in which two or more PV junctions are layered one on top of the other. The cell is made up of various semiconductor materials in thin-film form for each individual layer.

The advantage of this is that each layer extracts energy from each photon from a particular portion of the light spectrum that is bombarding the cell. This layering of the PV materials increases the overall efficiency and reduces the degradation in efficiency that occurs with standard amorphous silicon cells.

Dye-Sensitive PV Cells – This type of technology is considered to be the 3rd generation of solar cells. Instead of using solid-state PN-junction technology to convert photon energy into electrical energy, an electrolyte, liquid, gel or solid is used to produce a photo-electrochemical PV cell. These types of photovoltaic cells are manufactured using microscopic molecules of photosensitive dye on a nano-crystalline or polymer film. The photon light energy being absorbed by the dye releases electrons into the conduction band causing a flow of the electricity through the semiconductor. The advantage of a dye-sensitive nano- crystalline photo-electrochemical photovoltaic cell is that the dye can be screen printed onto any surface producing conversion efficiencies of around 10%.

3D Photovoltaic Cells – This type of photovoltaic cell uses a unique three-dimensional structure to absorb the photon light energy from all directions and not just from the top as in convectional flat PV cells. The cell uses a 3D array of miniature molecular structures which capture as much sunlight as possible boosting its efficiency and voltage output while reducing its size, weight and complexity.

Solar panel type	Advantages	Disadvantages
Monocrystalline	• High efficiency/performance • Aesthetics	• Higher costs
Polycrystalline	• Low cost	• Lower efficiency/performance
Thin-film	• Portable and flexible • Lightweight • Aesthetics	• Lowest efficiency/performance

Table: Comparison of types of Solar cells

China is the world's largest manufacturer of solar panels.

PV Module I-V Characteristics

Solar Cell I-V Characteristic Curves show the current and voltage (I-V) characteristics of a particular photovoltaic (PV) cell, module or array giving a detailed description of its solar energy conversion ability and efficiency. Knowing the electrical I-V characteristics (more importantly P_{max}) of a solar cell, or panel is critical in determining the device's output performance and solar efficiency.

The main electrical characteristics of a PV cell or module are summarized in the relationship between the current and voltage produced on a typical solar cell I-V characteristics curve. The intensity of the solar radiation (insolation) that hits the cell controls the current (I), while the increases in the temperature of the solar cell reduces its voltage (V).

Solar cells produce direct current (DC) electricity and current times voltage equals power, so we can create solar cell I-V curves representing the current versus the voltage for a photovoltaic device.

Solar Cell I-V Characteristics Curves are basically a graphical representation of the operation of a solar cell or module summarising 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.

Solar Cell I-V Characteristic Curve

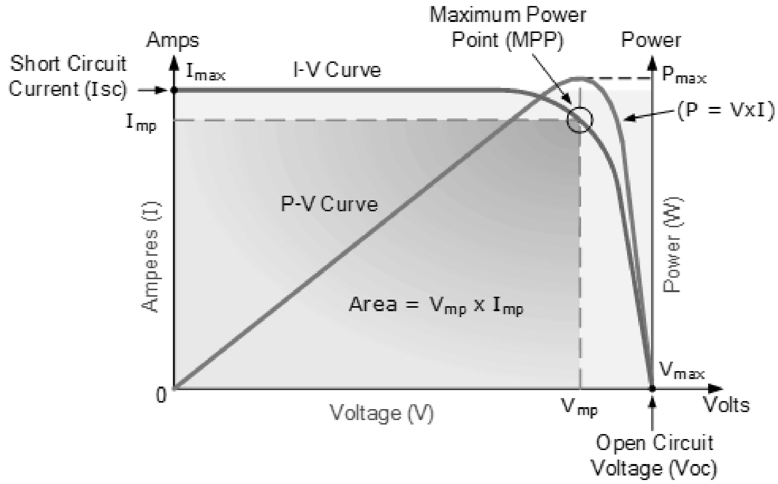


Fig. 31. Solar Cell I-V Characteristic Curve

The above graph shows the current-voltage (I-V) characteristics of a typical silicon PV cell operating under normal conditions. The power delivered by a solar cell is the product of current and voltage (I × V). If the multiplication is done, point for point, for all voltages from short-circuit to open-circuit conditions, the power curve above is obtained for a given radiation level.

With the solar cell open-circuited, that is not connected to any load, the current will be at its minimum (zero) and the voltage across the cell is at its maximum, known as the solar cells open circuit voltage, or V_{oc}. At the other extreme, when the solar cell is short circuited, that is the positive and negative leads connected together, the voltage across the cell is at its minimum (zero) but the current flowing out of the cell reaches its maximum, known as the solar cells short circuit current, or I_{sc}.

Then the span of the solar cell I-V characteristics curve ranges from the short circuit current (I_{sc}) at zero output volts, to zero current at the full open circuit voltage (V_{oc}). In other words, the maximum voltage available from a cell is at open circuit, and the maximum current at closed circuit. Of course, neither of these two conditions generates any electrical power, but there must be a point somewhere in between were the solar cell generates maximum power.

However, there is one particular combination of current and voltage for which the power reaches its maximum value, at Imp and V_{mp}. In other words, the point at which the cell generates maximum electrical power and this is shown at the top right area of the green rectangle. This is the ―maximum power point‖ or MPP. Therefore the ideal operation of a photovoltaic cell (or panel) is defined to be at the maximum power point.

The maximum power point (MPP) of a solar cell is positioned near the bend in the I-V characteristics curve. The corresponding values of Vmp and Imp can be estimated from the open circuit voltage and the short circuit current: $V_{mp} \cong (0.8–0.90)V_{oc}$ and $I_{mp} \cong (0.85–0.95)I_{sc}$. Since solar cell output voltage and current both depend on temperature, the actual output power will vary with changes in ambient temperature. **Solar Panel I-V Characteristic Curves**

Photovoltaic panels can be wired or connected together in either series or parallel combinations, or both to increase the voltage or current capacity of the solar array. If the array panels are connected together in a series combination, then the voltage increases and if connected together in parallel then the current increases. The electrical power in Watts, generated by these different photovoltaic combinations will still be the product of the voltage times the current, (P = V × I). However the solar panels are connected together, the upper right hand corner will always be the maximum power point (MPP) of the array.

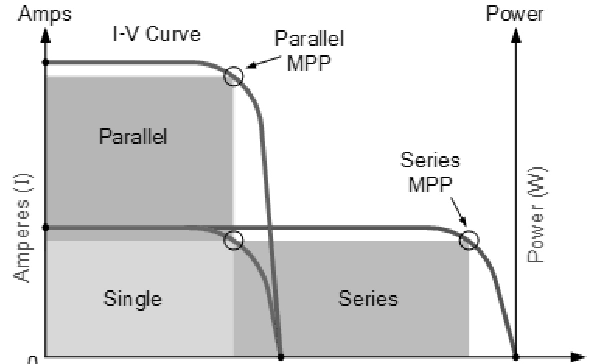


Fig. 32. Solar Panel I-V Characteristic Curves The

Electrical Characteristics of a Photovoltaic Array

The electrical characteristics of a photovoltaic array are summarised in the relationship between the output current and voltage. The amount and intensity of solar insolation (solar irradiance) controls the amount of output current (I), and the operating temperature of the solar cells affects the output voltage (V) of the PV array. Solar cell I-V characteristic curves that summarise the relationship between the current and voltage are generally provided by the panels manufacturer and are given as:

Solar Array Parameters

- V_{OC} = open-circuit voltage: – This is the maximum voltage that the array provides when the terminals are not connected to any load (an open circuit condition). This value is much higher than V_{mp} which relates to the operation of the PV array which is fixed by the load. This value depends upon the number of PV panels connected together in series.
- I_{SC} = short-circuit current – The maximum current provided by the PV array when the output connectors are shorted together (a short circuit condition). This value is much higher than I_{mp} which relates to the normal operating circuit current.
- 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 = $I_{mp} \times V_{mp}$. 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 times the short-circuit current, ($V_{oc} \times I_{sc}$) 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 (monocrystalline, polycrystalline, amorphous or thin film) being used.

Photovoltaic I-V characteristics curves provide the information needed for us to configure a solar power array so that it can operate as close as possible to its maximum peak power point. The peak power point is measured as the PV module produces its maximum amount of power when exposed to solar radiation equivalent to 1000 watts per square metre, 1000 W/m^2 or $1kW/m^2$.

Efficiency & Quality of the Cell

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Terrestrial solar cells are measured under AM1.5 conditions and at a temperature of 25°C. Solar cells intended for space use are measured under AM0 conditions.

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$P_{max} = V_{OC} I_{SC} FF \quad \eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

Where, V_{oc} is the open-circuit voltage;
I_{sc} is the short-circuit current;
FF is the fill factor and η
is the efficiency.

Factors affecting conversion efficiency

- **Wavelength:** The sunlight that reaches the earth's surface has wavelengths from ultraviolet, through the visible range, to infrared. When light strikes the surface of a solar cell, some photons are reflected, while others pass right through. Some of the absorbed photons have their energy turned into heat. The remainder have the right amount of energy to separate electrons from their atomic bonds to produce charge carriers and electric current.
- **Recombination:** It is one of the fundamental factors that limits efficiency. Indirect recombination is a process in which the electrons or holes encounter an impurity, a defect in the crystal structure, or interface that makes it easier for them to recombine and release their energy as heat.
- **Temperature:** Solar cells generally work best at low temperatures. Higher temperatures cause the semiconductor properties to shift, resulting in a slight increase in current, but a much larger decrease in voltage. Extreme increases in temperature can also damage the cell and other module materials, leading to shorter operating lifetimes.
- **Reflection:** A cell's efficiency can be increased by minimizing the amount of light reflected away from the cell's surface. For example, untreated silicon reflects more than 30% of incident light. Anti- reflection coatings and textured surfaces help decrease reflection. A high-efficiency cell will appear dark blue or black.

Quality of solar cell

The Fill Factor (FF) is essentially a measure of quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power that would be output at both the open circuit voltage and short circuit current together. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. A larger fill factor is desirable, and corresponds to an I-V sweep that is more square-like. Typical fill factors range from 0.5 to 0.82.
Most solar panels are between 15% and 20% efficient, with outliers on either side of the range. High-quality solar panels can exceed 22% efficiency in some cases (and almost reach 23%), but the majority of photovoltaic panels available are not above 20% efficiency.

Increasing efficiency of solar cell

There are ways to improve the efficiency of PV cells, all of which come with an increased cost.

- One way is to decrease the number of semiconductor impurities and crystal structure deformations. This can be achieved through the production of monocrystalline, or "single-crystal" cells. A more pure and uniform cell has a higher chance of interacting with incoming photons.
- Another method is to use a more efficient semiconducting material such as Gallium Arsenide. Although it's much more rare and expensive than silicon, gallium arsenide has an optimal band-gap of 1.4 electron volts, allowing for a higher percentage of the Sun's energy to be harnessed.
- Multiple layers of semiconductor material called p-n junctions can also be used to increase cell efficiency. These multi-junction cells harness energy from multiple sections of the solar spectrum as

each junction has a different band gap energy.

- Efficiency can also be increased through concentrated photovoltaics. This method involves concentrating the Sun's energy through various methods to increase the intensity of energy hitting the solar cell.

Regulations for quality

The manufacture of photovoltaic modules is governed by several standards required by the IEC (International Electrotechnical Commission) in order to be marketed on the international market.

These standards are as follows:

- The standard IEC 61215 (crystalline) or IEC 61646 (amorph) certifies a guarantee of quality in terms of respect for electrical parameters and mechanical stability. The requirements of this standard refer to the qualification of the design and approval of photovoltaic modules for land application and for long-term use.
- The standard IEC 61730 specifically addresses the topics of prevention against electric shock, fire hazard and bodily injury due to mechanical and environmental constraints.
- This standard, whose specificities concern the safety aspects of the modules, complements the IEC 61215 standard, which fixes the electrical performance.

At the end of May 2019, the cumulative solar power capacity of Germany reached 47.72 GW.

Series and parallel connections

Depending on the equipment that the system uses and the size of the system, your solar installer may decide to wire your solar panels in series, in parallel, or in a combination of the two. Here are the fundamental differences between wiring solar panels in series vs. in parallel:

Wiring solar panels in series

When a solar installer wires your solar panels in a series, each panel is connected to the next in a ―string.‖ The total voltage of each solar panel is summed together, but the amps of electrical current stay the same. When you wire in series, there is just a single wire leading from the roof for each string of solar panels.

Wiring solar panels in parallel

When an installer wires your solar panels in parallel, each panel‘s wires are connected to a centralized wire leading from the roof. The amps of electrical current for each solar panel are summed together, but the system voltage stays the same. Wiring your solar panels in parallel results in more wires running from your solar panel system.

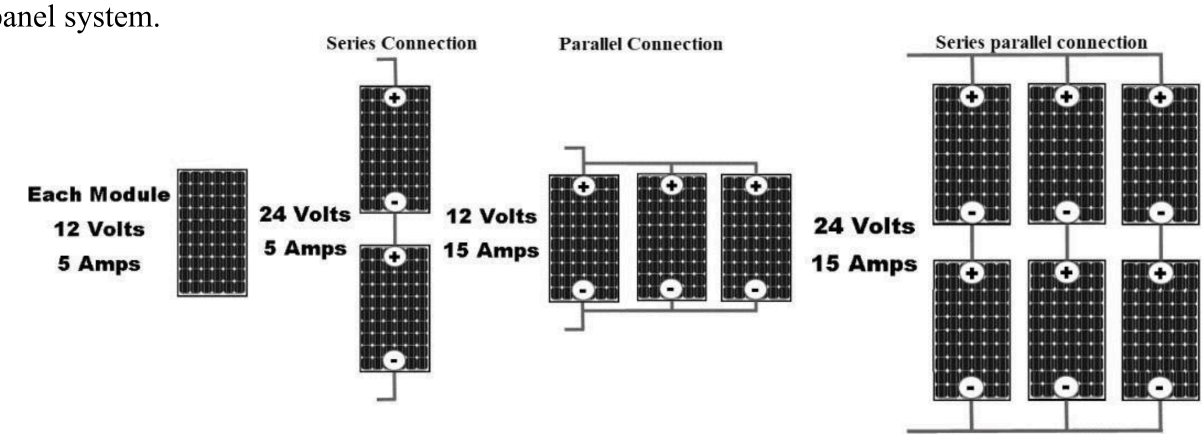


Fig. 33. Series, parallel Series parallel connections

In theory, parallel wiring is a better option for many electrical applications because it allows for continuous operation of the panels that are not malfunctioning. But, it is not always the best choice for all applications. When designing your solar system, your installer might decide that series wiring is better suited for your application or he might choose a hybrid approach by series wiring some panels and parallel wiring others.

Maximum power point tracking

MPPT or Maximum Power Point Tracking is an algorithm that is included in charge controllers used for extracting maximum available power from PV module under certain conditions. The voltage at which

PV module can produce maximum power is called maximum power point (or peak power voltage). Maximum power varies with solar radiation, ambient temperature and solar cell temperature.

Typical PV module produces power with maximum power voltage of around 17 V when measured at a cell temperature of 25°C, it can drop to around 15 V on a very hot day and it can also rise to 18 V on a very cold day.

The major principle of MPPT is to extract the maximum available power from PV module by making them operate at the most efficient voltage (maximum power point). MPPT checks output of PV module, compares it to battery voltage then fixes what is the best power that PV module can produce to charge the battery and converts it to the best voltage to get maximum current into battery. It can also supply power to a DC load, which is connected directly to the battery.

MPPT is most effective under these conditions:

- Cold weather, cloudy or hazy days: Normally, PV module works better at cold temperatures and MPPT is utilized to extract maximum power available from them.
- When battery is deeply discharged: MPPT can extract more current and charge the battery if the state of charge in the battery is lowers.

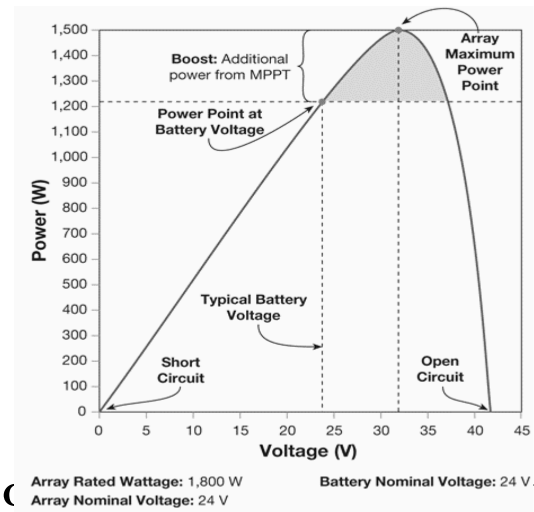


Fig.34. C ... V Curve Example:

MPPT On a Cold Winter Day

- If the outside temperature is 20°F (-7°C) and the wind is blowing a bit, the PV cell temperature rises to only around 32°F (0°C). The Vpp = 18V. Batteries are a bit low, and loads are on, so the battery voltage = 12.0.
- The ratio of Vpp to battery voltage is 18:12 = 1.5:1.
- Under these conditions, a theoretically perfect MPPT (with no voltage drop in the array circuit) would deliver a 50% increase in charge current. In reality, there are losses in the conversion just as there is friction in a car's transmission. Reports from the field indicate that increases of 20 to 30% are typically observed.

MPPT solar charge controller

- A MPPT solar charge controller is the charge controller embedded with MPPT algorithm to maximize the amount of current going into the battery from PV module.
- MPPT is DC to DC converter which operates by taking DC input from PV module, changing it to AC and converting it back to a different DC voltage and current to exactly match the PV module to the battery.

Smart Grids can integrate solar sourced electricity such as Rooftop solar PV along with traditional power generation allowing higher flexibility to have localized and right sized power plants with reduced transmission loss, zero environmental concerns and higher efficiency.

Examples of DC to DC converter are

- Boost converter is power converter which DC input voltage is less than DC output voltage. That means PV input voltage is less than the battery voltage in system.

- Buck converter is power converter which DC input voltage is greater than DC output voltage. That means PV input voltage is greater than the battery voltage in system.
- MPPT algorithm can be applied to both of them depending on system design. Normally, for battery system voltage is equal or less than 48 V, buck converter is useful. On the other hand, if battery system voltage is greater than 48 V, boost converter should be chosen.
- MPPT solar charge controllers are useful for off-grid solar power systems such as stand-alone solar power system, solar home system and solar water pump system, etc.

Main features of MPPT solar charge controller

- In any applications which PV module is energy source, MPPT solar charge controller is used to correct for detecting the variations in the current-voltage characteristics of solar cell and shown by I- V curve.
- MPPT solar charge controller is necessary for any solar power systems need to extract maximum power from PV module; it forces PV module to operate at voltage close to maximum power point to draw maximum available power.
- MPPT solar charge controller allows users to use PV module with a higher voltage output than operating voltage of battery system.
- For example, if PV module has to be placed far away from charge controller and battery, its wire size must be very large to reduce voltage drop. With a MPPT solar charge controller, users can wire PV module for 24 or 48 V (depending on charge controller and PV modules) and bring power into 12 or 24 V battery system. This means it reduces the wire size needed while retaining full output of PV module.
- MPPT solar charge controller reduces complexity of system while output of system is high efficiency. Additionally, it can be applied to use with more energy sources. Since PV output power is used to control DC-DC converter directly.
- MPPT solar charge controller can be applied to other renewable energy sources such as small water turbines, wind-power turbines, etc.

Conditions That Limits the Effectiveness of MPPT

The V_{mp} of a solar module decreases as the temperature of the module increases. In very hot weather, the V_{mp} may be close or even less than battery voltage. In this situation, there will be very little or no MPPT gain compared to traditional controllers. However, systems with modules of higher nominal voltage than the battery bank will always have an array V_{mp} greater than battery voltage. Additionally, the savings in wiring due to reduced solar current make MPPT worthwhile even in hot climates.

Applications.

- **Residential Application:** Use of solar energy for homes has number of advantages. The solar energy is used in residential homes for heating the water with the help of solar heater. The photovoltaic cell installed on the roof of the house collects the solar energy and is used to warm the water. Solar energy can also be used to generate electricity. Batteries store energy captured in day time and supply power throughout the day. The use of solar appliances is one of the best ways to cut the expenditure on energy.
- **Industrial Application:** Sun's thermal energy is used in office, warehouse and industry to supply power. Solar energy is used to power radio and TV stations. It is also used to supply power to lighthouse and warning light for aircraft.
- **Remote Application:** Solar energy can be used for power generation in remotely situated places like schools, homes, clinics and buildings. Water pumps run on solar energy in remote areas. Large scale desalination plant also use power generated from solar energy instead of electricity.
- **Transportation:** Solar energy is also used for public transportation such as trolleys, buses and light-rails.
- **Pool heating:** Solar heating system can be used to heat up water in pool during cold seasons.

- **Solar Green Houses:** A green house is a structure covered with transparent material (glass or plastic) that acts as a solar collector and utilises solar radiant energy to grow plants. It has heating, cooling and ventilating devices for controlling the temperature inside the green house.
- **Solar Cooking:** The solar cooker requires neither fuel nor attention while cooking food and there is no pollution, no charring or overflowing of food and the most important advantage is that nutritional value of the cooked food is very high as the vita-mins and natural tastes of the food are not destroyed.
- **Solar furnace:** In a Solar furnace, high temperature is obtained by concentrating the solar radiations onto a specimen using a number of heliostats (turn-able mirrors) ar- ranged on a sloping surface.
- **Solar Drying of Agricultural and Animal Products:** Solar drying, especially of fruits improves fruit quality as the sugar concentra-tion increases on drying. Other agricultural products commonly solar-dried are potato-chips, berseem, grains of maize and paddy, ginger, peas, pepper, cashew-nuts, timber drying and tobacco curing. Spray drying of milk and fish drying are examples of solar dried animal products.
- **Solar-pumping:** In solar pumping, the power generated by solar-energy is utilized for pumping water for irrigation purposes.
- **Solar-distillation:** In arid semi and or coastal areas there is scarcity of potable water. The abundant sunlight in these areas can be used for converting saline water into portable distilled water by the method of solar distillation.

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Module 4

Hydroelectric Plants and Ocean Thermal Energy

Hydroelectric plants: Advantages & disadvantages of water power, Hydrographs and flow duration curves, numericals, Storage and pondage, General layout of hydel power plants-components such as Penstock, surge tanks, spill way and draft tube and their applications, pumped storage plants, Detailed classification of hydroelectric plants, water hammer. Ocean Thermal Energy:

Ocean thermal energy conversion, Principle and working of Rankine cycle, Problems associated with OTEC.

The hydroelectric or the hydel power plants, generate power using the potential energy of water available on earth's surface. The rain water collected at different altitudes on the earth's surface has potential energy with respect to the level of the oceans towards which the water flows. This energy of the rain water is utilised to drive hydraulic turbines, and in turn to run electric generators and produce electrical energy. The hydel power developed depends on the head of water and the quantity of natural rainfall. Generally, reservoirs are constructed to collect the natural rain and used to generate power throughout the year. Thus the reservoir area, which is a measure of the water collected and the height of the dam, which is the measure of the head of the water are two important factors. However, the quantity of water available depends upon the hydrological cycle and the total rain-fall received by the area in which the power plant is located.

Hydrographs

It is a graph representing the discharge of flowing water with respect to time for a specific period. The time axis may have units of hour, day, week or month. The discharge units may be m^3/sec, km^2 -cm/hr or day-second-metre. Discharge hydrographs are also known as flood or run-off hydrographs)

Fig. 4-5 shows typical hydrographs or discharge curves based on daily, monthly and yearly flows.

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Uses of a Hydrographs

A hydrograph is useful to determine a number of parameters, such as:

1) Rate of flow at any instant during the specific recorded period.

2) Total volume of flow in a given period, as the area under the hydrograph represents the volume of water in a given duration.

3) The mean annual run-off for any of the recorded period.

4) The maximum and minimum run-off for any selected period

5) The maximum rate of run-off during the floods and duration of frequency of floods (peak of the curve indicates the flood)

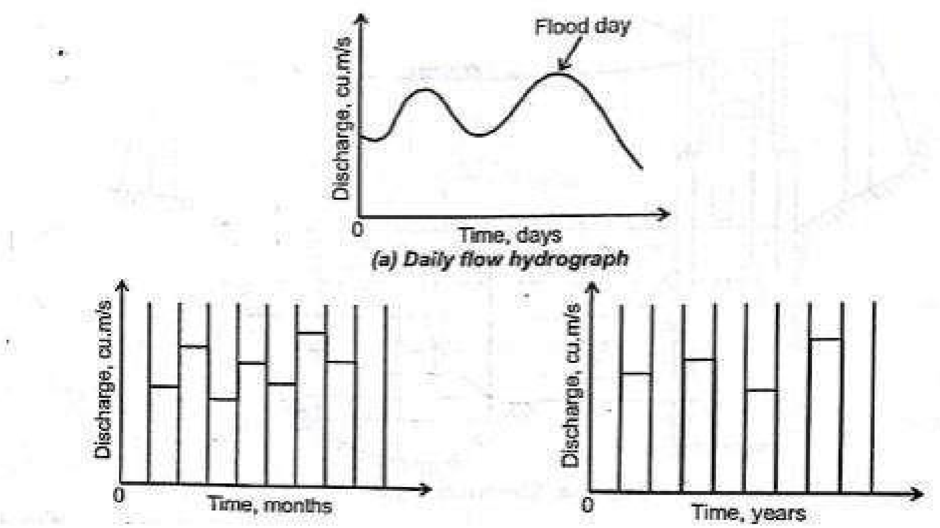

Fig. 4-5. Hydrographs or discharge curves

Unit Hydrograph

A unit hydrograph is a hydrograph with a volume of 1 cm of run-off resulting from a rainfall of specified duration and a real pattern, which is constructed using the hydrograph data. The theory of unit hydrograph was introduced by Sherman. He indicated that the time base is common to all hydrographs resulting from rainfalls of a given duration. When the rainfall distribution is similar with respect to time and area, then the ordinate of each hydrograph will be proportional to the volume of run-off.

Limitations to the use of unit hydrograph are:

1) The rainfall distribution varies from one area to another. Hence, the use of unit hydrograph is limited area of basin of about 5000 sq. km.

2) For long and narrow basins, and odd shaped basins the rainfall distribution is not even, hence unit hydrograph is not suitable.

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Flow Duration Curve This is another useful graphical representation of the run-off for a given period. The run-off data on the ordinate against the corresponding percentage of time on the abscissa represents a Flow Duration Curve. The area under the curve represents the average yield from the stream.

Fig. 4-6 shows a typical flow duration curve. the flow may be expressed as m^3/sec/ week or any other convenient unit of time When the available head of water is known, then the total energy of flow can be computed. Thus by flow duration curve it is possible to estimate the total power available at the site. A flow duration curve can be used to determine the minimum and maximum conditions of flow of water. If the magnitude on the ordinate is the estimated power contained in the stream flow against the corresponding percentage of time on the abscissa, then the curve is known as Power Duration Curve.

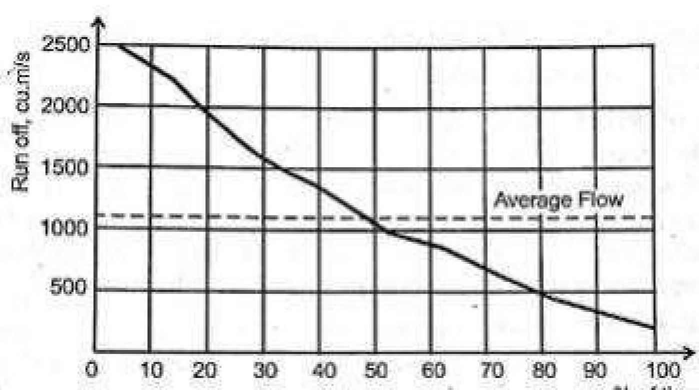

Fig. 4-6. Flow duration curve

Selection of Site for Hydel Plants

There are many factors that are to be considered while selecting site for a hydel power plant. The important factors are as follows:

1) Availability of Water. The site selected should be such that requisite quantity of water is be available throughout the year for economical generation of power. To estimate the availability of water, geographical, meteorological and geological investigations of the site are to be carried-out. Previous records of rainfall of the particular area are to be studied. If needed, aerial and ground survey can be conducted. Stream flow rate, minimum and maximum quantity of water available in a year is to be estimated.

2) Storage of Water. The site selected should have good storage capacity, sufficient enough to use for a full year. This depends upon the reservoir capacity and the catchment area. It is always intended to store water enough to use even during dry periods, to the extent possible.

3) Head of Water. Head of water is the highest level of water at the upstream from where water flows down for power generation. Higher the head available, lesser the quantity of water required for a known power output and hence, lesser is the storage requirement. Power generated depends mainly on the head of water available, which is seen from the relation,

$$\text{Power} = \frac{mgH\eta}{1000}$$

Where, m = discharge or rate of water flow, kg/sec.

H = head of water, m g = acceleration due to gravity, 9.81 m/s^2

η= efficiency of the prime mover and generator (about 0.8 to 0.9) Hence, the site selected should give the highest head of water.

4) **Ground Water Data.** It is an important factor to be considered, since it decides the stability of the ground at the reservoir and dam construction area. It is essential to select a site which has lesser ground water movement, as it provides a solid reservoir base and also seepage will be minimum. A strong reservoir base also helps in reducing the foundation costs for the darn construction.

5) Distance from the Load Centre. It is always essential that the site selected should be as nearer as possible to the load centre. Increased distances lead to increased power transmission costs and higher transmission losses. Other factors to be considered in the selection of a good site are the easy accessibility to the site by road and/or rail, cheap cost of the land and the availability of non-polluted, clean water for power generation.

Advantages and Disadvantages of Hydel Plants Advantages

1) Operating cost of the plant including auxiliaries is low.

2) The maintenance of the plant is comparatively less.

3) Less labour is required to operate the plant.

4) No nuisance of smoke, exhaust gases, soot and other pollution.

5) The sites of hydel plants are usually away from the developed areas and hence the land is very cheap.

6) Load fluctuations can be met rapidly without loss of efficiency.

7) There are no stand-by losses.

8) Since no fuel used, there are no problems of handling, charging and disposal.

Disadvantages

1) Initial cost of the plant including the cost of dam is very high.

2) The feasibility of a hydel plant depends mainly on the availability of water and hence the natural phenomenon of rain and thus the problems of stopping the plant may arise during dry seasons.

3) Usually the sites will be away from the load centres, which causes loss of power and high costs in transmission lines.

4) It takes considerably long time for erection compared to the erection of thermal plants.

CLASSIFICATION OF HYDEL PLANTS

Hydel power plants can be classified as follows:-

1. **Quantity of water available**

a) Run-off river plants without pondage

b) Run-off river plants with pondage

c) Pumped storage plant

2. **Head of water**

a) Low head plant

b) Medium head plant

c) High head plant.

3. Nature of load

a) Base load plant

b) Peak load plant

4. Capacity of plant

a) Low capacity plant (100-999 kW)

b) Medium capacity plant (1 MW-10 MW)

c) High capacity plant (above 10 MW)

Run-off River Plants without Pondage

In such plants water is not stored, but only the running water is used for power generation. In such power plants the power generated directly depends upon the rate of flow available. Hence, during rainy seasons some excess quantity of water may run waste without doing any power generation. During dry periods the power production will be very poor, since the water flow rate will be low.

Run-off River Plants with Pondage

In such plants, the excess water available during rainy seasons is stored in the reservoirs. The plant works with the normal run-off during the rainy season, while the stored water from the reservoir is utilised to supplement the low flow rate during dry periods. Power production will not be affected by the dry seasons. Hence, plants with pondage can generate a constant rate of power through out the year. If Pumped Storage Plants Such plants are most suitable for supplying sudden peak load requirements. However, such demands can be met only for a short duration. In the normal operation they can meet the average demand only.

Pumped storage plant

Fig. 4-8 shows the schematic of a pumped storage plant. Such type of plant consists of two storage reservoirs. The upstream reservoir is the main (head race) storage reservoir to which water flows from the catchment area. The second reservoir is the down stream (tail race) reservoir, in which the used water from the upstream is collected.

The water in the down stream reservoir is pumped back to the main upstream reservoir, during off peak periods. This facilitates making use of the excess water during peak hours. A pumped storage plant is a peak load plant and operates in combination with other base load plants such as a thermal power plant. The off peak load capacity of the thermal plant is used for pumping water from the down stream reservoir to the main upstream reservoir. The schematic arrangement of pumped storage plant operating along with a thermal plant to meet the peak load demands, is shown in Fig. 4-9

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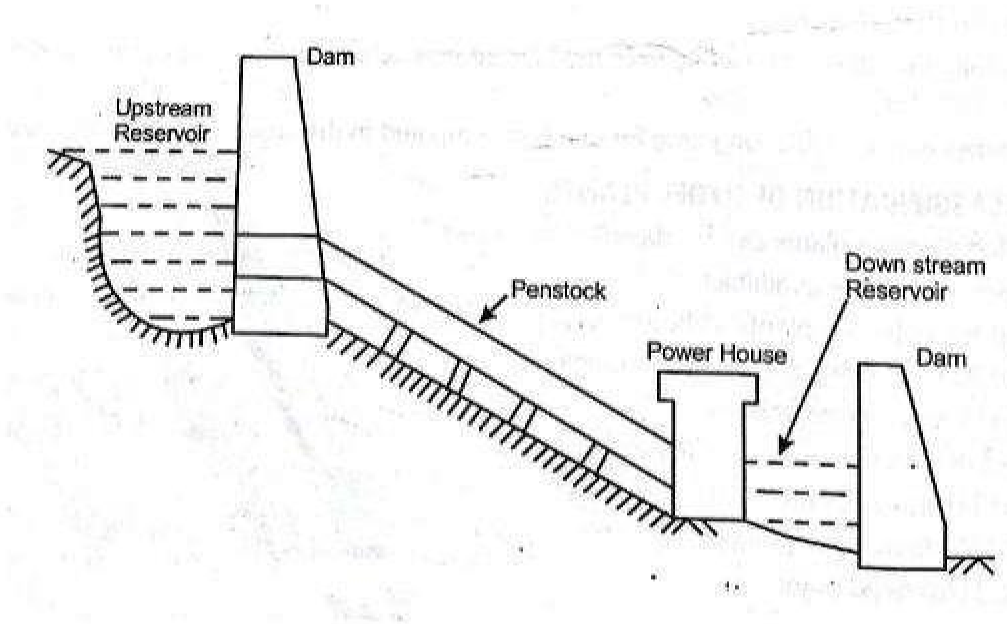

Fig. 4-8. Pumped storage plant

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Advantages of Pumped Storage Plants

1) Compared to peak load plants, the initial cost of this plant is low.

2) The power plant operation is flexible, since it can operate both as peak load and base load plant.

3) Such plant can meet sudden peak hour demands, and is highly reliable in operation.

4) Since they operate at higher load factors, the overall efficiency of the plant is high.

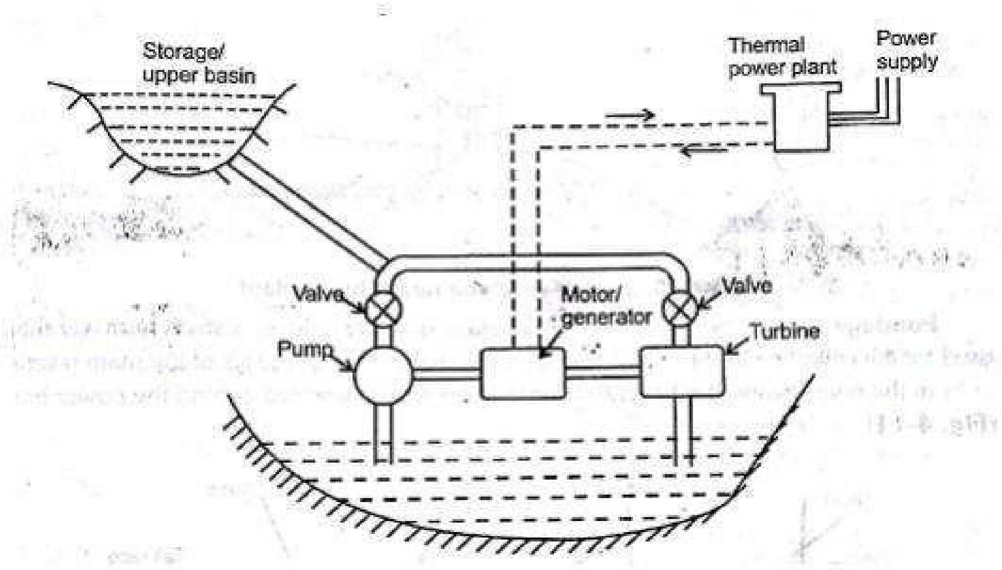

Fig. 4-9. Pumped storage plant for peak load

torage and Pondage

Storage plants are the plants with facilities for storing water at their sites. However, often such plants cannot store as much water as required for the full year operation. For continuous operation, it is always preferred to have one or more reservoirs upstream. Depending upon the place of storage and the function, the reservoirs are grouped as storage and pondage. Storage: Storage can be defined as the collection of a large quantity of run-off during mansoon seasons, which is essentially used in the dry seasons for the plant operation. This is the main or the upstream reservoir, made by the construction of a dam across the stream (Fig. 4-10).

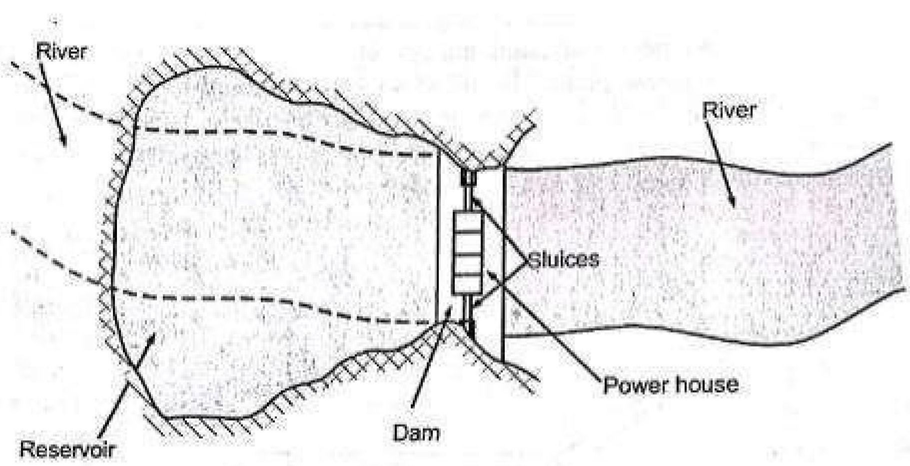

Fig.4-10. Storage reservoir based hydel plant

Pondage:

It is defined as a regulating means of water, and is a small reservoir that is used for the collection of the excess flow water from the dam spill ways of the main reservoir or from the river stream. It is basically a small pond or reservoir just behind the power house (Fig. 4-11).

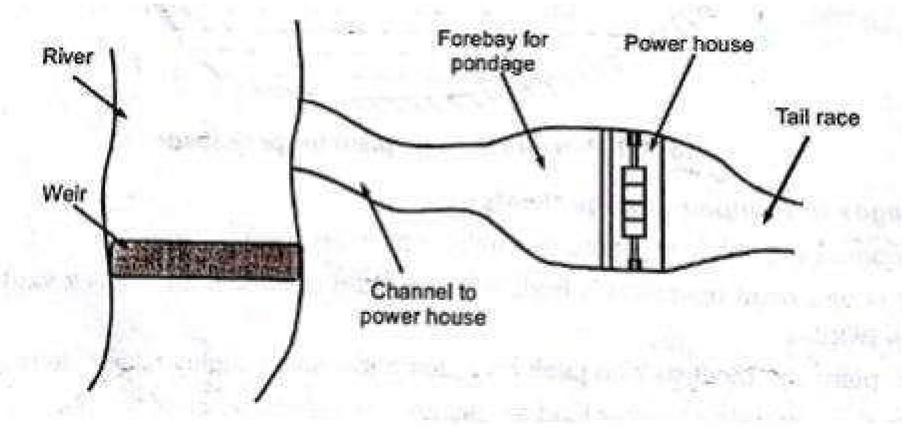

Fig. 4-11. Pondage reservoir based hydel plant

The amount of regulation obtained with pondage usually involves storing water during low loads (during low power demand periods such as early morning hours and Sundays) to aid carrying peak loads during the week. The water that would go over the dam spill-way unused during low-loads can be released and added to normal river flow to supply peak loads, usually for a few hours of duration. For fluctuating loads, pondage increases the maximum capacity that a plant can carry.

Plants with reservoirs upstream can store excess water of spring floods for release during summer to supplement the low rates of flow during this dry season. Reservoir water elevation will generally be lowest during the year at the end of the summer.

Pondage increases the capacity of a river for a brief period only, like for a week. But, _ storage increases the capacity of a river over an extended period such, like 6 months to 2 years.

Low Head Hydel Plant hydel plant

Hydel Plant with a water head of less than50 meter is termed &low head plant (the such plants, a small dam is constructed across a river to obtain the necessary water head:, The excess water is allowed to over the dam, while the water head is made use to run a hydraulic turbine. The water from the dam is taken through a canal to the turbine. For low head plants Francis or Kaplan turbines are used. There is no water hammer problem in such plants, hence no, surge tank is provided in the water line. The schematic arrangement of a typical low head hydel plant is shown in Fig. 4-12

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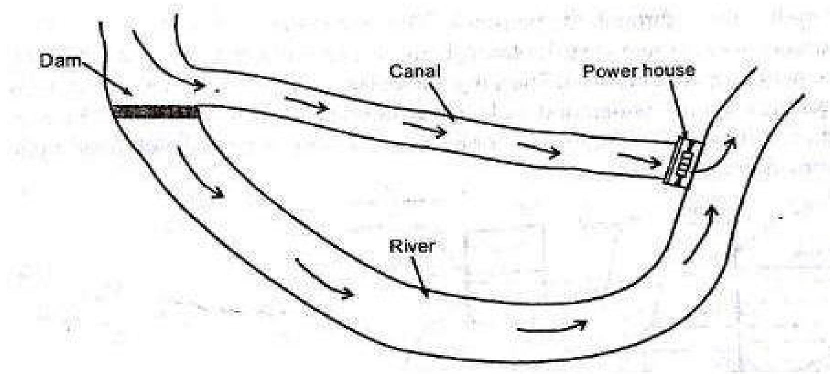

Fig. 4-12. Low head hydel plant

Medium Head Hydel Plant

A hvdel with a water head of in the range of 50 to 100 meters is termed a medium head plant. In this, the water is stored in a main reservoir. This water is allowed to a small pond or forebay through a canal. The water from the forebay is taken to the turbine through penstock. In such plants the forebay itself acts as the surge tank, and hence receives the excess water during the low demand periods. Francis turbine is most suitable for medium head hydel plant. The schematic arrangement of a typical medium head by n Fig. 4-13.

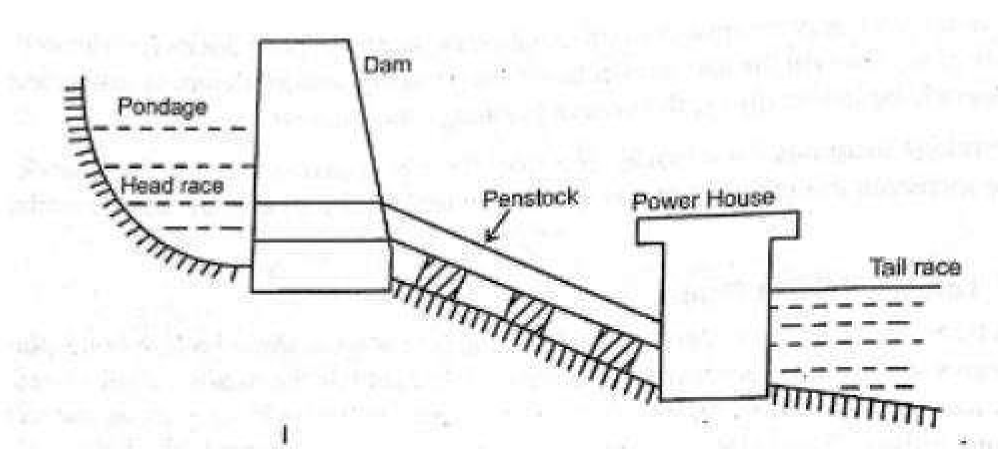

Fig. 4-13. Medium head hydel plant

High Head Hydel Plant

Hydel plant with a water head of more than 100 meters is termed a high head plant. In this case, the water from the main reservoir is carried through tunnels up to the surge tank, ord. Where it is taken through the penstock. Since the water head is very high, the effect of water hammer is too severe in such plants. Thus, it is essential to provide a surge tank in the water line at appropriate location. The surge tank takes care of the increasing and decreasing water levels during the low-demand and high demand periods, respectively. The Francis and Pelton wheel turbines are most suitable for high head plants. A typical high head hydel power plant is shown in Fig. 4-14.

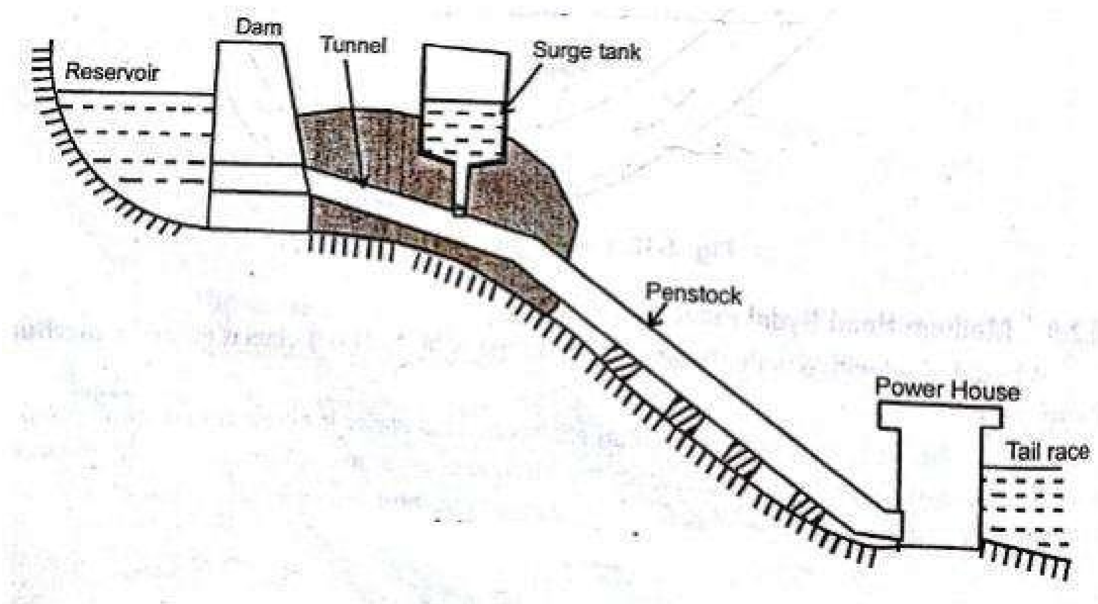

Fig. 4-14. High Head Hydel

GENERAL LAYOUT OF A HYDEL PLANT

Fig. 4-15 shows the general layout of a storage type hydel power plant with necessary components and protective devices. The main components of a storage type hydel power plant arc as follows:

1. Catchment area
2. Storage Reservoir
3. Dam
4. Penstock
5. Forebay
6. Power house
7. Draft tube
8. Trash rack
9. Spill way
10. Surge tank

The last three units are the protective devices, which help in the safe functioning of the hydel plant.

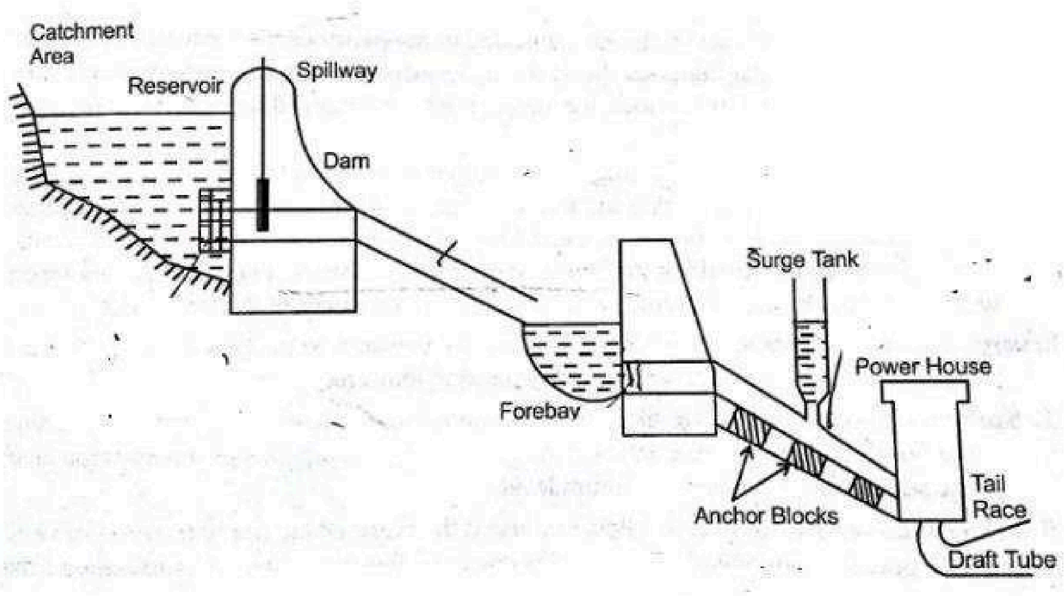

Fig. 4-15. General layout of a hydel power plant

The different components and their functions are briefly discussed below.

1. **Catchment Area:** The complete area around the reservoir, around the river and the river basins near the reservoir is termed the catchment area. A larger catchment area results in better run-off into the reservoir. The reservoir capacity and the dam size are dependent on the size of the catchment area and the intensity of the rainfall.

2. **Reservoir**: The main purpose of reservoir is to store water during rainy season and supply the same during dry season. The reservoir is located at a region of heavy rain fall, with sufficient catchment area.

3. **Dam:** The function of a dam is to increase the height of water level behind it, hence to increase the reservoir capacity. The -darn also helps to increase the working head of the power plant.

4. **Trash Racks:** The water intakes from the dam or from the forebay are provided With trash racks to prevent the entry of debris. The debris if allowed may damage the wicket gates and turbine runners, or choke-up the nozzles of the impulse turbine, thus hampering the plant operation. If the winter is severe, arrangements to heat the trash racks by electrical means are made to prevent the clinging of ice around it. Sometimes bubbling arrangement is made near the trash racks, which brings them in contact with warm water and minimises the icing problem.

5. **Forebay**: It serves as a regulating reservoir and temporary storage pond. It receives the excess water when the load on the plant is reduced and provides water for initial increment of an increasing load, while the water in the canal is being accelerated. Thus, forebay is a naturally provided storage which is able to absorb the flow variations. This can also be considered as the naturally provided surge tank as it performs the work of a surge tank.

6. **Surge Tank:** It is a protective device connected to the penstock. Its function is to protect

penstock against water hammer effects during low demand periods and avoid vacuum effect during high demand periods. It achieves this by stabilizing the velocity and pressure in the penstock.

7. **Penstock:** A pipe between the surge tank and prime mover is known as penstock. The structural design of a penstock is same as other pipes, except for that it is made stronger inside, to withstand high pressures caused by water hammer during load fluctuations. Penstocks are usually made of steel through reinforced concrete. Penstocks are equipped with head gates at the inlet which can be closed during repair of the penstocks. In very cold weather conditions, it is better to bury the penstock to prevent the ice formation in the pipe and to reduce to number of expansion joints required.

8. **Spillway**: It is considered as a safety valve of a clam. It must have the capacity to discharge major floods without damage to the dam and at same time keeps the reservoir level below some predetermined maximum level.

9. **Power House / Prime Mover:** Power house is the place where prime mover is run and electric power is generated. The main purpose of the prime mover is to convert the kinetic energy of water into the mechanical energy to produce electric current. These are Pelton, Kaplan and Francis turbines. .

10. **Draft Tube:** This essential part of reaction turbine installation. It supplements the action of the runner by utilizing most of the remaining kinetic energy of the water at the discharged end of the runner.

Spillways

It is a safety device constructed with the dam. It functions when the dam faces flood problems. If allows the passage of excess water from the reservoir, whenever the level raises above the predetermined safer level, thus avoiding the damage to the darn. The different types of spill ways are:

1) **Ogee Spillway:** Fig. 4-17a shows a ogee spillway. It is the crust of the dam, designed in such a way that, whenever the reservoir level reaches the safe limit the water starts flowing out. This is the simplest spillway and widely used for concrete dams.

2) **Chute Spillway**: A chute spillway is shown in Fig. 4-17b. In this type of spillway, the excess water during floods flows-out of the dam and gets discharged through concrete channels constructed along the sloping dam as shown in figure. This type of spillway is suitable for earthen dams.

3) **Shaft Spillway**: Fig. 4-17c shows a shaft spillway. In this, water flows through a horizontal tunnel to the penstock from the reservoir. In the dam a vertical shaft is constructed connecting the horizontal tunnel. Whenever the water level exceeds the safe limit, excess water starts flowing through the vertical shaft as shown in figure.

4) **Siphon Spillway:** Fig. 4-17d shows a siphon spillway. When the water level reaches A-A the siphon starts working and siphons out water up to B-B. This type is suitable for small

capacity reservoirs.

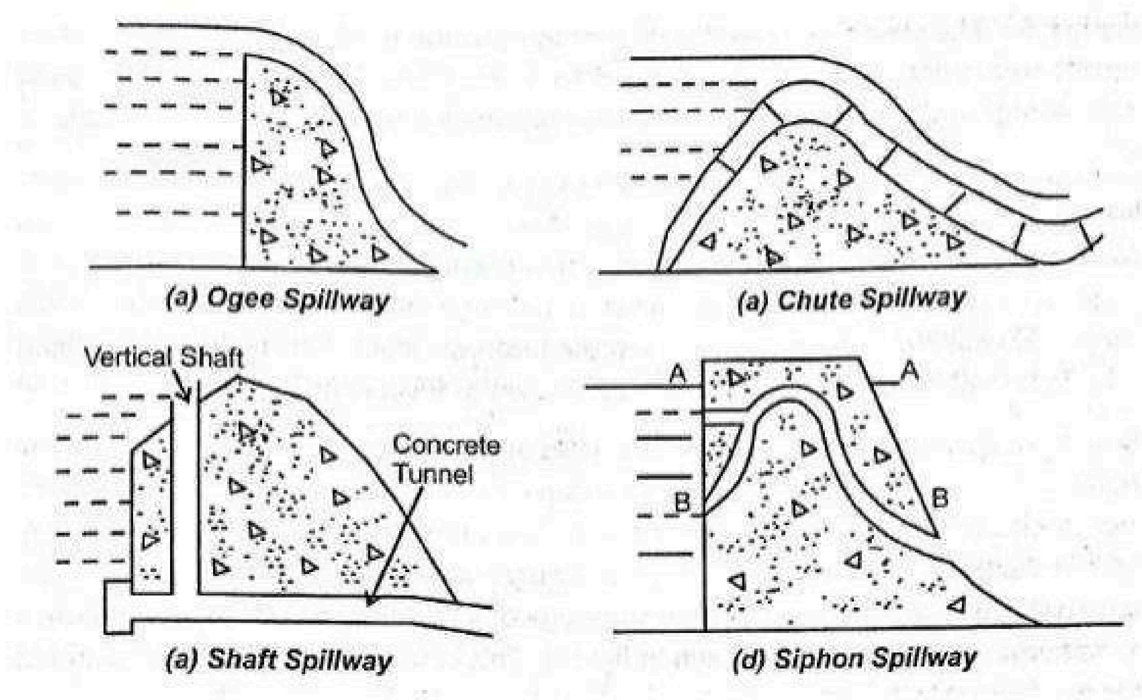

Fig. 4-17. Spillways

Penstocks

Penstocks are the pipelines that connects between the water source (such as the reservoir, forebay, water way) and the hydraulic turbine. These are usually large circular pipes with diameters ranging form 1 meter to 8 meters. Penstocks are usually made of steel or concrete pipes. Care should be taken to keep the entry to the penstock at the dam or the forebay at a low level, submerged always under the water. If the entry is open to air, it may take air along and create aeration prob11Ams in the prime mover, thus affecting the performance. The penstocks should be laid in such a way that there are no sharp bends. Sharp bends cause frictional losses and reduce the effective water head. Generally penstocks are exposed type, since they are economical and easy to repair and maintain. However, covered penstocks can be used when the regions are prone to sliding rocks, snow, earth and such dangers, so as to avoid damage to the pipe line.

Water Hammer - Surge Tanks

Whenever there is a sudden fall in the demand, the governor closes the penstock valve to a minimum. This sudden closure of the valve increases the pressure inside the penstock due to the kinetic energy of the water which is high enough to damage the penstock pipe. This effect is termed Water Hammer. Also, whenever there is a sudden rise in the load demand the gates are opened instantly by the governor, thereby creating vacuum in the penstock pipe. This causes to bubbling and foaming action. This leads to operational problems in the turbine. These problems can be overcome by providing a surge tank in the penstock line. Basically, a surge tank is a cylindrical Open top storage unit, which connected to the penstock line and located very close to the turbine.

Function of Surge Tank

During the normal demand/flow periods, the turbine gates are open to normal position, since there are no fluctuations in the water level in the surge tank. The normal water level in the surge tank is always lower than that of the basic reservoir level. This is due to the head loss due to the frictional losses in the flow line. It is shown as level A in Fig. 4-18. During low demand periods, the turbine gates are closed partly and water flow is reduced to keep the turbine speed constant. Due to sudden closure of the flow path, the flowing water in the penstock comes to a halt thereby building pressure in the line. If there is no surge tank this creates a water hammer in the penstock and may cause damage to the pipe line. With the surge tank present in the line, this sudden stoppage of water flow results in an increase in the level in the surge tank (level B, as shown in figure). This causes a retarding head and reduces the velocity of water in the penstock thereby avoiding water hammer effect.

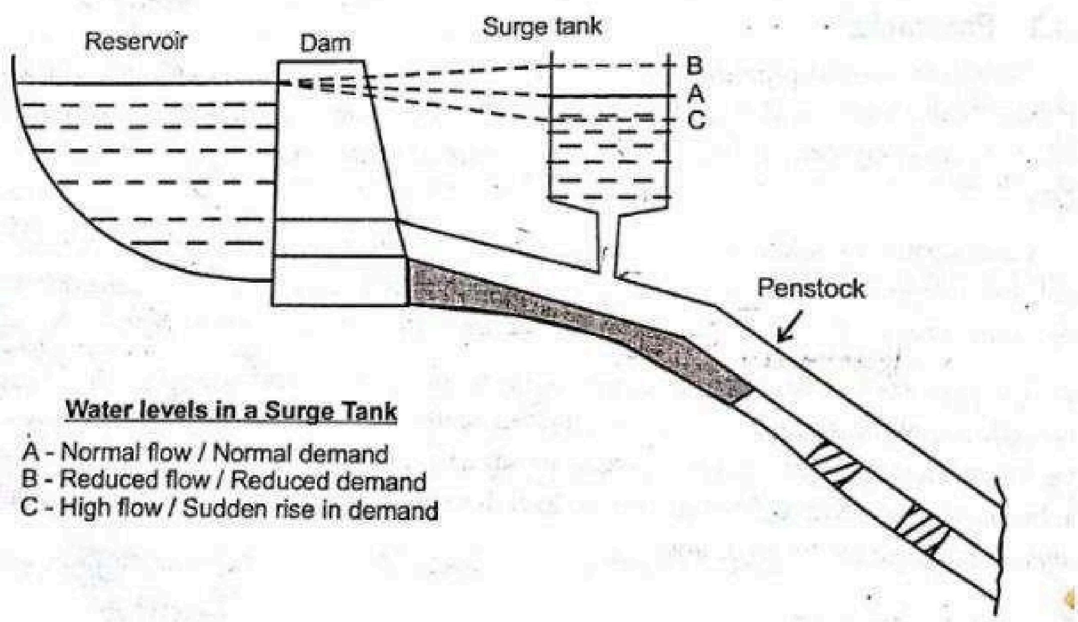

Fig. 4-18. Function of a surge tank

Similarly, when the demand is normal, the gate is opened to the normal position, so that the flow velocity on the penstock reaches the normal value. For this, the required water is supplied by the surge tank, and the water level in the surge tank suddenly reduces and fluctuates up and down till its motio7n is damped down by friction.

When there is a sudden rise in the load, additional water required is supplied by the surge tank thus avoiding the possibility of vacuum formation in the penstock. During this the water level suddenly drops down below the normal as the water excess water is supplied by the surge tank. This is indicated as level C in Fig. 4-18.

Types of Surge Tanks

Different types of surge tanks are used in the power plants depending upon the design and topographical requirements. Some important types of surge tanks are as follows:

a) Cylindrical Surge tank

This is the simplest design. It is simply a plain cylindrical tank connected to the penstock line through a short connecting conduit (Fig. 4-19a). The tank size is kept to a level so as to maintain a stable flow to the turbine, and minimum fluctuations in the water level. However, this design is not a common design due to its slow response to demands and also it is expensive. This is not a commonly used design in hydel plants.

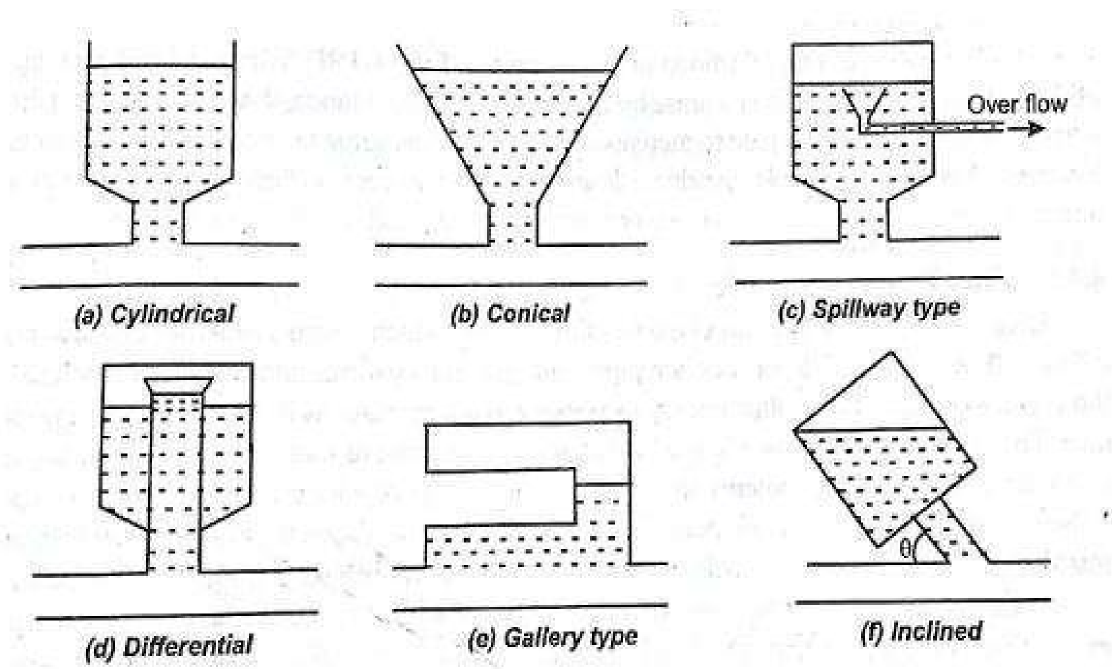

Fig. 4-19. Types of surge tanks

b) Conical Surge tank

It is a conical shaped vessel connected to the penstock (Fig. 419b). it is a better design than the cylindrical surge tank. Since it has an increasing area of cross section, it can handle the water fluctuations more effectively. Also, it has a considerably faster response to load fluctuations.

c) Spillway type Surge tank

This is a closed cylindrical vessel with a bell mouth spill way connected to it (Fig. 4 19c). The tank is designed to meet the water demand from the stock available in it, while the excess water during low demand periods over flows out of the surge tank through the spill way,

d) Differential Surge tank

This is cylindrical tank with a central riser with small ports at the lower end (Fig. 4-19d). Water movement in the tank is through the ports. It responds effectively to the variations in load demands, and also the oscillations in the wafer level are minimal.

e) Gallery type Surge tank

This is special surge tank design. It has two separate water galleries (Fig. 4-19e). The upper gallery stores the water when the load on the turbine drops, while the lower gallery supplies water when there is a sudden increase on the turbine load.

f) Inclined Cylindrical Surge tank

This is a cylindrical tank inclined at some angle q (Fig. 4-19f). With this inclination the effective area of water surface increase by an amount cosec q. Hence, the actual height of the surge tank can be reduced. Due to increased water area, this surge tank can respond faster to load variations than the simple cylindrical design. However, its construction is difficult, expensive and preferred only when the topographical situations demand for such requirements.

Draft Tubes Draft tube is an integral part of the reaction turbine, which connects the runner exit to the tail race. It can be a metallic or concrete pipe having gradually increasing cross section towards the outlet to ensure that as little energy as possible is left in water as it discharges into the tail race. The area of the draft tube at the top is circular and same as that of the turbine outlet, so that shock and aeration problems are minimum. Draft tube provides a negative suction head at the runner outlet by which it is possible to install the turbine above the tail race level without any loss of head. Since the velocity of the water leaving the runner is quite high, the kinetic energy will be lost if water is allowed to discharge freely. The draft tube reduces outlet velocity and increases the useful pressure head thereby increasing the turbine output.

The different types of draft tubes used in hydel plants are illustrated schematically in Fig. 4- 20.

1) **Straight divergent tube** (Fig. 4-20a), is used in low specific speed vertical shaft Francis turbines. It has a circular inlet and rectangular outlet. The cone angle should be less than 8° for optimum turbine performance. It gives a better speed regulation when the turbine load drops down.

2) **Moody spreading tube** (Fig. 4-20b) has two split section at the outlet. This section reduces the whirl action of water flowing at high velocity.

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3) **Simple elbow tube** (Fig. 4-20c) has circular cross section throughout.

4) **Elbow type draft tube** has a circular inlet and a rectangular outlet (Fig. 4-20d)

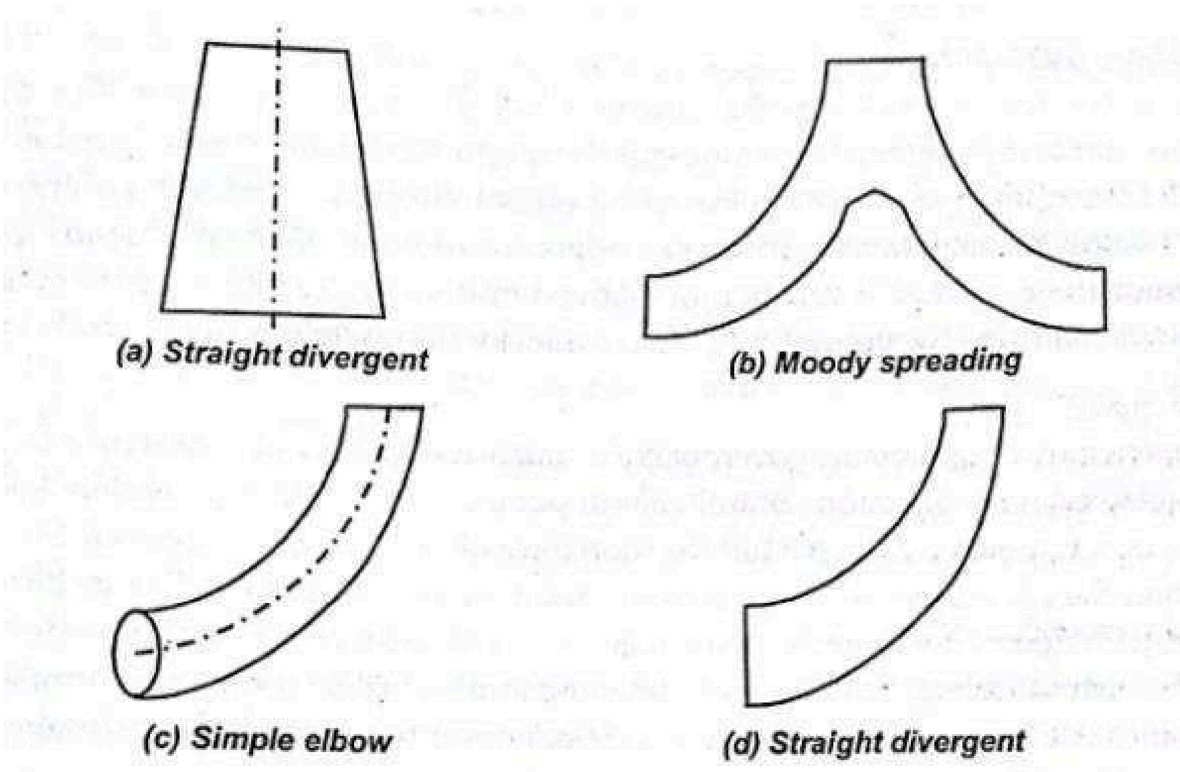

Fig. 4-20. Types of draft tubes

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OTE Power Plant Development

In 1882, D'Arsonval suggested that it is possible generate power based on the ocean thermal energy, by utilising the energy in the warm surface water of the ocean and rejecting heat to the colder water of the lower layer.

The first attempt to utilize the OTE was made in 1926 by G. Claude, a French scientist. He constructed a 40 kW land-based OTEC power plant near Cuba. In his plant, a part of the warm surface water was converted into steam in a low-pressure flash evaporator operating at a high vacuum. In the flash evaporating process, sensible (heat) energy in the water gets converted into latent energy. The steam produced in the evaporator was expanded in a turbine and subsequently condensed by direct contact with the cold sea water piped from the lower layer in the ocean.

However, Claude's system to utilize the OTE for power generation was not successful, mainly due to reasons like corrosive nature of the sea water (corrosion resistance materials were expensive), the pressure was low as water was evaporated at low temperature, high pumping work required for operations, requirement of very large turbine, and conveying the cold sea-water to the power plant over a long distance.

Thus, Claude's experiment demonstrated that the OTE power plant will inherently require large components, have a relatively low power output, and operate at a high vacuum when the working fluid is water.

Problems Encountered in Harnessing OTE

1) The sea water is more corrosive, thus the life of the plant is less.

2) The water can be evaporated (in a flash evaporator) at low temperatures only, thus the corresponding pressure is low, thus only smaller outputs are possible.

3) Much pumping work is required to remove the non- condensable gases.

4) The specific volume is more due to low pressure and temperature. This necessitates a large turbine.

5) The plants have to be based at lands, some distance away from the OTE source. This requires long pipelines to convey cold sea water to the power plant.

6) Due to low output and large components the cost of the OTE power plant is high.

7) The plant requires expensive and large size structures for installation and operation.

Advantages and Disadvantages of OTE plants Advantages

1) OTE is available free of cost, and in large quantities.

2) OTE is non-polluting and non-depleting in nature.

Disadvantages

1) Arrangement of the plants very difficult.

2) The power developed is not continuous.

3) Transmission costs are high.

4) Cost per unit of power generated is high.

5) Sea water corrosion problem is severe.

Closed Rankine Cycle OTEC System

In 1965, J.H. Anderson presented in considerable detail a conceptual design of an OTE power plant encased in a submerged structure anchored in deep water of the Caribbean sea. The plant was designed to operate with a thermal differential of 20°C between the warm surface water and the colder water in a layer 600 m below the surface. Approximately 14% of the gross power generated by the plant was consumed by the plant auxiliary equipment.

The closed Rankine cycle OTEC power plant operates with a low boiling fluid like propane as the working medium (the other low boiling fluids that can be used are ammonia, R-12, R- 22, etc.). The schematic representation of this system is shown in Fig. 7-7.

The warm sea water flows through a heat exchanger, the boiler, in which the low-boiling point propane is evaporated. Propane vapour at a pressure of about 1035 kPa (absolute), propane expands ill the turbine to a pressure of about 690 kPa (absolute). Condensation of the vapor is effected in a surface condenser by transfer of heat to the cold sea water. The temperature increase in the cooling water is about 3 to 4°C. Special attention must be given for the design of heat exchangers, in order to reduce all secondary temperature drops, because these elements (Heat exchangers) are very large, and to obtain highest possible drop in temperature through turbine.

Special attention must be given for the design of heat exchangers, in order to reduce all secondary temperature drops, because these elements (Heat exchangers) are very large, and to obtain highest possible drop in temperature through turbine.

Also, the operating pressure in the closed propane cycle is high, and hence a turbine of reasonable size and cost is to be used. Vacuum and dearation problems are eliminated by operation of the thermal cycle above atmospheric pressure.

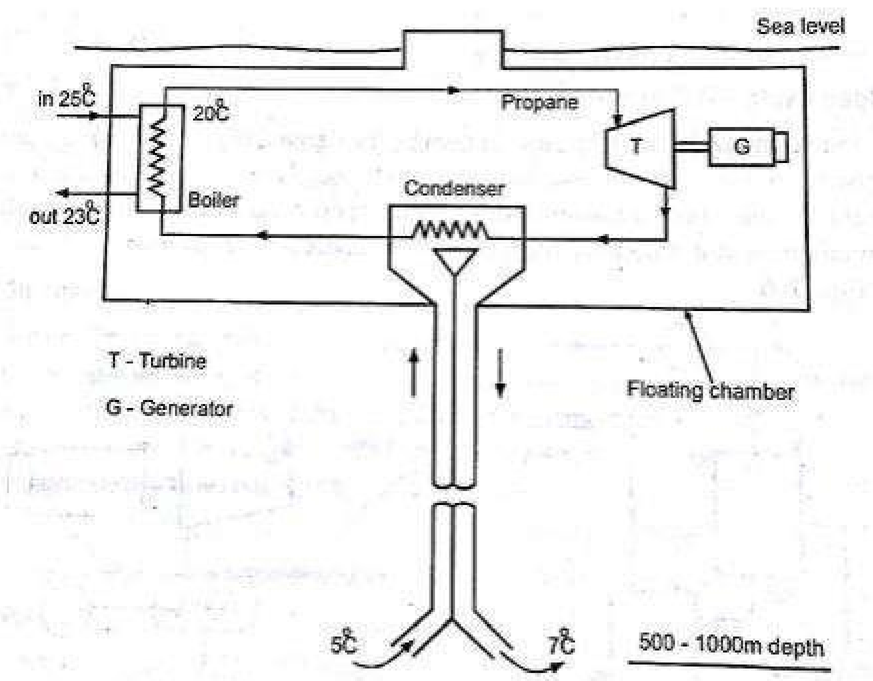


Fig. 7-7. Closed Rankine cycle OTEC system

Geothermal Energy, Tidal Energy

Geothermal Energy: Forms of geothermal energy, Dry steam, wet steam, hot dry rock and magmatic chamber systems.

Tidal Energy: Tidal power, Site selection, Single basin and double basin systems, Advantages and disadvantages of tidal energy.

GEOTHERMAL ENERGY CONVERSION (GTEC)

Geothermal energy is the thermal energy stored in under ground deposits as steam, hot water and hot dry rock. The inner core of the earth is highly radioactive, and as a consequence a natural flow of heat occurs from the core to the surface of earth, which can be harnessed into useful energy.

Geothermal energy is normally found in two basic forms, namely, in subterranean hot water or hot dry rock. In some locations, the vapour phase of the hot water is predominant, hence the geothermal energy source is described as steam. Where the hot water is entirely in the liquid phase, the term geo-hydrotherma or geo-pressurized, is applied.

he utilization of GTE is being investigated through a number of research and development programs. Like the solar and wind energy, GTE is quantitatively significant, but the extraction of this energy from the ground and subsequent conversion to electrical energy is not cost free and not without certain operating problems. But, geothermal energy generation is not subject to interruptions that are inherent in solar and wind power generation. The Geothermal power plant is capable of continuous operation,--provided that the generating capability properly matches the energy supply. There are many locations in the world where geothermal steam and water (hot) are utilized for heating buildings. Even it can be used for industrial processing.

Geothermal Power Plant Operation

The geothermal power plant operates on a simple, low-pressure steam power cycle. At the Geysers, the turbines operate with inlet steam pressures of 450 and 690 kPa. Boiler and handling equipment are not required. Also, since there is no need to conserve the condensate, a direct-contact condenser can be used.

The geothermal steam discharged from a well contains a quantity of non-condensable gases that can cause operating difficulties, including corrosion in the condensing system. These gases are removed from the steam in the condenser by the vacuum pump, usually a steam jet ejector, and expelled into the atmosphere.

Most of the wells drilled for geothermal power production discharge a mixture of steam and water. If the hydrostatic pressure is sufficiently high at the bottom of the well, the water will

flow, unaided to the surface. Hot water rising in the well and subjected to reduced pressure, partially flashes into vapour. At the well head the water is mechanically removed from the mixture in cyclone separators, and the relatively dry steam is transported to the power station.

The steam and water mixture flowing from the geothermal wells contains dissolved solids that are particularly trouble some. It ranges from 1 to 20 gm per kg of water. In addition to the dissolved solids some wells may give out the mixture containing some acids. In general, the dissolved solids and acids in geothermal water cause scaling and corrosion. Scale formation can be particularly severe in the outflow pipeline in which the discarded water is carried away from the separator.

Geothermal power production cause air and water pollution in operation. Ear splitting noise caused by escaping steam and the escape of radioactive gases are other objectionable characteristics that have been observed.

Flash steam power plants are the most common and use geothermal reservoirs of water with temperatures greater than 360°F (182°C). This very hot water flows up through wells in the ground under its own pressure. As it flows upward, the pressure decreases and some of the hot water boils into steam. The steam is then separated from the water and used to power a turbine/generator. Any leftover water and condensed steam are injected back into the reservoir, making this a sustainable resource.

un

Binary cycle power plants operate on water at lower temperatures of about 225-360°F (107- 182°C). Binary cycle plants use the heat from the hot water to boil a working fluid, usually an organic compound with a low boiling point. The working fluid is vaporized in a heat exchanger and used to turn a turbine. The water is then injected back into the ground to be reheated. The water and the working fluid are kept separated during the whole process, so there are little or no air emissions.

Currently, two types of geothermal resources can be used in binary cycle power plants to generate electricity: enhanced geothermal systems (EGS) and low-temperature or co-produced resources.

Advantages and Disadvantages of GTE Advantages

1) GTE is available free of cost, in large quantities.

2) There are no interruptions in GTE conversion as in solar and wind energy conversions.

3) It is capable of continuous operation.

4) Boiler and Fuel handling equipment are not required.

5) There is no need to conserve the condensate, thus a direct contact condensate can be used.
6) Operation and maintenance costs are less.

Disadvantages

1) Such plants will always be located far away from the load centers.

2) Erection and installation costs are high.

3) It causes air, water, thermal and noise pollution. Ear-splitting noise caused by the escaping steam causes noise pollution.

4) The hot water geothermal sources have higher mineral contents and their disposal is a problem.

5) Seismic activities are caused, if water is injected into hot rocks to recover the thermal energy

Sources of Geothermal Energy

The various sources of geothermal energy are as follows

1) Hydrothermal systems: In these, water is heated by contact with hot-rock in the earth's crust. The temperature of the steam raised by this is in the range of 150 to 200°C.

2) Geopressure system: These sources are similar to hydrothermal systems, and are reservoirs of high temperature water under high pressures (50 to 100 MPa).

3) Hot dry rocks (HDR): Also termed petrothermal systems, are very hot solid rocks available in the earth's crust at medium depths (2 to 5 km). The temperature is of the order of 300°C.

4) Magma source: These are molten rocks with temperature much above 750°C, available in deep earth's crust. Presently, the hydrothermal systems and hot dry rocks are more feasible for geothermal energy harnessing.

1. **Hydrothermal Systems** In these, water is heated by contact with hot-rock in the earth's crust.

These are two types of hydrothermal systems:

a) Steam dominated systems

In this type of geothermal system, water is vaporised into steam at the lower level in the earth's crust. The steam rises to the earths surface in a dry state (about 200°C and more than 2 MPa pressure). This dry steam can be used conveniently and directly to run steam turbines and generate electric power. The schematic of such a system is illustrated in Fig.

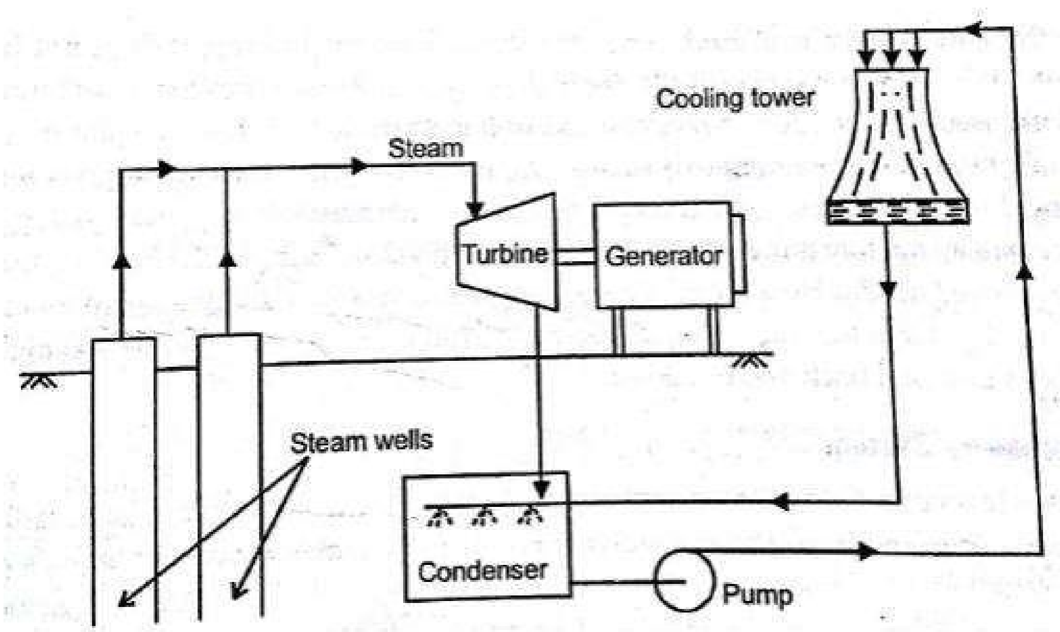


Fig. 7-8. Steam dominated geothermal energy system

b) Liquid dominated systems - Flash steam Open System
This is a major geothermal energy source, which is liquid dominated (hot water), and steam is obtained by the use of a flash separator. The schematic arrangement of a flash steam open geothermal system is illustrated in Fig.

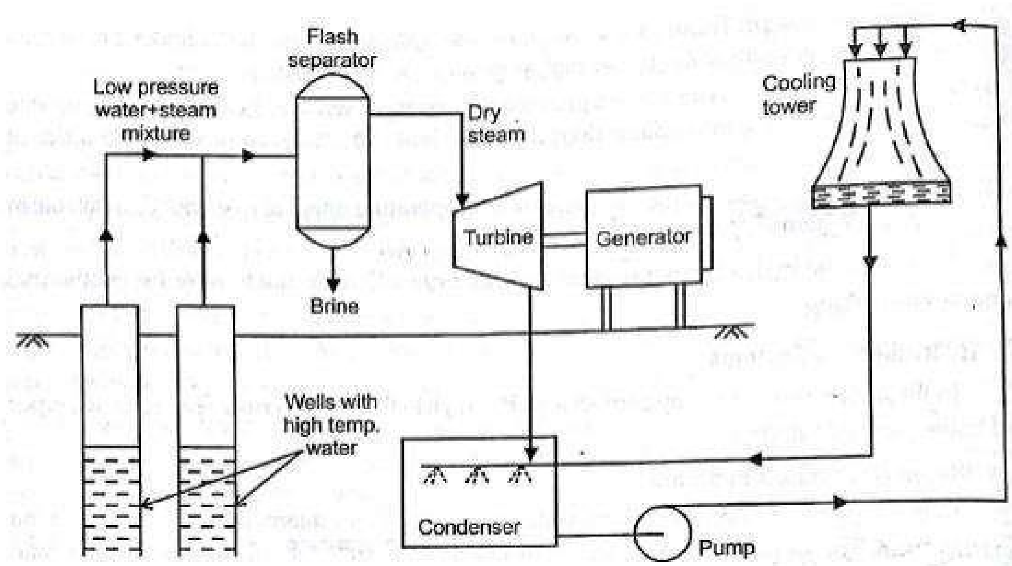


Fig. 7-9. Liquid dominated (flash steam) geothermal energy system

In this type of geothermal system, hot water at about 150°C under high pressure available under the earth's crust is utilised. Since the water is under pressure, it does not boil even above 100°C. When trapped by wells, the high pressure hot water rises to the well surface and looses its pressure. The drop in pressure causes it to partially flash to a two phase mixture of low quality (i.e., water dominated) steam. During this the hot water undergoes a constant enthalpy throttling process, and changes into a two- phase water-steam low quality mixture. This low quality mixture is then throttled in a flash separator, further reducing the pressure but with a improved quality. Here the mixture gets separated into dry saturated steam and saturated brine. The dry steam from the separator is used to run turbines and generate electricity, while the brine is pumped back into the ground.

2. **Geopressure System**

These sources are similar to hydrothermal systems and are available in large sedimentary basins, deep down the crust. These are reservoirs of high temperature water under high pressures (50 to 100 MPa). This water contains natural gas of high calorific value in dissolved state, which can be obtained with the release of pressure. Geopressured water is trapped in very deep underground aquifers. The depths are in the range of 2.5 to 10 km. This high pressure water exists in the temperature range of 150- 160°C and above 100 MPa. It has high salinity of about 5-10% (as good as brine). Geopressure systems are sources of both steam power and natural gas.

3. **Hot Dry Rocks**

Hot dry rocks are also termed petrothermal systems. These are very hot solid rocks available in the earth's crust at medium depths (2 to 5 km). The temperature of the dry rocks is of the order of 300°C, which is quite sufficient to produce steam. These dry rocks in real hot i condition, as there is no water contact. To exploit this hot energy source, cold water is pumped into the hot rocks, which becomes hot and get evaporated. The hot water or steam so produced is passed through a suitable heat exchanger, to produce steam and run a steam turbine, for power generation. The schematic of such a system is illustrated in Fig

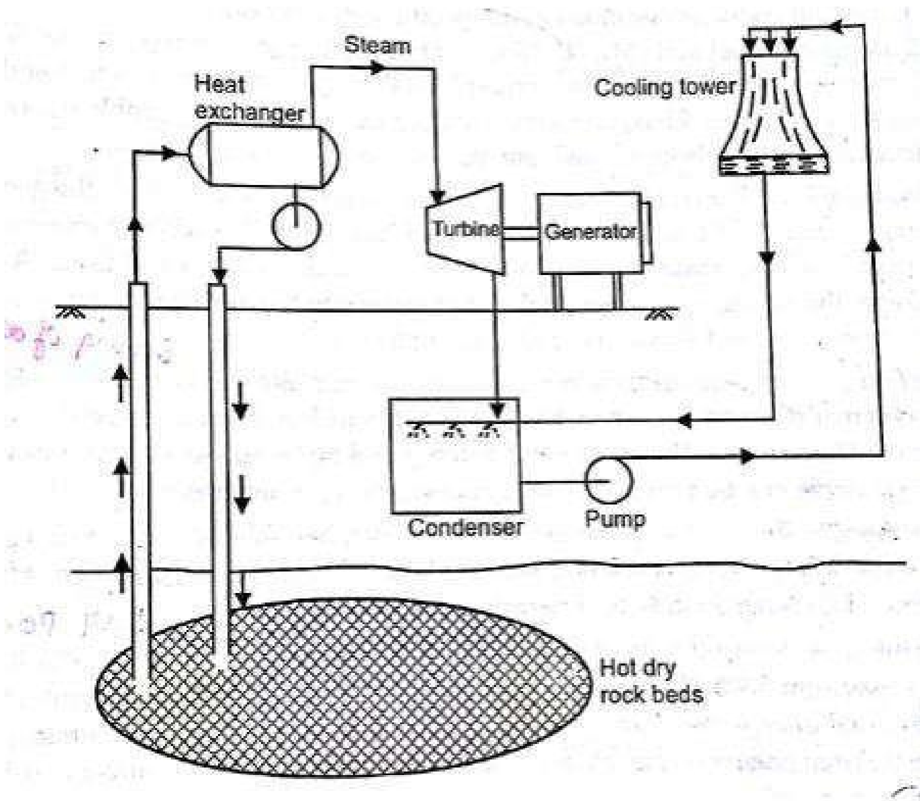


Fig. 7-10. Hot dry rock (HDR) geothermal energy system

4. **Magma Source**

   These are molten rocks with temperature much above 750°C, available in deep earth crust. Such beds are found generally in the active volcanic regions these have very large geothermal energy content, but it is difficult to extract energy because of very high temperatures. To generate the power the heat energy of the magma has to be tapped by drilling holes close to the magma chamber, where the temperature is around 18000C. The energy is then extracted by circulating water to produce steam and then run turbines

Problems in Geothermal Energy Conversion Systems

There are a number problems associated with the operation of geothermal systems. Some of the major problems are discussed here.

1) **Solid particles and non-condensable Gases:** The steam/water from hydrothermal reservoirs contain solid particles and non-condensable gases. The solid particles are removed

using centrifugal separators at the well exit and by strainers before the turbine entry. This leads to pressure and temperature loss and hence loss of the thermal efficiency of the complete system. The main non-condensable4ase9p-the geothermal sources are CO_2 (70 to 80%) and small amounts of methane, H_2 , N_2 , NH_3 and H_2S. These gases along with the fluid enter equipments and also escape to the atmosphere through condenser, ejectors and cooling towers. These gases in the equipments cause corrosion and scaling problems. The gases, particularly H_2S (a poisonous gas), are also harmful to the living beings:

2) Discharge of Used Water: Discharging large quantities of used water from the geothermal systems to rivers and seas will cause water pollution (both thermal and chemical). This may make the water toxic and becomes hazardous to the animals and users. A possible solution to this problem is to reinject the used water into the well so that land subsidence can be minimised and also avoid environmental pollution.

3) Noise Pollution: In geothermal systems noise pollution is also a major problem. Exhausts, blow down and centrifugal separators work always with high noise, which is hazardous to the working people. The noise can be minimised by using silencers and its effect on working people can be reduced by using noise protective devices.

4) Atmospheric Pollution: The harmful gases in the geothermal water after use will escape,(from the cooling tower, separator, etc.) and cause atmospheric pollution. Hydrogen, sulphide (H_2S} is highly toxic and harmful to the living beings. Air pollution is severe due to the emission aft heavy radioactive gases and hydrogen sulphide gas from the wells. Due to its poor steam condition, geothermal plant discharges more thermal energy into environment (3 times that of a conventional thermal plant) causing thermal pollution. The steam-water from well brings many corrosive substances which when mixed with atmospheric water, cause water pollution.

5) Subsidence: The removal of huge quantities of underground water causes land subsidence (collapse of ground layers, and fall in the ground level). Subsidence causes stressing of pipelines and damage to the structures/foundations. This problem can be greatly reduced by reinjection of the used water.

6) Seismic Activity: it is also possible that underground water exploitation is done. land subsidence. Even the reinjection of high temperature difference. earth quakes may take place, if continuous One cause could be the large underground used water may cause seismic activity due to high temperature difference.

7) Fog due to escaping steam: The entry of steam from the cooling towers, separators into the environment may lead to the formation of dense fog which many drift to the nearby busy living areas and cause problems. Also the temperature of the environment may increase leading to thermal pollution and cause discomfort in the surrounding areas due to increases in humidity.

8) Sand & other solid particles: The high pressure water from the geothermal system usually carries sand and other solid particles. These cause separation problem, erosion and scaling problems in the equipments. This-Causes a lot of maintenance problems for the plant and loss of efficiency

Tidal Power

Tide is a periodic rise and fall of the water level of the sea. Tides occur due to the attraction of sea water by the moon and the sun. These tides can be used to produce electrical power, and it is termed as Tidal Power. When the water is above the mean sea level it is termed flood tide or high tide, and when the level is below the mean sea level it is termed ebb tide or low tide.

Principle of Generation of Tides

As mentioned, tides are produced by the gravitational forces of the moon and the sun on sea water. The gravitational force of the moon is a major cause of the tides (about three-fourth of the tides) while that of the sun is minor (about one-fourth). Hence, moon contributes to a major portion of the tidal energy. In the tide formation, the sea water at the surface is pulled out from the earth (due to attraction from the moon), while the solid earth below the waters is pulled away from the water on the bottom side (due to attraction from the sun). This leads to the formation of high tides in the two opposite directions, and at the same time forming low tides at the intermediate points, perpendicular to the direction of gravitational pull. Due to the earth's rotation, the relative. positions of earth and moon change, and hence the position of the tides also change periodically. This causes the formation of two tidal cycles (2 high tides and 2 low tides) during a lunar day. Each lunar day is equal to 24 hrs and 50 minutes, which is the apparent time of revolution of the moon about the earth. Thus, the time between a high tide and a low tide is about 6 hrs. 12 minutes. A high tide will be experienced at that time when earth is directly under the moon. At the same time, a diametrically opposite point on the earth's surface will also undergo a high tide due to dynamic balancing. The rise and fall of the water level follows a sinusoidal Curve, as shown in Fig

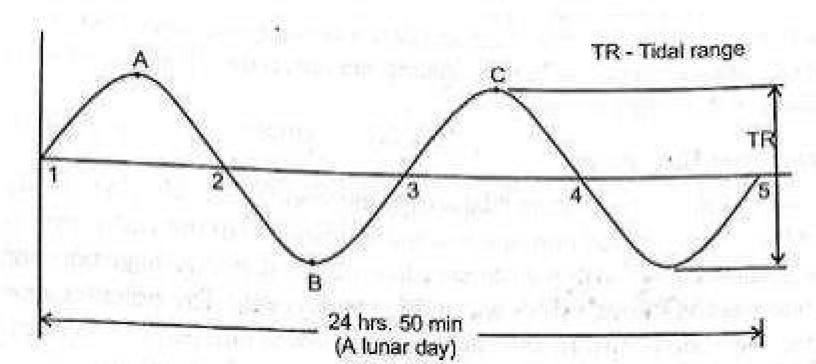


Fig. 7-1. High and low tide curve

In the figure, point A indicates the high tide and point B indicates the low tide. The average time for each tide to rise to its peak and fall back to the mean sea level (from point 1 to A and back to point 2) is about 6 hrs. 12.5 minutes. Similarly, for the tide to reach its lowest point is approximately takes the same time. From rise and fall of the tide from point 1 to A to 2 to B and to 3, completes one cycle of the tide, which takes about half a lunar day.

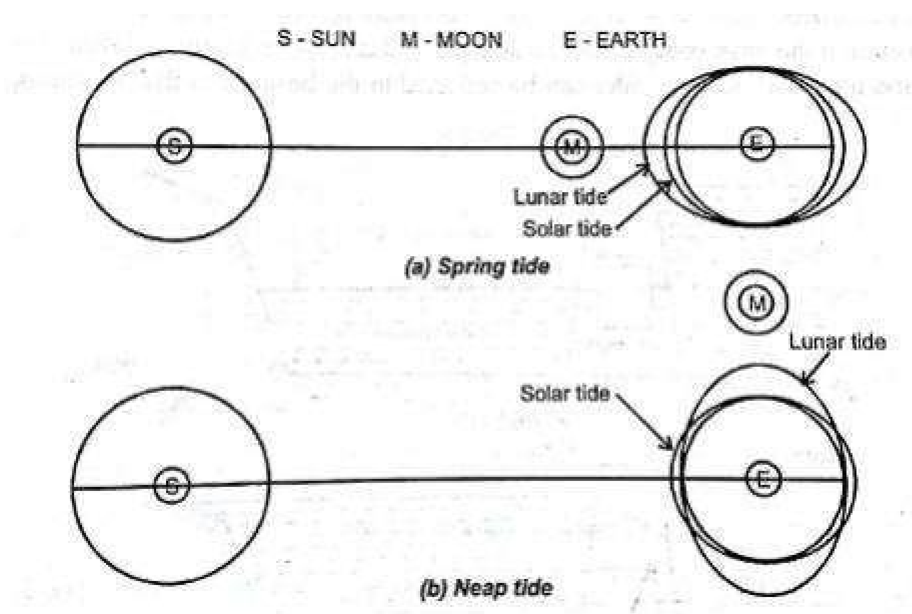


Fig. 7-2. Tides due to sun and moon positions

The rise and fall of the tide from its peak to its lowest point is termed the tidal range (TR in figure). During full moon and new moon days the sun, moon and the earth fall approximately in a straight line. This increases the gravitational forces of sun and moon on the earth, and thus increasing the tidal range. In these periods, the tidal range is very large with high tides and low tides on their extremes. These high tides are termed spring tides (Fig. 7-2a). During the first and third quarters of the moon, when the sun and moon are at right angles with respect to the earth the low tide occurs and this is termed neap tide (Fig.-7-2b). Hence, the tidal range varies from the new moon day to full moon day. The typical mean range is about one-third of the spring range.

Power from Tidal Waves

The basic principle of harnessing tidal energy involves the construction of a dam in such a way that.a basin is separated from the sea and a difference in the water level is obtained between the basin and sea. The constructed basin is filled during high tide and emptied during low tide passing through slices and turbine respectively. The potential energy of the water stored in the basin is used to drive the turbine which in turn generates electricity as it is coupled directly to an alternator. The main components of a tidal plant are:

a) The power house

b) The barrage (dam) to form the basin

c) Sluice-ways

d) Turbine-generator

The construction and working of a tidal power plant is shown in Fig. 7-3. The barrage (or small dam) is the basic component of a tidal plant. It is essential to form a barrier between the sea and the basin, so that water can be collected in the basin from the sea during high tides.

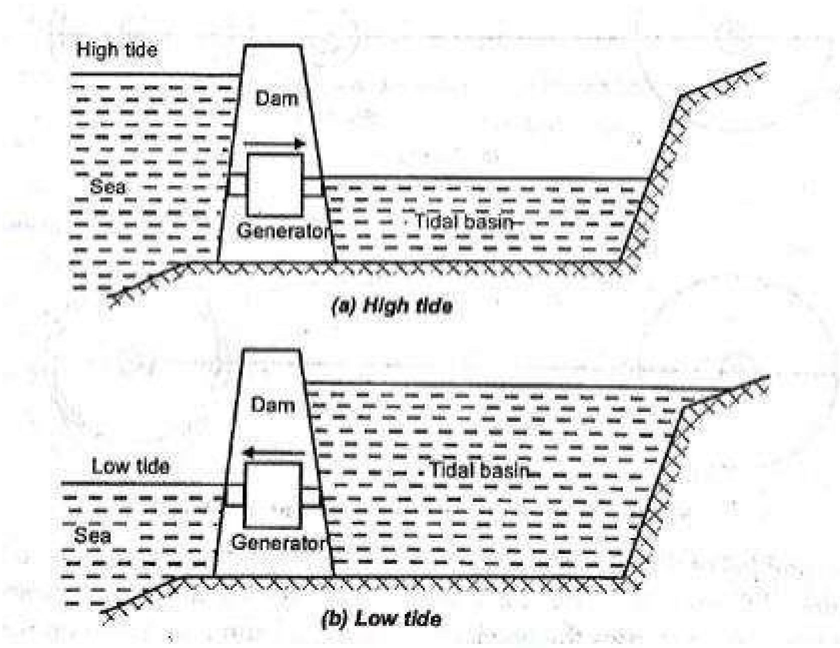


Fig. 7-3. Operation of tidal power plant

The sluice-ways are required either to fill the basin during the high tide or empty the basin during the low tide. These are in the form of gates and used as and when operational requirements arise. Power house is situated adjacent to the sluice-ways. It has the turbine-generator kept inside.

Classification of Tidal Plants

The different techniques for tidal energy harnessing available are:

1) Single basin - one way system

2) Single basin - two way system

3) Single basin - two way system with pumped storage

4) Double basin system

5) Double basin with pumped storage

1) Single Basin-One Way Cycle

In this a basin is allowed to fill in flood tide. There is a dam with sluice gates and power house at the neck of the basin as shown in Fig. 7-4. During ebb-tide the basin starts emptying through tubes, which are connected to turbines, thus running them. These turbines in turn run a generator to produce power.

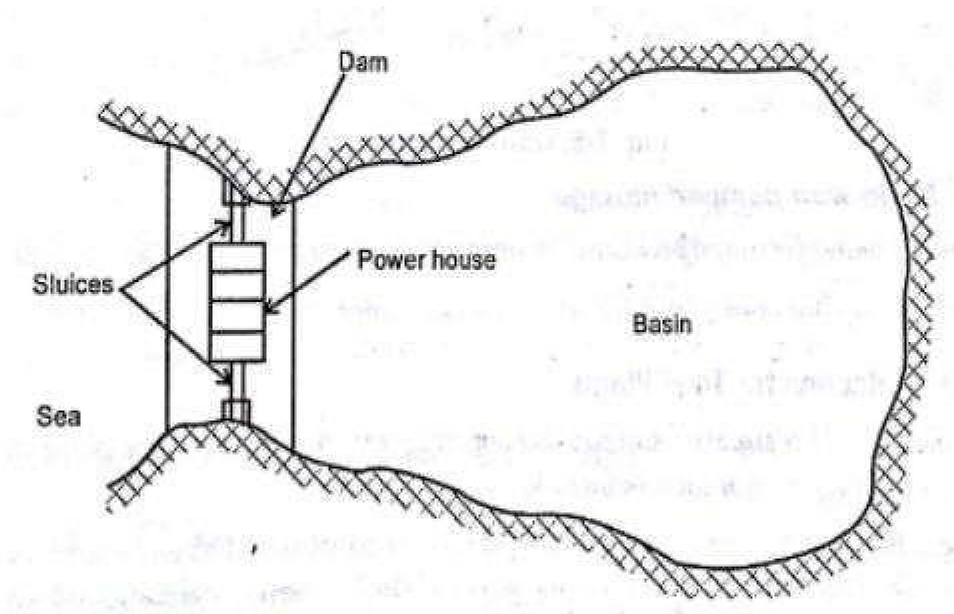


Fig. 7-4. Single basin plant

2) Single Basin-Two Way Cycle

This is similar to one way cycle type. But power is developed during both flood-tide and ebb-tide. During flood tide the sea water level increases and flows to the basin, while turbine is run and power are generated. The collected water flows back from the basin to the sea during ebb-tide, and again turbine is run and power is developed. The main difficulty in this system is that, the same prime mover (turbine) should be arranged and designed to run in both direction of flood and ebb-tides. In pumped type, pumps are used to pump the water driven by the same generator.

3) **Double Basin type**

In this type of system, a turbine-generator is set up between two basins as shown in Fig. 7-5. One basin is intermittently filled by the flood tide and other is intermittently drained by the ebb-tide. Therefore a small capacity but continuous power is made available with this system.

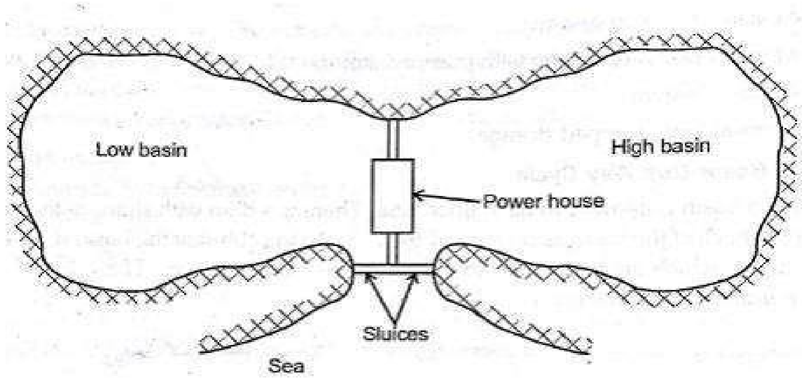


Fig. 7-5. Double basin plant

4) **Double basin-with pumped storage** In this the water from the low basin is pumped back to the high basin during peak-off periods, using the energy produced by the generator.

Site Selection for Tidal Plants

The selection of a suitable site for the construction of a tidal power plant depends on various factors. Some major factors include:

1. **Barrage**: Barrage is a dam of small height (20 m) constructed to withstand water heads, between the sea and the basin. The site selected shall be convenient and naturally suitable for the barrage construction, preferably with a narrow junction.

2. **Sea condition:** The site selected should have a flat sea bottom with strong soil characteristics, so that barrage can be constructed easily. If the sea bottom is sandy it requires piling, which makes the construction costly.

3. **Basin location:** The basin is the small reservoir which is separated by the barrage from the sea. The basin should be naturally formed, and should have sufficient capacity to hold the water due to high tide. Also, it should be at a convenient altitude with respect to the sea bottom.

4. **Plant capacity:** The tidal plant capacity is proportional to product of tidal range and the volume of water flowing from the sea to the basin, and later from the basin back to the sea. The site selected should be optimum to meet this power capacity requirement, so that power can be generated economically

Advantages and Disadvantages of Tidal Plants Advantages

1. Tidal power is available freely, and in abundance.

2. It is free from pollution and noise.

3. It is superior to hydro-power plants, as it is totally independent of rain, which always fluctuates year to year. Therefore, there is certainty of power supply as the tide cycle is very definite.

4. It has a unique capacity to meet the peak power demand effectively when it works in combination with thermal or hydroelectric system.

5. It can provide better recreational facilities to visitors and holiday makers, in addition to the possibility of fish farming in the tidal basins.

6. It is highly economical as the initial investment and maintenance costs are minimal.

Disadvantages

1. These power plants can be developed only if natural sites are available.

2. The sites are available on the bay, which will be always far away from the load centers, hence the power generated must be transported to long distances. This makes the cost of production expensive.

3. The supply of power is not continuous, as it depends upon the timing of tides.

4. The capital cost of the plant (Rs. 5000 per kW) is considerably large as compared to the conventional power plants, such as the hydroelectric plant.

5. Sedimentation and siltation of the basins are some of the problems with the tidal power plants

Unit - 5

A **stand-alone power system** (**SAPS** or **SPS**), also known as **remote area power supply** (**RAPS**), is an off-the-grid electricity system for locations that are not fitted with an electricity distribution system. Typical SAPS include one or more methods of electricity generation, energy storage, and regulation.

Electricity is typically generated by one or more of the following methods:

- Solar panel
- Wind turbine
- Geothermal source
- Micro combined heat and power
- Micro hydro
- Diesel or Bio-fuel generator

Storage is typically implemented as a battery bank, but other solutions exist including fuel cells. Power drawn directly from the battery will be direct current extra low voltage (DC ELV), and this is used especially for lighting as well as for DC appliances. An inverter is used to generate AC low voltage, which more typical appliances can be used with.

Wind Stand Alone Systems

Wind energy is one the renewable power supply options for remote areas. Its advantages include low environmental impact and occupy relatively small area of land in proportion to their electrical output. The output from wind generators increases significantly as the wind speed increases, and wind speed increases as height above the ground increases. In evaluating any available wind data the effect of the local topography/geography needs to be considered as it may cause uneven wind patterns that will affect the turbine's output (Ackermann, 2005). A wind turbine installed in an area with a good wind resource can produce energy cost-effectively.

This energy option however has limited use because modern energy converter systems are expensive to set up and if located near homes or workplaces noise of the rotor can be annoying. Another problem is that wind does not blow all the time and in some cases the speeds may not be enough for electricity generation. They are not suitable for mobile needs and maintenance costs are high. If wind- driven generators are linked to diesel generators the efficiency of the diesel plant can be reduced (Wichert, 1997).

Stand-Alone Photovoltaic Systems

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principal classifications are grid-connected or utility-interactive systems and stand-alone systems.

Wichert (1997) argues purports that stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads. These types of systems may be powered by a PV array only, or may use wind, an engine-generator or utility power as an auxiliary power source in what is called a PV-hybrid system. The simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load (Figure 2). Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours, making these designs suitable for common applications such as ventilation fans, water pumps, and small circulation pumps for solar thermal water heating systems. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well-performing direct-coupled system. For certain loads such as positive-displacement water pumps, a type of electronic DC-DC converter, called a maximum power point tracker (MPPT), is used between the array and load to help better utilize the available array maximum power output.

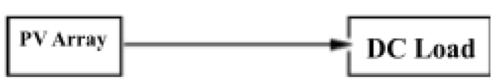


Figure 1. Direct-coupled PV system.

In many stand-alone PV systems, batteries are used for energy storage. Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed (during the night and periods of cloudy weather). Other reasons batteries are used in PV systems are to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and overdischarge (Wichert, 1997).Figure 2 shows a diagram of a typical stand-alone PV system powering DC and AC loads

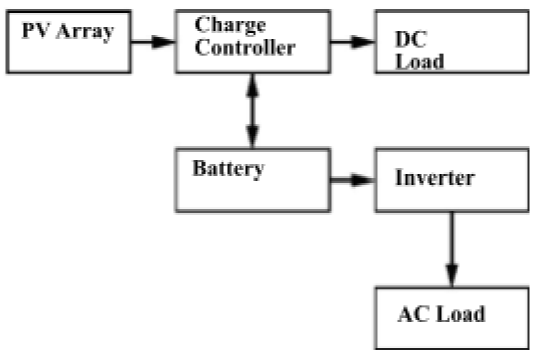


Fig. 2 Diagram of stand-alone PV system with battery storage powering DC and AC loads.

PV systems are like any other electrical power generating systems, though the equipment used is different from that used for conventional electromechanical generating systems. However, the principles of operation and interfacing with other electrical systems remain the same, and are guided by a well-established body of electrical codes and standards. Although a PV array produces power when exposed to sunlight, a number of other components are required to properly conduct, control, convert, distribute, and store the energy produced by the array. Depending on the functional and operational requirements of the system, the specific components required may include major components such as a DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical load (appliances)

The performance of PV modules and arrays are generally rated according to their maximum DC power output (Watts) under Standard Test Conditions (STC). Standard Test Conditions are defined by a module (cell) operating temperature of 25^{O} C (77^{O} F), and incident solar irradiance level of 1000 W/m and under Air Mass 1.5 spectral distribution. Since these conditions are not always typical of how PV modules and arrays operate in the field, actual performance is usually 85 to 90 percent of the STC rating. Photovoltaic modules are extremely safe and reliable products, with minimal failure rates and projected service lifetimes of 20 to 30 years. Most major manufacturers offer warranties of 20 or more years for maintaining a high percentage of initial rated power output. When selecting PV modules, one should look for the product listing, qualification testing and warranty information in the module manufacturer's specifications (Wichert, 1997).

Merits and demerits of PV Systems

Photovoltaic systems have a number of unique advantages over conventional power-generating technologies. PV systems can be designed for a variety of applications and operational requirements, and can be used for either centralized or distributed power generation. PV systems have no moving parts, are modular, easily expandable and even transportable in some cases. Energy independence and environmental compatibility are two attractive features of PV systems. The fuel (sunlight) is free, and no noise or pollution is created from operating PV systems. In general, PV systems that are well designed and properly installed require minimal maintenance and have long service lifetimes (Gabrovska et al, 2004).

Diesel Power System

Stand-alone diesel generator sets are relatively inexpensive to purchase but expensive to operate and maintain. Specific fuel consumption characteristics of a typical diesel engine show that a diesel generator must be operated above a certain minimum load level in order to maintain efficiency and to reduce the possibility of premature failures. This is shown in figure 4 which shows a typical curve for specific fuel consumption versus load ratio.

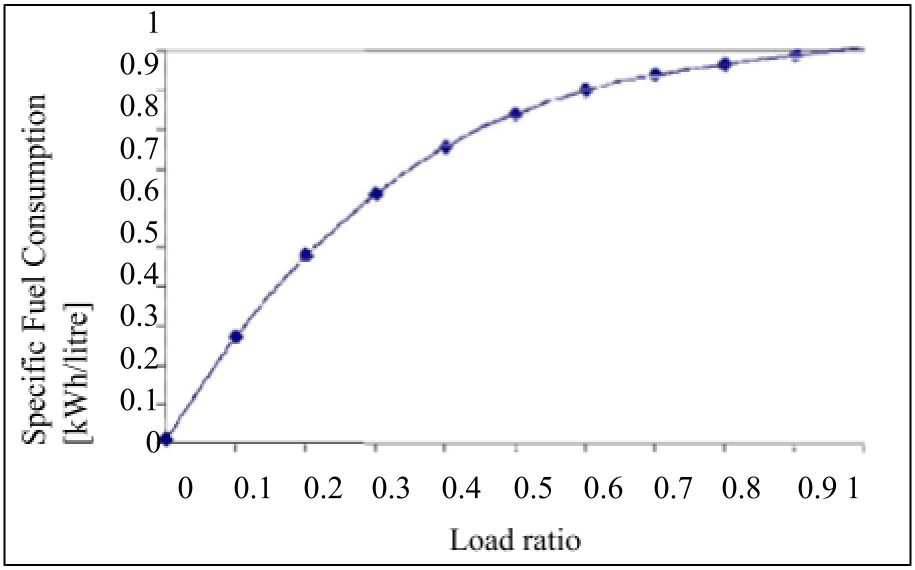


Figure 3 A typical curve for specific fuel consumption versus load ratio.

The typical specific fuel consumption versus load ratio curve generally shows that specific fuel consumption increases as the load ratio increases. The relationship between the two is such that low load ratios result in high fuel consumption.

The problem of selecting a diesel generator size for a newly emerging community, or one which has not had continuous power previously, is difficult while population fluctuations, seasonal demand, increase in number and use of electrical appliances are complex issues for designers to assess. A generator should never be operated at its maximum power output for more than 30 minutes. Rated power, or the power that a generator can produce for long periods of time, is a more reliable measure of generator power (Beyer et al, 2003).

The conventional approach for a stand-alone diesel is to select the diesel generator set according to the peak load. During periods of low loads, the diesel generators will be poorly loaded with the consequences of poor fuel efficiency, wet stacking, low combustion and carbon deposits (glazing) on the cylinder walls, causing premature engine wear. Common practice is to install “dump lo ads” which deliberately dissipate energy when useful demand is low, to protect the diesel engines.

The same authors argue that several approaches have been considered to maximise the economy of operating diesel generators. One system employs a number of diesel generators that need to operate parallel to achieve peak load supply, but can be shut down systematically as load reduces. This system will require automatic sequencing and synchronisation controls A two-diesel system-one small set and the other larger with manual change over switch- is used to meet the load requirements .The small set is operated during low-demand periods while the larger set is reserved for the high-demand periods. This scheme is a relatively low-cost one, but offers little protection to the larger generator with low demand and is not very convenient.

Although diesel generators have a low initial capital cost and there is support available on how to operate and maintain them, experience has shown that there are significant limitations associated with this method of generation. Getting a maintenance crew on time in such isolated area is a problem. Transportation of fuel is another problem. Diesel gensets have problems with short durability, which is due to the fact that they work very inefficiently when running just at fractions of their rated capacity. Frequent start-up and shut-down procedures also decrease their lifetime (Haupt and Haupt, 1998).

These diesel generators are very expensive to run and maintain and every litre of diesel releases about 3 kg of CO2 gases (Lenzen, 1999). The diesel generator remain in the system to equalize the battery and to act as a backup generator for extended periods of low renewable energy input or high load demand. Such systems are usually installed in locations where fuel supplies are expensive and unreliable, or where strong incentives for the use of renewable energy exist (Drouilet, 1997).

MICROGRID

A micro-grid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. If desired, a microgrid can connect and disconnect from the grid to enable it to operate in both grid connected or island mode.

Micro-grid Key Attributes (Defining Characteristics):

- Grouping of interconnected loads and distributed energy resources
- Can operate in island mode or grid connected if desired
- Can connect and disconnect from the grid if desired
- Acts as a single controllable entity to the grid

Why are micro-grids important?

1. *Enables Grid Modernization*

- Key component of grid modernization
- Enables integration of multiple Smart Grid technologies

2. *Enhance the integration of Distributed and Renewable Energy Sources*

- Facilities integration of combined heat and power (CHP)
- Promotes energy efficiency and reduces losses by locating generation near demand
- Potential to reduce large capital investments by meeting increased consumption with locally generated power. (Local generation may lower investment in the macro-grid)
- Encourages third party investment in the local grid and power supply
- Potential to reduce peak load

3. *Meets End User Needs*

- Ensure energy supply for critical loads
- Power quality and reliability controlled locally
- Promotes demand- side management and load leveling
- Promotes community energy independence and allows for community involvement in electricity supply
- Designed to meet local needs and increase customer (end - use) participation

4.Supports the Macro-grid

- Enables a more flexible macro-grid by handling sensitive loads and the variability of renewable locally
- Enhances the integration of distributed and renewable energy resources including CHP
- Potential to supply ancillary services to the bulk power system
- Potential to lower overall carbon footprint by maximizing clean local generation
- Potential to resolve voltage regulation or overload issues

How does a micro-grid work?

The grid connects homes, businesses and other buildings to central power sources, which allow us to use appliances, heating/cooling systems and electronics. But this interconnectedness means that when part of the grid needs to be repaired, everyone is affected.

This is where a micro-grid can help. A micro-grid generally operates while connected to the grid, but importantly, it can break off and operate on its own using local energy generation in times of crisis like storms or power outages, or for other reasons.

A micro-grid can be powered by distributed generators, batteries, and/or renewable resources like solar panels. Depending on how it's fueled and how its requirements are managed, a microgrid might run indefinitely.

How does a micro-grid connect to the grid?

A micro-grid connects to the grid at a point of common coupling that maintains voltage at the same level as the main grid unless there is some sort of problem on the grid or other reason to disconnect. A switch can separate the micro-grid from the main grid automatically or manually, and it then functions as an island.

Why would a community choose to connect to micro-grids?

A micro-grid not only provides backup for the grid in case of emergencies, but can also be used to cut costs, or connect to a local resource that is too small or unreliable for traditional grid use. A micro-grid allows communities to be more energy independent and, in some cases, more environmentally friendly.

How much can a micro-grid power?

A micro-grid comes in a variety of designs and sizes. A micro-grid can power a single facility like the Santa Rita Jail micro-grid in Dublin, California. Or a micro-grid can power a larger area. For example, in Fort Collins, Colorado, a micro-grid is part of a larger goal to create an entire district that produces the same amount of energy it consumes.

Micro-grid Concept

Micro-grid has two critical components, the static switch and the micro-source. The static switch has the ability to autonomously island the micro-grid from disturbances such as faults, IEEE 1547 events or power quality events. After islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. This synchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid insuring a transient free operation without having to match frequency and phase angles at the connection point. Each microsource can seamlessly balance the power on the islanded Microgrid using a power vs. frequency droop controller. This frequency droop also insures that the Microgrid frequency is different from the grid to facilitate reconnection to the utility. Basic microgrid architecture is shown in Figure 1. This consists of a group of radial feeders, which could be part of a distribution system or a building's electrical system. There is a single point of connection to the utility called point of common coupling. Some feeders, (Feeders A-C) have sensitive loads, which require local generation. The non-critical load feeders do not have any local generation. Feeders A-C can island from the grid using the static switch that can separate in less than a cycle. In this example there are four micro-sources at nodes 8, 11, 16 and 22, which control the operation using only local voltages and currents measurements.

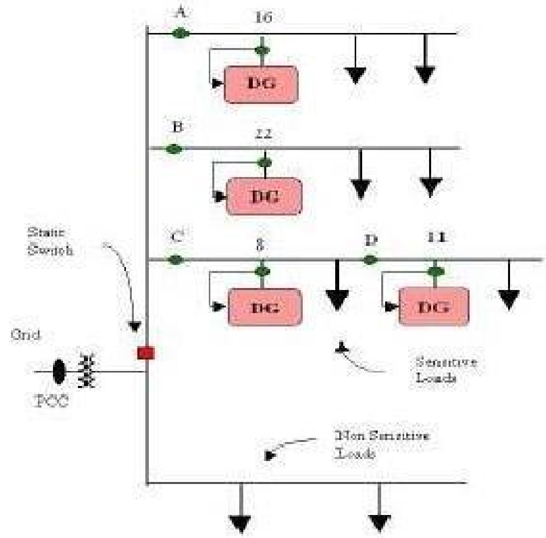


Figure 1.1 Microgrid Architecture Diagram

When there is a problem with the utility supply the static switch will open, isolating the sensitive loads from the power grid. Non sensitive loads ride through the event. It is assumed that there is sufficient generation to meet the loads' demand. When the microgrid is grid-connected power from the local generation can be directed to the non-sensitive loads. To achieve this we promote autonomous control in a peer-to-peer and plug-and-play operation model for each component of the microgrid. The peer-to- peer concept insures that there are no components, such as a master controller or central storage unit that is critical for operation of the microgrid. This implies that the microgrid can continue operating with loss of any component or generator. With one additional source (N+1) we can insure complete functionality with the loss of any source. Plug-and-play implies that a unit can be placed at any point on the electrical system without re-engineering the controls. The plug-and-play model facilitates placing generators near the heat loads thereby allowing more effective use of waste heat without complex heat distribution systems such as steam and chilled water pipes.

Microgrid Components

- Distributed Generation
- Loads
- Immediate storage
- Controller
- Point of Common Coupling

Distributed Generation

Distributed energy, also **district** *or* **decentralized energy** is generated or stored by a variety of small, grid-connected devices referred to as **distributed energy resources** (**DER**) or distributed energy resource systems.

Conventional power stations, such as coal-fired, gas and nuclear powered plants, as well as hydroelectric dams and large-scale solar power stations, are centralized and often require electricity to be transmitted over long distances. By contrast, DER systems are decentralized, modular and more flexible technologies, that are located close to the load they serve, albeit having capacities of only 10 megawatts (MW) or less.

DER systems typically use renewable energy sources, including, but not limited to, small hydro, biomass, biogas, solar power, wind power, geothermal power and increasingly play an important role for the electric power distribution system. A grid-connected device for electricity storage can also be classified as a DER system, and is often called a **distributed energy storage system** (**DESS**). By means of an interface, DER systems can be managed and coordinated within a smart grid. Distributed generation and storage enables collection of energy from many sources and may lower environmental impacts and improve security of supply.

HYBRID POWER SYSTEMS

As convention fossil fuel energy sources diminish and the world's environmental concern about acid deposition and global warming increases, renewable energy sources (solar, wind, tidal, biomass and geothermal etc) are attracting more attention as alternative energy sources. These are all pollution free and one can say eco friendly. These are available at free of cost. In India, there is severe power shortage and associated power quality problems, the quality of the grid supply in some places is characterized by large voltage and frequency fluctuations, scheduled and un scheduled power cuts and load restrictions. Load shedding in many cities in India due to power shortage and faults is a major problem for which there is no immediate remedy in the near future since the gap between the power demand and supply is increasing every year. This led to rapid usage of stand-by petrol or diesel generator sets and conventional battery inverter sets in both urban and rural areas. Shopkeepers, house owners and offices commonly use 1-5 kW fuel generators in India when utility exercises load shedding.

In India wind and solar energy sources are available all over the year at free of cost whereas tidal and wave are costal area. Geothermal is available at specific location. To meet the demand and for the sake of continuity of power supply, storing of energy is necessary.

The term hybrid power system is used to describe any power system combine two or more energy conversion devices, or two or more fuels for the same device, that when integrated, overcome limitations inherent in either.

Usually one of the energy sources is a conventional one (which necessarily does not depend on renewable energy resource) powered by a diesel engine, while the other(s) would be renewable viz. solar photovoltaic, wind or hydro.

The design and structure of a hybrid energy system obviously take into account the types of renewable energy sources available locally, and the consumption the system supports. For example, the hybrid energy system presented here is a small-scale system and the consumption of power takes place during nights, so the wind energy component will make a more significant contribution in the hybrid system than solar energy. Although the energy produced by wind during night can be used directly without storage, a battery is needed to store solar and wind energy produced during the day.

In addition to the technical considerations, cost benefit is a factor that has to be incorporated into the process of optimizing a hybrid energy system. In general, the use of wind energy is cheaper than that of solar energy. In areas where there is a limited wind source, a wind system has to be over-dimensioned in order to produce the required power, and this results in higher plant costs.

It has been demonstrated that hybrid energy systems (renewable coupled with conventional energy source) can significantly reduce the total life cycle cost of a standalone power supplies in many off-grid situations, while at the same time providing a reliable supply of electricity using a combination of energy sources. Numerous hybrid systems have been installed across the world, and expanding renewable energy industry has now developed reliable and cost competitive systems using a variety of technologies. Research in the development of hybrid systems focused on the performance analysis of demonstration systems and development of efficient power converters, such as bi-directional inverters, battery management units (storage facilities), and optimization of different sources of energy Sources, etc.

Hybrid power systems combine two or more energy conversion devices, or two or more fuels for the same device, that when integrated, overcome limitations inherent in either.

Hybrid systems can address limitations in terms of fuel flexibility, efficiency, reliability, emissions and / or economics.

Value Propositions

1. High Efficiency
2. High Reliability

3. Low Emissions

4. Acceptable Cost

Higher Efficiency

Incorporating heat, power, and highly-efficient devices (fuel cells, advanced materials, cooling systems, etc.) can increase overall efficiency and conserve energy for a hybrid system when compared with individual technologies.

EX-Combining heat and power systems, such as those at this University of Maryland test bed, can greatly improve overall energy efficiency.

High Reliability

Achieving higher reliability can be accomplished with redundant technologies and/or energy storage. Some hybrid systems typically include both, which can simultaneously improve the quality and availability of power.

EX- The PV/Propane/Battery hybrid at Dangling Rope Marina significantly increased the reliability of the power system.

Low Emissions

Hybrid systems can be designed to maximize the use of renewables, resulting in a system with lower emissions than traditional fossil-fueled technologies.

EX- The SEGS solar thermal power plants in Southern California produce far fewer emissions than traditional electricity generation technologies.

Acceptable Cost

Hybrid systems can be designed to achieve desired attributes at the lowest acceptable cost, which is the key to market acceptance.

EX- By cutting diesel fuel consumption, the King Cove, Alaska run-of-the- river hydroelectric plant and battery system reduced electricity costs for the town's residents.

2.3 Hybrid Power System Configurations

According to Wichert (1997), hybrid energy systems with or without renewables, are classified according to their configuration as series, switched hybrid, or parallel hybrid.

2.3.1 Series hybrid system

In this system either the renewable energy source or the diesel generator is used to maintain charge in a large battery bank. During periods of low electricity demand the diesel generator is switched off and the load can be supplied from PV together with stored energy. Power from the battery bank is converted to AC at mains voltage and frequency by a converter and is then fed to the load. Battery charging can be controlled by controlling the excitation of the alternator (Wichert, 1997). The charge controller prevents overcharging of the battery bank from PV generator when the PV power exceeds the load demand and the batteries are fully charged. The system can be operated in manual or automatic mode, with the addition of appropriate battery voltage sensing and start/stop control of the engine-driven generator.

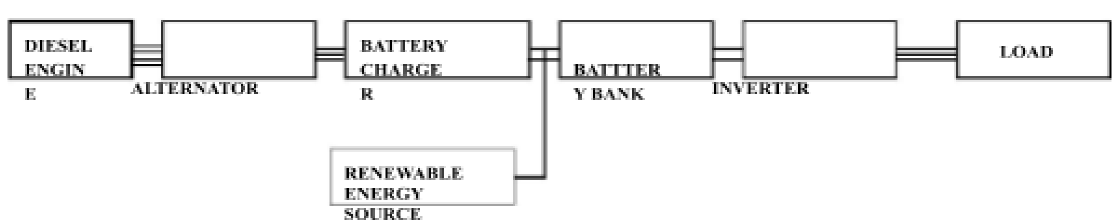


Figure 6 Series hybrid system

Advantages of this configuration include that the engine-driven generator can be sized to be optimally loaded while supplying the load and charging the battery bank, until the state of charge (SOC) of 70-80% is reached. No switching of AC power between the different energy sources is required thus simplifying the electrical output interface. Also the power supplied to the load is not interrupted when the diesel generator is started and the inverter can generate a sine-wave, modified square-waves, or square-wave, depending on the application.

Although the design principles of the series hybrid systems are relatively simple to implement. Islam (1999) highlights its disadvantages to include: low overall efficiency due to the series configuration of system elements; substantially larger battery capacity than the maximum peak load demand resulting in the system being more expensive component to the system; and with renewable inputs, there is limited control of diesel alternator because the system is based on level of charge in the battery rather than the site load.

A series hybrid system is characterized by low overall system efficiency since the diesel cannot supply power directly to the load; large inverter and due to the cycling profile large battery bank is required to limit the depth of discharge; and limited optimisation of diesel alternator and renewable energy sources(SOPAC Miscellaneous Report 406, 2005). The battery bank is cycled frequently, shortening its lifetime. If the inverter fails there is complete loss of power to the load, unless the load can be supplied directly from the diesel generator for emergency purposes.

2.3.2 Switched hybrid system

This system allows with either the engine-driven generator or the inverter as the AC source but no parallel operation of the main generation source is possible (Islam, 1999). Both the diesel generator and the PV array can charge the battery bank. The diesel alternator meets the load during the day and evening peak while the battery

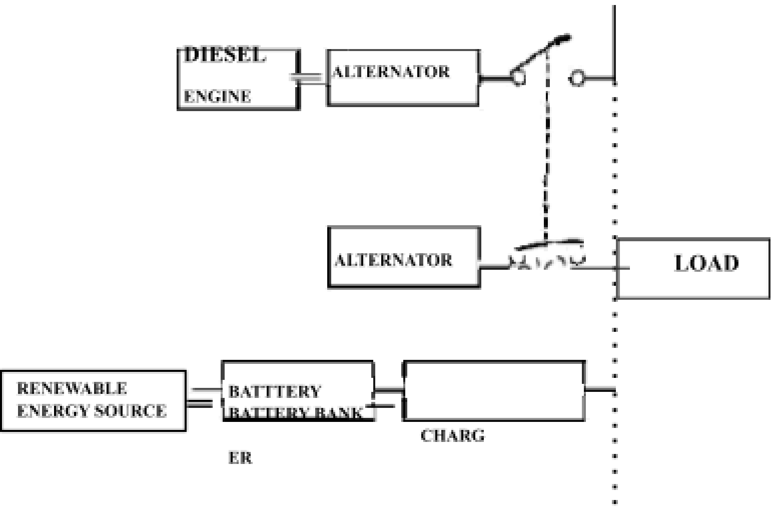


Figure Switched configuration

The main advantages of the system are quiet operation at night and partial improvements in diesel consumption. A switched hybrid system is also characterized by the fact that the diesel generator can supply the load directly, therefore improving the system efficiency and reducing the fuel consumption (SOPAC Miscellaneous Report 406, 2005). As for the series system, the diesel generator is switched off during periods of low electricity demand and the inverter can generate a sine-wave, modified square-wave, or square-wave, depending on the application. Switched hybrid energy systems can be in manual mode, although the increased complexity of the system makes it highly desirable to include an automatic controller, which can be implemented with the addition of appropriate battery voltage sensing start/stop control of the engine-driven.

The diesel system and inverter are typically designed to meet the peak loads, which reduces their efficiency at part load operation and there is no optimisation control on the diesel as the source switching solution is based on a simple time clock. Power to the load is interrupted momentarily when the AC power sources are transferred

2.3.3 Parallel hybrid System (Source/ Parallel Inverter/ Storage)

The parallel configuration shown in figure – allows all energy sources to supply the load separately at low or medium demand, as well as supplying quick load from combined sources by synchronizing the inverter with the alternator output wave form the bi-directional inverter can charge the battery bank when access energy is available from the engine driven generator, as well as act as DC-AC converter In this case the renewables and the diesel generator supply part of the load demand directly. The diesel generator and the inverter run in parallel.

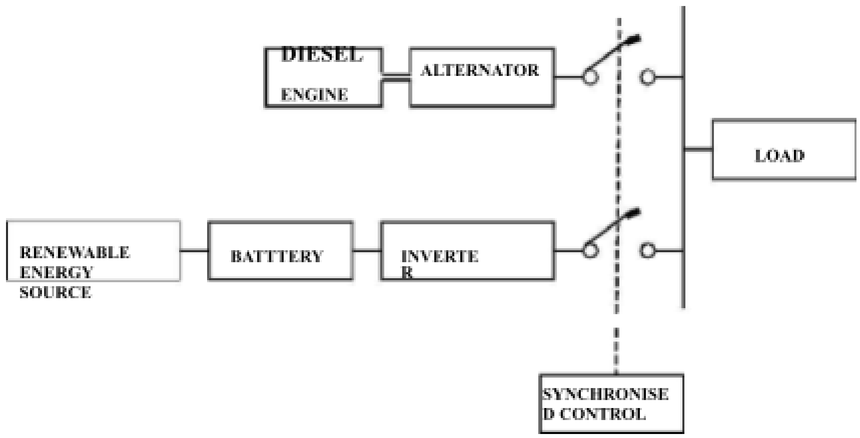


Figure :Parallel configuration

Advantages of this configuration over other system configurations are that the system load can be met in the most optimal way, diesel efficiency can be maximized, diesel generator maintenance can be minimized and there is a reduction in the capacities of diesel, battery and renewable sources while load peaks are being met. However, automatic control is essential for the reliable operation of the system and the system operation is less transparent to the untrained user of the system. Also the inverter has to be a true sign wave inverter with the ability to synchronize with a secondary AC source.

Diesel Energy:

In hybrid system diesel energy is only work as a backup source. When the demand on its peak, so that the available sources are insufficient for that then the diesel backup is required.

Hybrid system Economics

Life Cycle Costing

Engineering economy is the application of economic factors and criteria to evaluate alternatives, considering the time value of money. The engineering economy study involves computing a specific economic measure of worth for estimated cash flows over a specific period of time.

The terms interest, interest period and interest rate are useful in calculating equivalent sums of money for an interest period. Interest is the manifestation of the time value of money. It is the difference between an ending amount of money and the beginning amount over an interest period. For more than one interest period, the terms simple interest and compound interest become important.

1.1. Simple Interest:

Simple interest is calculated using the principal only, ignoring any interest accrued in preceding interest periods. The total simple interest over several periods is computed as:

Simple Interest = (Principal) x (Number of Periods) x (Interest Rate)

Here the interest rate is expressed in decimal form. The total sum accrued at the end of n interest periods is given by:

$$S = P\left(1 + n \cdot i\right) \qquad (1)$$

S = Sum accrued at the end of interest periods (also called Future
Worth) P = Principal (also called Present Worth)

n = Number of interest periods (normally one year is taken as one interest
period) i = Interest rate (normally annual interest rate)

1.2. Compound Interest:

For compound interest, the interest accrued for each interest period is calculated on the principal plus the total amount of interest accumulated in all previous periods. Compound interest reflects the effect of the time value of money on the interest also. The interest for one period is calculated as:

Compound Interest = (Principal + All accrued Interest) x (Interest Rate)

The total sum accrued after a number of interest periods can be calculated from the following expression:

$$S_n = P(1 + i)^n \text{ ....}$$

(2) S_n = Sum accrued at the end of n interest periods

P = Principal

i = Interest rate expressed in decimal form (annual interest rate) n = Number of interest periods (number of years)

We can see from the above two expressions that the sum accrued at the end of first year would be same for both simple interest and compound interest calculations. However for interest periods greater than one year, the sum accrued for compound interest would be larger.

What happens if the interest is compounded more than once in a year?

We need to modify equation (2) and is given by:

$$S_n = P\left(1 + \frac{i}{m}\right)^{nm} \text{ .... (3)}$$

m = Number of periods the interest is compounded in one year i = Annual interest rate in decimal form

n = Number of years

We can extend equation (3) to calculate the sum accrued if the interest is compounded continuously. Here m tends to ∞. Taking the limits such that m goes to infinity, we get the following expression:

$$S = P \cdot e^{in} \tag{4}$$

For all practical purposes, equation (2) is used for interest calculations and repeated here for convenience:

$$S_n = P(1+i)^n$$

Here,

Sn = Future Worth of money

P = Present Worth of the money

$(1+i)^n$ = Future Worth Factor.

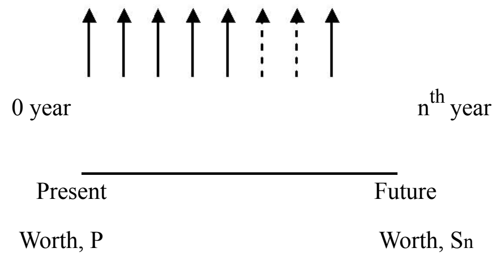
Given the present worth, annual interest rate and number of years, we can calculate the future worth. There may be situations when the future worth of money is given and we need to find the present worth of the money. The above equation can be re-arranged to calculate the present worth, given by:

$$P = \frac{S_n}{(1+i)^n} \tag{5}$$

Here,

$\frac{1}{(1+i)^n}$ = Present Worth Factor.

To carry out calculations, it is convenient to draw what is called as cash flow diagram.
The following figure gives one such cash flow diagram:



The cash flow diagram helps in analyzing the problem better.

Equations (2) and (5) are used in problems concerning single payment. In today's world we deal with problems that involve annual/monthly equal payments such as home mortgage payments, vehicle loans or loans for consumer electronic goods. The following relationships hold good for problems involving such uniform series:

$$P = A\frac{(1+i)^n - 1}{i(1+i)^n} \qquad (6)$$

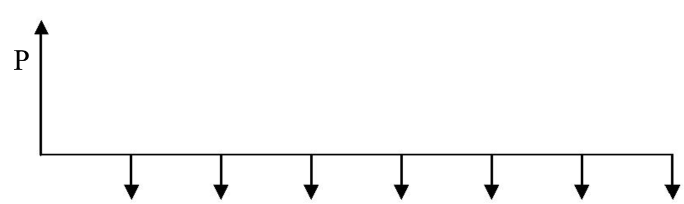
P = Present worth

A = Uniform Annual amount (installments)

$$\frac{\left((1+i)^n - 1\right)}{i} \qquad (7)$$

S_n = Future worth

From these equations, we can calculate present worth or future worth given uniform annual amounts. We can also calculate the uniform annual amounts given either present worth or the future worth. A typical example would be person borrowing money from a financial institute for buying a vehicle. Knowing the interest rate and number of installments, the person can calculate the uniform equal amounts he or she has to pay depending on the amount borrowed. A typical cash flow diagram would look as follows:



A

The up-arrow indicates the amount 'coming in' such as borrowing and the down arrow indicates the amount 'going out' such re-payments towards the borrowing.

1.3. Inflation:

In all the above equations, we had assumed that there is no inflation. Inflation is an increase in the amount of money necessary to obtain the same amount of product before the inflated price was present. Inflation occurs due to downward change in the value of the currency. If 'C' is the cash in hand today for buying a product, f is the inflation rate, then the amount we need to pay for the same product after n years would be $C(1 + f)^n$,

assuming uniform inflation over the years. The present worth of such money with interest component added is given by:

$$P = C \frac{(1+f)^n}{(1+i)^n} \quad \text{.............................(8)}$$

Pf = Present worth with inflation taken into account.

If i = f, no change in worth, year after year.

If i > f, save and do not buy the product now.

If i < f, buy the product now and do not save.

An important relationship between the present worth and the uniform annual amount taking inflation into account is given by the following equation:

$$P = A \cdot \frac{1+f}{i-f} \cdot \left[1 - \left(\frac{1+f}{1+i}\right)^{n}\right] \quad \text{………………………………………………………….} \quad (9)$$

for i ≠ f . If i = f, then we get the following relationship:

$$P = A \cdot n \qquad (10)$$

1.4. Life Cycle Cost:

Life cycle costing or LCC is an important factor for comparing the alternatives and deciding on a particular process for completing a project. The different components taken into account for calculating LCC are:

LCC = Capital + Replacement cost + Maintenance cost + Energy cost – Salvage

Here, Capital is the present worth. Replacement cost that may occur at a later years need to converted to present worth. Maintenance cost is annual maintenance cost and needs to be converted to present worth and so is the energy cost. Salvage is the money that is obtained while disposing the machinery at the end of life cycle period. Even this amount has to be converted to present worth for calculating LCC. Once we have the LCC value, we can easily find the Annual Life Cycle Costing using the following equation:

$$ALCC = \frac{LCC}{\qquad} \qquad (11)$$

$$\frac{1+f)}{i-f} \quad \square 1 \quad - \quad \frac{1 \quad +f}{1+i}^{\,n}$$

These equations would be clearer once we do some problems.

1.5. Example:

A community has 500 people. The source of water to the community is from the bore-wells and the supply of water from the bore-wells is by hand-pumps. Six hand-pumps are installed to meet the water requirement of the community. Per-capita water consumption of the community is 40 liters/day. Bore-well depth is 20 meters. The cost of each hand-pump is Rs.5,000.00. Cost of digging of each bore -well is at the rate of Rs.250.00 per meter. Life of the hand-pump is 10 years. Annual maintenance cost per pump is Rs.1250.00. If the rate of interest is 10%, what is the unit water cost for the life cycle period of 20 years?

Solution:

Step 1: Calculate capital cost (K):

For digging 6 bore-wells = (Rs.250.00 x 20) x 6 = Rs.30,000.00

Cost of 6 hand-pumps = Rs.5,000.00 x 6 ………………………. = Rs.30,000.00

Total capital cost ……………………………………………… = Rs.60,000.00

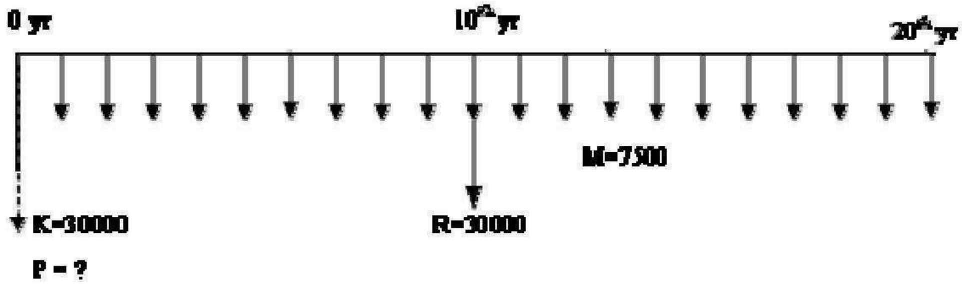
Step 2: Calculate replacement cost (R):

Cost for replacing 6 hand-pumps after 10 years ……………. = Rs.30,000.00

Step 3: Calculate annual maintenance cost (M):

Annual maintenance cost for 6 hand-pumps = Rs.1250.00 x 6 = Rs.7,500.00

Now let us draw the cash-flow diagram for the above data:



From figure, K is the capital at 0^{th} year. Let us call it **P1 = Rs.30000.00**

R is the replacement cost for hand-pumps occurring in 10^{th} year. We need to find the Present worth of this replacement cost. Let P2 be the present worth. Hence, the value of

$$\mathbf{P2} = \frac{R}{(1+i)^n} = \frac{30000}{(1+0.1)^{10}} = \mathbf{Rs.11566.30}$$

M is the annual maintenance cost for 6 hand- pumps occurring at the end of each year. The present worth of the uniform series needs to be found. Let P3 be the present worth.

Hence, the value of **P3** = $M\left[\frac{1 - \frac{1}{(1+i)^n}}{i}\right] = 7500\left[\frac{1 - \frac{1}{(1+0.1)^{20}}}{0.1}\right]$ = **Rs.63851.73**.

Step 4: Find the total present worth or LCC

Now the total present worth showed by dotted line in the cash flow diagram is the sum of all the present worth. That is: P = P1 + P2 + P3.

Hence, Life Cycle Cost or **LCC** = Rs.60000.00 + Rs.11566.30 + Rs.63851.73 =

Rs.135418.03.

From LCC value, we can calculate Annual Life Cycle Cost or ALCC by using the following expression:

$$ALCC = \frac{LCC}{\frac{1}{i}\left[1 - \left(\frac{1}{1+i}\right)^{n}\right]} = \frac{135418.03}{\frac{1}{0.1}\left[1 - \left(\frac{1}{1+0.1}\right)^{20}\right]} = \textbf{Rs.15906.15}$$

Step 6: Find unit water cost.

Annual water requirement = 500 people x 40 liters/day x 365 days = 7300000 liters.

Cost of water = $\frac{ALCC}{Annual\ Water\ Requirement} = \frac{15906.15}{7300000}$ = **Rs.0.00218/liter**.

1.6. Example:

A PV array of 500 watts has been installed to pump water from a bore-well of 2 meters deep using a submergible motor and pump system to an over-head tank. The length of pipe required to pump the water is 30 meters. Following are the costs involved for the sub-systems and their life spans:

PV Array : $8/peak watt; Life span – 15 years
Motor and pump: $2/watt; Life span – 7.5 years
Pipe cost: $8/meter; Life span – 5 years

Cost of digging the bore-well:

$20/meter Maintenance cost: $80/year

Miscellaneous cost: $3.5/watt

years and also water cost per year (ALCC).

Solution:

Step 1: Calculate the Capital cost (K)

Cost of PV array = $8/watt x 500 watts = $4000

Cost of motor and pump = $2/watt x 500 watts =
$1000 Cost of pipe = $8/meter x 30 meters = $240

Cost of digging the bore-well = $20/meter x 2 meters = $40
Miscellaneous cost = $3.5/watt x 500 watts = $1750

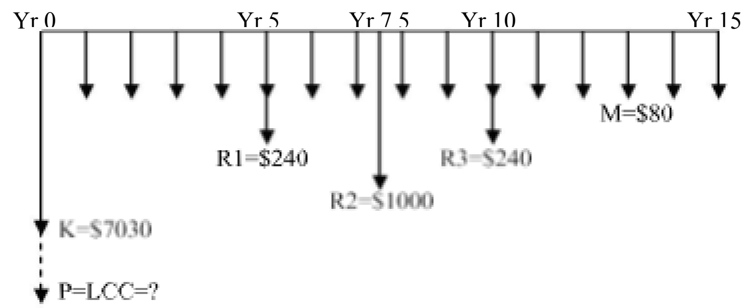
Total capital cost = $4000 + $1000 + $240 + $40 + $1750 =
$7030 *Step 2*: Calculate Replacement cost (R)

Replacement cost of motor and pump after 7.5 years = $1000

Replacement cost of pipe at the end of 5^{th} year and at the end of 10^{th} year = $240
each *Step 3*: Calculate maintenance cost (M)

The annual maintenance cost is given as $80.

Let us draw the cash-flow diagram for the above data.



From the figure, K is the capital cost at year 0. Let us call it **P1 = $7030**.

R1 is the replacement cost of pipe in year 5. Let us call the present worth of R1 as P2.

This can be calculated as follows: $P2 = \frac{R1}{(1+i)^n} = \frac{240}{(1+0.1)^5} =$ **$149.02**

R2 is the replacement cost of motor and pump in year 7.5. Let us call the present worth of R2 as P3. Hence, $\mathbf{P3} = \frac{R2}{(1+i)^n} = \frac{1000}{(1+0.1)^{7.5}} =$ **$489.28**

R3 is the replacement cost of pipe in year 10. Let us call the present worth of R3 as P4.

Hence, $\mathbf{P4} = \frac{R3}{(1+i)^n} = \frac{240}{(1+0.1)^{10}} =$ **$92.53**

M is the annual maintenance cost starting at the end of year 1 till the end of year 15. Let us call the present worth of this uniform series is **P5**. Hence $P5 = M \cdot \frac{1}{i} \cdot \left(1 - \frac{1}{(1+i)^n}\right) =$

$80 \cdot \frac{1}{0.1} \cdot \left(1 - \frac{1}{(1+0.1)^{15}}\right) =$ **$608.49**

Step 4: Calculate LCC

The total present worth = LCC = P = P1 + P2 + P3 + P4 + P5

LCC = $7030 + $149.02 + $489.28 + $92.53 + $608.49 = **$8369.32**

Step 5: Calculate ALCC. This gives water cost per year.

$$ALCC = \frac{LCC}{\frac{1}{i} \cdot \left(1 - \frac{1}{(1+i)^n}\right)} = \frac{8369.32}{\frac{1}{0.1} \cdot \left(1 - \frac{1}{(1+0.1)^{15}}\right)} = \mathbf{\$1100.35}$$

Hence the water cost per year is $1100.35.

1.7. Example:

A micro- hydel plant of 1kW power capacity has been installed. Following are the cost involved in installation of the whole system:

Installation cost of the plant = Rs.16000 Cost

of mains transmission = Rs.16000 Cost of

distribution transformer = Rs.2500 Cost of

11 kV line per Kilometer = Rs.4000

Life span of the plant is 25 years. If the rate of interest is 12%, find the unit cost per Kilometer.

Solution:

Step 1: Calculate the capital cost (K)

The problem involves only the initial cost incurred at year 0. There is no replacement cost or maintenance cost involved. Hence, we can calculate the total capital cost just by adding the given quantities. Let K be the capital cost. It is calculated as follows:

K = Rs.16000 + Rs.16000 + Rs.2500 + Rs.4000 x

d Here d is the distance to which 11 kV line runs.

Step 2: Calculate LCC

Since no other costs except capital cost is involved, LCC can be directly calculated. Therefore K= **LCC** = Rs.(**34500 + 4000d**)

Step 3: Calculate ALCC

Annual cost (ALCC) can be calculated from the above data.

$$ALCC = \frac{LCC}{\frac{1}{i}\cdot\left(1-\left(\frac{1}{1+i}\right)^{n}\right)} = \frac{34500+4000d}{\frac{1}{0.12}\cdot\left(1-\left(\frac{1}{1+0.12}\right)^{25}\right)} = \frac{34500+4000d}{7.84314}$$

ALCC = 4398.75 + 510d

Step 4: Calculate energy generated per year

Energy generated per year = 24 hours x 365 days x 1 kW = 8760

kWHr Transmission efficiency η = 30%

Hence, energy available = 8760 x 0.3 = 2628 kWHr

Step 5: Calculate cost per unit (1 unit = 1 kWHr)

$$\textbf{Cost per unit} = \frac{ALCC}{EnergyAvailable} = \frac{4398.75+510d}{2628} = \mathbf{1.674 + 0.1941d}$$

We can see that cost per unit depends on the value of d, the distance to which 11 kV line runs. As example, let us calculate cost per unit for d = 5 KM and d = 100 KM

Cost per unit for d = 5 KM : 1.674 + 0.1941 x 5 = Rs.2.64 Cost

per unit for d = 100 KM : 1.674 + 0.1941 x 100 = Rs.21.08.

We can see how adverse effect the distance has on the cost per unit. Hence, care must be taken that we do not run such 11 kV lines for long distances.

Comparison of Alternative Energy Systems using Life Cycle Cost Analysis

Electricity is a major secondary energy carrier and is predominantly produced from fossil fuels. Challenging concerns of the fossil fuel based power generation are depletion of fossil fuels and global warming caused by greenhouse gases (GHG) from the combustion of fossil fuels. To achieve the goal of environmental sustainability in the power sector, a major action would be to reduce the high reliance on fossil fuels by resorting to the use of clean/renewable sources and efficient generation/use of electricity. Because of the existence of number of alternative energy systems, there is a need of comparing their economic aspects in producing electricity. In order to consider the long-term implications of power generation, a life cycle concept is adopted, which is a cradle-to-grave approach to analyse an energy system in its entire life cycle. Life cycle assessment (LCA) is an effective tool to pinpoint the environmental implications. Life cycle cost analysis (LCCA) provides effective evaluation to pinpoint cost effective alternatives. LCA and LCCA should be combined to identify cost effective power generation alternative scheme. In this paper, for a given energy requirement, a sample comparison was done between solar PV, solar thermal, microhydel, wind, wave and biomass system using the life cycle costing (LCCA) approach.

SOLAR PV

To calculate the life cycle cost per KWh the basic components of a PV system are considered as follows.

2. PV panels
3. Batteries
4. Inverters
5. Charge controllers

We will ignore adding in the cost of the charge controller, since this is only a few hundred dollars (whereas the whole system cost will be in the thousands of dollars).

The user specified variables will be:

1. Peak power required to power appliances
2. Total energy produced/consumed per day
3. Hours of sunshine (average)

Cost of inverter as function of peak power required:

The amount of peak power the system can deliver will be determined by the size of the system inverter , the inverter being the device which converts the dc battery power to ac.

$$P_{peak,\ usage} = P_{peak,\ inverter}$$

As determined by surveying current market prices for inverters, the costs of an inverter are about Rs.50 per watt, or (multiplying by 1000):

$$Cost_{inverter} = Rs.\ 50000/kilowatt$$

Thus, the cost of the inverter, as a function of the peak power used, is therefore:

$$Cost_{inverter}\ (P_{peak,\ usage}) = P_{peak,\ usage} \times Cost_{inverter}$$

$$Cost_{inverter} = P_{peak,\ usage} \times Rs.\ 50000/kilowatt$$

Cost of solar panels as a function of energy usage:

The peak power produced by the solar panels is determined by the type and number of solar panels one uses:

$$P_{peak\ panels} = \text{number of panels} \times \text{power per panel}$$

But peak usage is not necessarily equal to peak panel power.

This is because the power generated by the solar panels is stored up over time by batteries, so more peak power (but not energy!) can be delivered by the inverter than is produced by the panels.

$$E_{produced} = E_{used}$$

Also, we need to know how long the sun shines each day on average. Let this be denoted by T_{sun},

T_{sun} = Hours of Sunshine on average.

Using the formula for power and energy (Power = Energy / Time), we have

$$P_{peak\ panels} = E_{used} / T_{sun}.$$

As determined from a survey of current market prices

$$Cost_{panels} = Rs.\ 4\ Lakhs/Kilowatt.$$

$$Cost_{panels} = (E_{used} / T_{sun}) \times Rs.\ 4\ Lakhs/kilo\text{-}watt$$

Cost of batteries as a function of energy usage:

The amount of energy stored (by batteries) determines how much energy can be used after dark, or on a rainy day.

The lifetimes of deep cycle batteries are fairly short (3 - 10 years), and depend on how well they are maintained (for example, one needs to avoid overcharging, and overdrawing.

We will assume, in order not to discharge the battery more than 50%, that the batteries will be able to store twice the amount of energy we use:

$$E_{stored} = 2 \times E_{used}$$

Presently, the cost of batteries is about Rs. 5000 per kilowatt-hour of storage:

$Cost_{batteries}$ = Rs. 5000/kilowatt-hour

The cost of batteries, therefore, *as a function of energy used*, is $Cost_{batteries} = 2 \times E_{used} \times$ \$100/kilowatt-hour

Calculation of life cycle cost per KWh:

Todays solar panels are estimated to last atleast 25 years. We will therefore use 25 years as our life time.

1.	PV panel	Rs. 4 Lakhs/KW	25 Years
2.	Inverter	Rs. 50000/KW	25 Years
3.	Battery	Rs. 10000/KWh	5 Years

Let us say i=10%

Capital Cost = 4Lakhs+ 50000+ 10000=Rs. 460000

$$\text{Replacement Cost} = \frac{10000}{(1+i)^5} + \frac{10000}{(1+i)^{10}} + \frac{10000}{(1+i)^{15}} + \frac{10000}{(1+i)^{20}}$$

=Rs. 13945/KWh

Maitenance Cost:As we are considering only from generating point of view maintenance cost is negligible part.

Energy Cost: It does not require any external energy (because the system uses sun energy) to produce the electrical energy.

2.8 System sizing

Major issues that arise when designing a system include that the load placed on the system is not constant, that the amount of energy available from the renewable energy source is variable and that technology that best suits site should be implemented (Hove, 2000). Therefore the design has to be iterative using simulation models that can evaluate instantaneous system performance.

Several software tools are available on the market and in research groups to optimize and simulate hybrid energy systems, but it is sometimes difficult to assess the adequacy of these tools to specific tasks. Also, more details are available from the system when performing optimization than at the planning phase. According to http://www.ecs.umass.edu/mie/labs/rerl/hy2/theory/pdf/users.pdf, use of such programs require high expertise and financial resource hence the development of simplified computational methods that are less costly. Also the user does not get an intuitive understanding of the system since figures are just fed into the system, hence the development of simpler home-made models. In the development of these homemade models the user is able to include specific things that one needs to use. A system can be designed with a smaller or larger solar array or battery, or may make more use of the diesel generator. The problem is to find a system that provides an optimal combination of solar array, battery and usage of the diesel engine.

2.8.1 Estimation of Electrical Load

The electrical loads can be estimated if the power used by each appliance is known. The total energy required will depend on this power draw and the operating time of the appliance. Overall electrical loads can be determined by drawing up a list of all items, their power use and their average operating time per day. The total will be used in determining the size and type of system required.

2.8.2 Load Profiles

The load profile has been defined by Karnavas and Papadopoulos (1999) as the power requirements for the demand-side converters (appliance loads) over time. Once energy conservation (demand side management) techniques are used to reduce the electrical load as far as economically possible whilst still providing the required service, the load profile should be determined to decide the type of hybrid system needed to provide power. The load profile may vary by the hour, day, week, month, season, or year. The peak demand spikes can be met from the batteries and the engine generator started and operated at a steady load when the battery state-of- charge drops below a pre-set level.

The most convenient method of determining the load profile of a system is by measuring electricity demand using an energy (kilowatt / kilowatt-hour) meter, and logging the output hourly, or more often, for at least a week, preferably a month or year (seasonal variations). This can be done either manually if someone can read the meter at regular intervals, or a data logger can be used, in which case much more detailed information is available. This will reveal the daily and weekly profiles. If seasonal variations in load are suspected, longer-term (yearly) load monitoring will be required to reveal the seasonal profile (Karnavas and Papadopoulos , 1999)

2.8.3 Photovoltaic Modules: Technician's method

According to Klein (1977) to determine the actual required PV array output, divide the daily energy requirement by the battery efficiency which is usually between 0.70 and 0.95 and depends on the coulombic efficiency of the batteries in both charging and discharging. Generally 0.95 is used for very efficient batteries installed in good conditions and 0.7 for the least efficient batteries.

The author highlights that to work out the output from the array, it is important to know under what conditions the output will be determined, and need to know what the inclination of the array will be. This is measured in peak sun hours, which is dependent on latitude, season and inclination of the array. The scenario generally chosen for solar / generator hybrid systems is the yearly average peak sun hours. If tables of peak sun hours are not available they can be determined from the average of daily total global radiation. To convert daily global radiation (MJ/m_2) to peak sun hours divide by 3.6. The output of the modules will be average annual peak sun hours times the module rating.

To determine the number of modules in the array first work out the number of modules in series so that the operating voltage is sufficient for battery charging. Divide the system voltage by the nominal operating voltage of each module. To determine the number of modules in parallel the array output required (Ah) is divided by the output of each module (Ah). However this method does not apply in this research as it does not take into account many things and in a hybrid system energy flows need to be known from hour to hour.

2.8.4 Sizing The Charge Controller/ Battery Charger

Generators in renewable systems are used to power the battery charger, particularly during poor weather, or to supply heavy loads. They can be automatically or manually controlled. In most systems, either diesel, petrol or gas driven generators are used (Hove, 2000).

A battery charger converts the AC output to DC for the purpose of battery charging. The battery charger should be selected such that it converts the 240 volt, 50 Hz AC to DC at the required bus voltage of the battery storage bank. It should be able to provide a direct current up to the maximum allowable charge rate of the batteries. The two critical factors to consider when selecting a battery charger are the system voltage and the maximum rate of charge of the batteries. There may not be a battery charger with exactly the maximum current specified so a charger with lower current would be chosen. The most likely available charger would be 24 Volt 60 Amps. The size of the battery charger is determined by the size of the battery bank (Hove, 2000).

A charge controller should be sized to pass the expected continuous current from the array (or sub-array) into the battery, and should be able to withstand temporary peak currents due to sunnier than normal conditions. It is critical that the controller be adequately sized since the costs associated with the controller are much greater than the cost of initially installing a slightly larger controller. A module will normally have a maximum current output which is its rated short circuit current (when battery voltage is low). It is possible for irradiance levels to reach 3000 watts/m^2; the short circuit current is normally rated for irradiance levels of 1000 watts/ m^2. Charge controllers should be sized therefore, to regulate 130% of a module's normal short circuit current. The size of a controller can be calculated by multiplying the I_{sc} current of a module by the number of modules in parallel and the 1.3 safety factor. Consult with the manufacturers to determine if they have already build a safety factor into their rating value; oversizing by 130% may not be necessary if the controller is already designed to handle higher than rated currents (Beyer, 2003).

2.8.5 Inverter Power

The inverter converts DC power from the battery bank and/or PV array to AC whenever power from diesel generator sets is not available. It changes DC energy stored within the batteries to AC energy, suitable for the standard appliance operating voltage of 240V. An inverter can generally only supply loads up to its kilowatt rating, although all inverters have a surge rating for electrical peaks. This allows for motor starting, or other brief overloads (http://www.energymatters.com.au/renewable-energy/solar-power/stand-alone-power-systems/).

The output power (wattage) of an inverter indicates how much power the inverter can supply during standard operation. It is important to choose an inverter, which will satisfy a system's peak load requirements. Most inverters are able to exceed their rated wattage for limited periods of time. This is necessary since appliances may require many times their rated wattage during start up and the minimum surge requirement may be calculated by multiplying the required wattage by three. Some Inverters have the added advantage that they have a built-in battery charger so that when the batteries need charging from an AC source (generator), the current can be fed into the inverter, changed to DC, and then used to charge the batteries (Behrendorff, 1999).

WHY FREQUENCY AND VOLTAGE CONTROL

The main purpose of an electrical power systems is to efficiently deliver reliable Electricity to consumers.voltage and frequency are the main variables to guarantee the stability.

The simplest electrical power system consists of a single electric generator and a Load.The frequency of the voltage in an electrical generator is directly proportional to the Rotational speed of rotor.According to the relation

$$f = PN/120$$

Where f=frequency

P=No.of poles in the alternator

N=rotational speed of rotor in r.p.m

An electrical power system consisting of thousands of interconnected generators and loads Behaves much like a simple one generator-load system, with frequency being same for whole interconnected power system.However,there is never a perfect equilibrium between generation and demand and there will be frequency shifts as a resultof the imbalances between generation and demand.

Regarding the first variable necessary to guarantee the stability of an electrical system, there are several reasons why it is desirable to keep frequency in a power system within narrow bounds.

- It ensures that electric motors operate at a virtually constant speed. A fixed speed is required in many consumer applications where an AC electric motor is used to drive a device at an approximately constant rate
- In electronic applications the main frequency can be used as a basis for time varying Processes.
- Transformers are sensitive to frequency variations and may be overloaded if the frequency drifts substantially from the nominal value.
- Finally ,and most importantly in traditional power stations the performance of the generators is dependent on the performance of all the auxulary electric motor drives That deliver fuel and air to the boiler,oil to bearings and cooling services to several systems.If these auxularies under perform due to low speed caused by low frequency,power station output can be reduced.this phenomenon could lead to run away situation with cascade shutdowns and blackouts.

Basic Concepts and Definitions of Power System Stability

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most of the system variables bounded so that practically the entire system remains intact . The disturbances mentioned in the definition could be faults, load changes, generator outages, line outages, voltage collapse or some combination of these. Power system stability can be broadly classified into rotor angle, voltage and frequency stability. Each of these three stabilities can be further classified into large disturbance or small disturbance, short term or long term.

Voltage stability

It is the ability of the system to maintain steady state voltages at all the system buses when subjected to a disturbance. If the disturbance is large then it is called as large-disturbance voltage stability and if the disturbance is small it is called as small-disturbance voltage stability. Unlike angle stability, voltage stability can also be a long term phenomenon. In case voltage fluctuations occur due to fast acting devices like induction motors, power electronic drive, HVDC etc then the time frame for understanding the stability is in the range of 10-20 s and hence can be treated as short term phenomenon. On the other hand if voltage variations are due to slow change in load, over loading of lines, generators hitting reactive power limits, tap changing transformers etc then time frame for voltage stability can stretch from 1 minute to several minutes.

The main difference between voltage stability and angle stability is that voltage stability depends on the balance of reactive power demand and generation in the system where as the angle stability mainly depends on the balance between real power generation and demand.

Frequency stability

It refers to the ability of a power system to maintain steady frequency following a severe disturbance between generation and load. It depends on the ability to restore equilibrium between system generation and load, with minimum loss of load. Frequency instability may lead to sustained frequency swings leading to tripping of generating units or loads. During frequency excursions, the characteristic times of the processes and devices that are activated will range from fraction of seconds like under frequency control to several minutes, corresponding to the response of devices such as prime mover and hence frequency stability may be a short-term phenomenon or a long-term phenomenon.

Though, stability is classified into rotor angle, voltage and frequency stability they need not be independent isolated events. A voltage collapse at a bus can lead to large excursions in rotor angle and frequency. Similarly, large frequency deviations can lead to large changes in voltage magnitude.

Each component of the power system i.e. prime mover, generator rotor, generator stator, transformers, transmission lines, load, controlling devices and protection systems should be mathematically represented to assess the rotor angle, voltage and frequency stability through appropriate analysis tools. In fact entire power system can be represented by a set of Differential Algebraic Equations (DAE) through which system stability can be analyzed. In the next few Chapters we will be concentrating on power system components modeling for stability analysis.

GRID INTEGRATION:

proven that wind power can
be successfully integrated with the power grid. The degree of this success and the level of wind penetration varies largely on:

- The design limits of the tie-line—the key design parameters being:

⇒ Voltage levels

⇒ Capacity

⇒ Voltage Regulation

⇒ Tie-line Stability

- Interface standards—mainly related to power quality, which in turn determines the renewable capacity limit. Power Quality issues are:

⇒ Harmonic Distortion

⇒ Voltage Transients and Sags

⇒ Voltage Flicker

⇒ Step Load Voltage

- The firm capacity of the windfarm and the associated wind power dispatch issues.

⇒ Load following

⇒ Scheduling

⇒ Reserve

- Response to abnormal conditions:

⇒ Voltage disturbances

⇒ Faults

STABILITY LIMIT

- The direction of the power flow across the Tie-Line depends on the sending and receiving end voltages.
- The magnitude of the real power transferred by the Tie-line depends on the power angle δ (the phase angel between V_s and V_r). If $\delta > 0$, the power flows from the windfarm to the grid. When $\delta < 0$, the windfarm draws power from the grid.
- The power flow is maximum when $\delta = 90^o$

• Beyond this maximum power (P_{max}), the Tie-Line becomes unstable and will lose synchronism. This is referred to as the steady state stability limit of the system.

• In practice, the line loading must be kept well below P_{max}, to allow for transients such as sudden load steps and system faults. The maximum power the line can transfer without losing the stability during transients is referred to as the dynamic stability limit.

• In typical systems, the power angel must be kept below 20º to assure dynamic stability.

POWER QUALITY

The rapid increase in the demand of power, depletion of fossil fuel and environmental threat to sustainable development are the basic reasons for the swift development in the field of Renewable Energy (RE) sector. Hence, the concept of micro-grid , which uses energy sources such as photovoltaic (PV), wind turbine (WT) and fuel cell (FC) came in to picture. These energy sources are positioned in the load center and can be seamlessly connected or disconnected to the low voltage utility grid. Due to intermittent nature of RE sources, more than one source is generally combined to form a HPS. These sources uses power conditioning devices like, DC-DC boost converter to raise the voltage level to nominal value or a DC-AC converter to integrate the resources to the utility grid. However, the proliferation of these power electronics switching devices introduces an alarming concern among the industrial energy customer and also to the utility grid; this is termed as PQ issues Among the various PQ issues notices so far, voltage transients, voltage sag and swell, harmonic distortion and flicker are of key concerns. In a view to improve the power quality a new methodology was suggested in which replaces the inverter by a DC motor -Alternator set to integrate the RE sources. In this framework, an attempt is made to measure and compare the various PQ indices for HPS model with the two different modes of grid integration, i.e. inverter mode and its counterpart i.e. a DC motor –Alternator set mode of grid integration. Various PQ indices such as voltage variation, voltage sag and swell, voltage imbalance, flicker, Total Harmonic Distortion (THD) are measured at the consumer terminal by using both integration schemes. Simulation results indicate that the quality of power injected into the grid by means of a MG set is superior to that coming from inverter.

Power quality is a measure of various parameters like voltage current and frequency within its predefined range. If there has any deviation generated various problems like voltage sag, voltage swell, transient, flicker, harmonics etc. which can be responsible for poor power quality.

Transient: - transient are short duration and sudden disturbances which can cause by a very rapid change in the steady state condition of voltage current or both. Transient disturbance is classified in to two categories oscillatory transient and impulsive transient.

short duration voltage variation: - in any supply voltage if there has any variation for very short time not more than 1 minute is called a short duration voltage variation. For the short duration voltage variation faults, energization of large loads intermittent loose connection in power wiring is responsible. Short duration voltage variation is classified into three categories as voltage sag voltage swells and interruptions.

long duration voltage variation: - for larger than 1 minute the voltage deviation surrounding the rms (root mean square) value of power frequency is called long voltage variation. Long duration voltage variations are classified in 3 categories as over voltage, under voltage and sustained interruptions.

wave form distortion: - the voltage and current waveform of healthy power supply are ideal sine wave .if there power frequency wave form has any steady state deviation is called wave form distortion. Wave form distortion is classified in to following categories .dc offset, harmonics, inter harmonics, notching, and noise.

voltage fluctuations: - the systematic random variation of voltage envelop is called voltage fluctuation. The main course of voltage variation is rapid change in current magnitude of load. A very rapid change of supply voltage. is called voltage flicker which is a type of voltage fluctuations.

3.6 power frequency variations :- for the satisfactory operation of any power system an fundamental frequency is predefined .in case there has any variation in its specified nominal value (e.g. 50 to 60 Hz) is called power frequency variation..rapid changes in the load which is connected in the system is responsible for power frequency variation .

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WINDFARM CAPACITY LIMIT:

Most utilities are faced with the issue of compatibility of wind farms for interfacing with the grid from the power quality point of view. The basic consideration in such decision is the source impedance before and after making the connection. This is often and otherwise referred to as the avail- able short-circuit MVA at the point of interconnection—also known as the system stiffness or the fault level.

- The higher the fault level, the stiffer the network
- A minimum grid stiffness in relation to the wind power capacity is required to maintain the power quality of the resulting network
- Not only is the magnitude of the equivalent source impedance of the two systems important, the resistance(R), and the reactance (X) components of this impedance have their individual importance.
- The system fault current decays exponentially as e^t/(X/R)
- High X/R ratios cause fault currents to decay slowly, making protective relaying more difficult.
- The X/R ratio influences voltage regulation, which may place a limit on the continuous maximum load the wind farm can deliver. The acceptable voltage regulation is typically 5 to 7%.

Interfacing Standards:

- Utilities have found it convenient to meet the power quality requirements by limiting the wind farm capacity to a small percentage of the short-circuit MVA of the grid at the point of interconnection.
- This limit is usually 2 to 5%
- Yet another rule of thumb to address the power quality issues for stiff grids has been to keep the wind farm capacity in MW to less than the grid line voltage in kV.
- In the case of weak grids, only 10 to 20% of the above capacity may be allowed.

It is complex to determine the maximum wind plant capacity at a given site, which will meet

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all electrical, operating and power quality requirements. The percentage of the short-circuit MVA at the point of interconnection, in the absence of more rigorous standards and simulation tools, is recommended