WIND AND SOLAR ENERGY SYSTEMS

B.Tech V semester - R18

LECTURE NOTES

ACADEMIC YEAR: 2020-2021

Prepared By:

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SYLLABUS

MODULE-I	DESIGN AND OPERATION OF WIND POWER SYSTEM
Wind Power System: Components, turbine rating, electrical load matching, variable-speed operation, system design features, maximum power operation, system control requirements, speed control, rate control and environmental aspects, wind energy conversion systems and their classification.	
MODULE-II	**DESIGN AND OPERATION OF PV SYSTEM**
Solar Photovoltaic Power System: The PV Cell, module and array, equivalent electrical circuit, open circuit voltage and short circuit current, I-V and P-V curves, array design, peak power point operation, PV system components; Solar Thermal System: Energy collection, synchronous generator, equivalent electrical circuit, excitation methods, electrical power output, transient stability limit, commercial power plants.	
MODULE-III	**POWER CONDITIONING SCHEMES FOR SOLAR ENERGY SYSTEMS**
Switching devices for solar energy conversion: DC power conditioning converters, maximum power point tracking algorithms. AC Power conditioners, Line commutated inverters, synchronized operation with grid supply, Harmonic reduction.	
MODULE-IV	**WIND ENERGY CONVERSION SYSTEMS**
Wind energy Conversion system (WECS): Performance of Induction generators for WECS, Self-excited induction generator (SEIG) for isolated power generators. Controllable DC power from SEIGs, system performance, Grid related problems, generator control, AC voltage controllers, Harmonic reduction and Power factor improvement.	
MODULE-V	**POWER QUALITY ISSUES IN INTEGRATION OF RENEWABLE ENERGY RESOURCES**
Stand alone and Grid connected systems, Power Quality issues, Impact of power quality problems on DG, Mitigation of power quality problems, and Role of custom power devices in Distributed Generation.	

MODULE-1
DESIGN AND OPERATION OF WIND POWER SYSTEM

Course Outcomes Mapped To Module I :

Students will be able to:

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

Program Outcomes Mapped To Module I :

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

Mapping Of CO(s) With PO(s) For Module I:

Course Outcomes (COs)	Program Outcomes (POs)											
	1	2	3	4	5	6	7	8	9	10	11	12
CO 1	√											
CO 2	√	√	√									
CO 3	√	√										

WIND ENERGY

Introduction:

Wind is simple air in motion. It is caused by the uneven heating of the earth's surface by the sun. Since the earth's surface is made of very different types of land and water, it absorbs the sun's heat at different rates. During the day, the air above the land heats up more quickly than the air over water. The warm air over the land expands and rises, and the heavier, cooler air rushes in to take its place, creating winds.

At night, the winds are reversed because the air cools more rapidly over land than over water. In the same way, the large atmospheric winds that circle the earth are created because the land near the earth's equator is heated more by the sun than the land near the North and South Poles. Today, wind energy is mainly used to generate electricity. Wind is called a renewable energy source because the wind will blow as long as the sun shines.

The History of Wind Since ancient times, people has harnessed the winds energy:

Over 5,000 years ago, the ancient Egyptians used wind to sail ships on the Nile River. Later, people built windmills to grind wheat and other grains. The earliest known windmills were in Persia (Iran). These early windmills looked like large paddle wheels. Centuries later, the people of Holland improved the basic design of the windmill. They gave it propeller-type blades, still made with sails. Holland is famous for its windmills.

The wind wheel, like the water wheel, has been used by man for a long time for grinding corn and pumping water. Ancient seamen used wind power to sail their ships. With the development of the fossil Characteristics of Wind Power Wind as a source of energy is plentiful, inexhaustible and pollution free but it has the disadvantage that the degree and period of its availability are uncertain. Also, movement of large volumes of air is required, to produce even a moderate amount of power.

As a result, the wind power must be used as and when it is available, in contrast to conventional methods where energy can be drawn upon when required. Wind power, therefore, is regarded as a means of saving fuel, by injection of power into an electrical grid, or run wind power plant in conjunction with a pumped storage plant. The power that can be theoretically obtained from the wind, is proportional to the cube of its velocity and thus high wind velocities are most important. The power developed using this law, in atmospheric condition

where
the density of air is 1.2014 kg/cu metre, is given as
Power developed = $13.14 \times 10^{-6} A V^3$ KW
where A is the swept area in sq. metre and V the wind velocity in Km/hr

A wind turbine is the popular name for a device that converts kinetic energy from the wind into electrical power.

Betz Law:

Betz's law calculates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow. It was published in 1919, by the German physicist Albert Betz. The law is derived from the principles of conservation of mass and momentum of the air stream flowing through an idealized actuator disk that extracts energy from the wind stream. According to Betz's law, no turbine can capture more than 16/27 (59.3%) of the kinetic energy in wind. The factor 16/27 (0.593) is known as Betz's coefficient. Practical utility-scale wind turbines achieve at peak 75% to 80% of the Betz limit

Speed and Power Relations:

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator. The turbine is mounted on a tall tower to enhance the energy capture. Numerous wind turbines are installed at one site to build a wind farm of the desired power generation capacity. Obviously, sites with steady high wind produce more energy over the year. Two distinctly different configurations are available for turbine design, the horizontalaxis configuration (Figure) and the vertical-axis configuration. The horizontal-axis machine has been the standard in Denmark from the beginning of the wind power industry. Therefore, it is often called the Danish wind turbine. The vertical-axis machine has the shape of an egg beater and is often called the Darrieus rotor after its inventor. It has been used in the past because of its specific structural advantage. However, most modern wind turbines use a horizontal axis design. Except for the rotor, most other components are the same in both designs, with some differences in their placements.

The kinetic energy in air of mass m moving with speed V is given by the following in joules: The power in moving air is the flow rate of kinetic energy per second in watts:
kinetic energy = $\frac{1}{2}mv^2$

The power in moving air is the flow rate of kinetic energy per second in watts:
Power = $\frac{1}{2}(\text{mass flow per second})^2$

If
P= mechanical power in the moving air (watts),

ρ = air density (kg/m3),

A= area swept by the rotor blades (m2), and

V= velocity of the air (m/sec),

then the volumetric flow rate is AV, the mass flow rate of the air in kilograms per second is ρAV, and the mechanical power coming in the upstream wind is given by the following in watts:
$P = \frac{1}{2}(\rho Av)v^2 = \frac{1}{2}\rho Av^3$

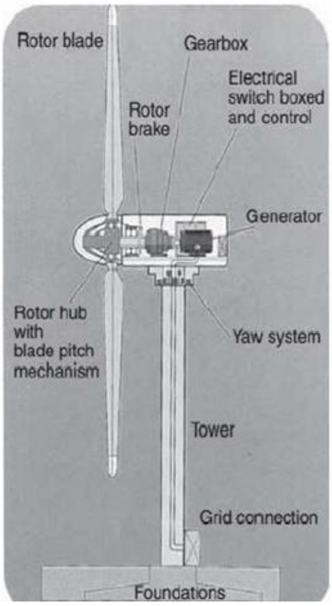


Figure: Horizontal-axis wind turbine showing major components.

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 in watts per square meter of the rotor-swept area

Specific power of the site = $\frac{1}{2}\rho v^3$

This is the power in the upstream wind. It varies linearly with the density of the air sweeping the blades and with the cube of the wind speed. The blades cannot extract all of the upstream wind power, as some power is left in the downstream air that continues to move with reduced speed. 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. The blades cannot extract all of the upstream wind power, as some power is left in the downstream air that continues to move with reduced speed.

Power Extracted From The Wind:

The actual power extracted by the rotor blades is the difference between the upstream and downstream wind powers. Using Equation , this is given by the following equation in units of watts:

$P_0 = \frac{1}{2}$(mass flow per second)$\{v^2 - v_0^2\}$

where

Po= mechanical power extracted by the rotor, i.e., the turbine output power,

V= upstream wind velocity at the entrance of the rotor blades, and

Vo= downstream wind velocity at the exit of the rotor blades

Let us leave the aerodynamics of the blades to the many excellent books available on the subject, and take a macroscopic view of the airflow around the blades. Macroscopically, the air velocity is discontinuous from V to Vo at the "plane" of the rotor blades, with an "average" of .(V + Vo). Multiplying the air density by the average velocity, therefore, gives the mass flow rate of air through the rotating blades, which is as follows**:**

Mass flow rate = $\rho A\frac{V+V_0}{2}$

The mechanical power extracted by the rotor, which drives the electrical generator, is Therefore

$P_0 = \frac{1}{2}[\rho A\frac{V+V_0}{2}](V^2 - Vo^2)$

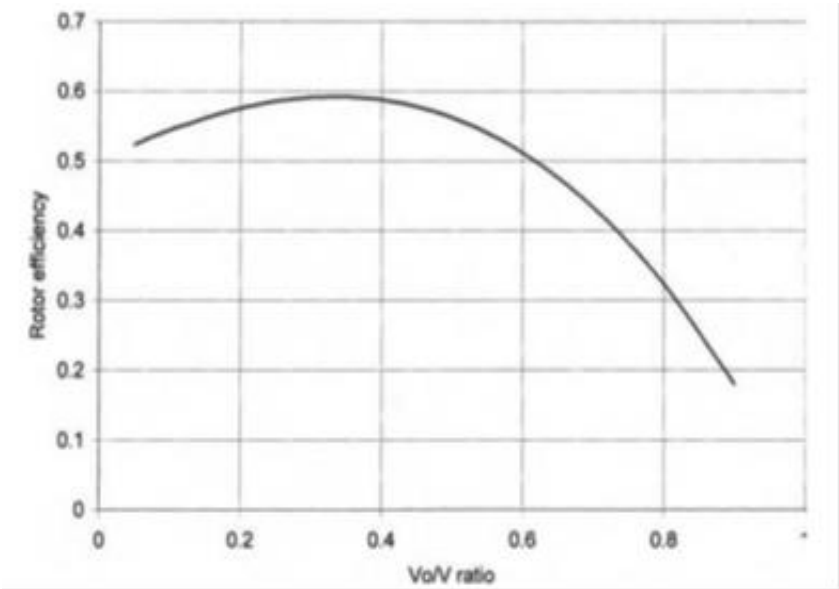


Figure: Rotor efficiency vs. Vo/V ratio has a single maximum.

Wind Speed Distribution:

Having a cubic relation with power, wind speed is the most critical data needed to appraise the power potential of a candidate site. The wind is never steady at any site. It is influenced by the weather system, the local land terrain, and its height above the ground surface. Wind speed varies by the minute, hour, day, season, and even by the year. Therefore, the annual mean speed needs to be averaged over 10 yr or more.

Such a long term average gives a greater confidence in assessing the energy-capture potential of a site. However, long-term measurements are expensive and most projects cannot wait that long. In such situations, the short-term data, for example, over 1 yr, is compared with long-term data from a nearby site to predict the long-term annual wind speed at the site under consideration.

This is known as the measure, correlate, and predict (mcp) technique. Because wind is driven by the sun and the seasons, the wind pattern generally repeats over a period of 1 yr. The wind site is usually described by the speed data averaged over calendar months. Sometimes, the monthly data is aggregated over the year for brevity in reporting the overall “windiness” of various sites. Wind speed variations over the period can be described by a probability distribution function.
Energy Distribution:

If we define the energy distribution function

$$e = \frac{\text{KWh contribution in the year by the wind between v and } (V+\Delta V)}{\Delta V}$$

then, for the Rayleigh speed distribution (k = 2), the energy distribution would look like the shaded curve in Figure. The wind speed curve has the mode at 5.5m/sec and the mean at 6.35 m/sec. However, because of the cubic relation with speed, the maximum energy contribution comes from the wind speed at 9.45 m/sec. Above this speed, although V3 continues to increase in a cubic manner, the number of hours at those speeds decreases faster than V3. The result is an overall decrease in the yearly energy contribution reason, it is advantageous to design the wind power system to operate at variable speeds in order to capture the maximum energy available during high-wind periods.

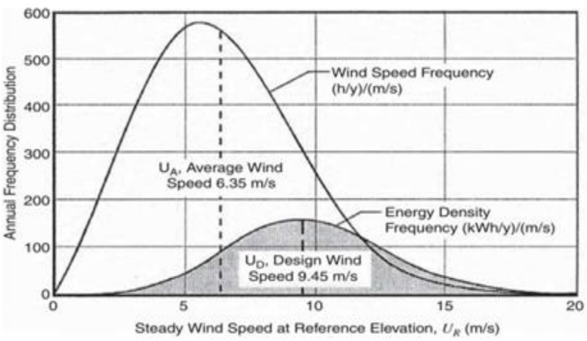


Figure: Annual frequency distributions of hours vs. wind speed and energy density per year

Wind Speed Prediction:

Because the available wind energy at any time depends on the wind speed at that time, which is a random variable, knowing the average annual energy potential of a site is one thing and the ability to accurately predict when the wind will blow is quite another thing. For the wind farm operator, this poses difficulties in system scheduling and energy dispatching as the schedule of wind power availability is not known in advance.

However, a reliable forecast of wind speed several hours in advance can give the following benefits:

- Generating schedule can efficiently accommodate wind generation in a timely manner
- Allows the grid-connected wind farm to commit to power purchase contracts in advance for a better price
- Allows investors to proceed with new wind farms and avoid the penalties they must pay if they do not meet their hourly generation targets

Wind Power System Components:

The wind power system comprises one or more wind turbine units operating electrically in parallel. Each turbine is made of the following basic components:

- Tower structure
- Rotor with two or three blades attached to the hub
- Shaft with mechanical gear
- Electrical generator
- Yaw mechanism, such as the tail vane
- Sensors and control

Because of the large moment of inertia of the rotor, design challenges include starting, speed control during the power-producing operation, and stopping the turbine when required. The eddy current or another type of brake is used to halt the turbine when needed for emergency or for routine maintenance. In a modern wind farm, each turbine must have its own control system to provide operational and safety functions from a remote location.

It also must have one or more of the following additional components:

- Anemometers, which measure the wind speed and transmit the data to the controller.
- Numerous sensors to monitor and regulate various mechanical and electrical parameters. A 1-MW turbine may have several hundred sensors.
- Stall controller, which starts the machine at set wind speeds of 8 to 15 mph and shuts off at 50 to 70 mph to protect the blades from overstressing and the generator from overheating.
- Power electronics to convert and condition power to the required standards.
- Control electronics, usually incorporating a computer.
- Battery for improving load availability in a stand-alone plant.
- Transmission link for connecting the plant to the area grid.

The following are commonly used terms and terminology in the wind power industry:
Low-speed shaft: The rotor turns the low-speed shaft at 30 to 60 rotations per minute (rpm).

High-speed shaft:
It drives the generator via a speed step-up gear.

Brake:
A disc brake, which stops the rotor in emergencies. It can be applied mechanically, electrically, or hydraulically.

Gearbox:
Gears connect the low-speed shaft to the high-speed shaft and increase the turbine speed from 30 to 60 rpm to the 1200 to 1800 rpm required by most generators to produce electricity in an efficient manner. Because the gearbox is a costly and heavy part, design engineers are exploring slow speed, direct-drive generators that need no gearbox.

Generator:
It is usually an off-the-shelf induction generator that produces 50- or 60-Hz AC power.

Nacelle:
The rotor attaches to the nacelle, which sits atop the tower and includes a gearbox, low- and high-speed shafts, generator, controller, and a brake. A cover protects the components inside the nacelle. Some nacelles are large enough for technicians to stand inside while working.

Pitch:

Blades are turned, or pitched, out of the wind to keep the rotor from turning in winds that have speeds too high or too low to produce electricity.

Upwind and downwind:

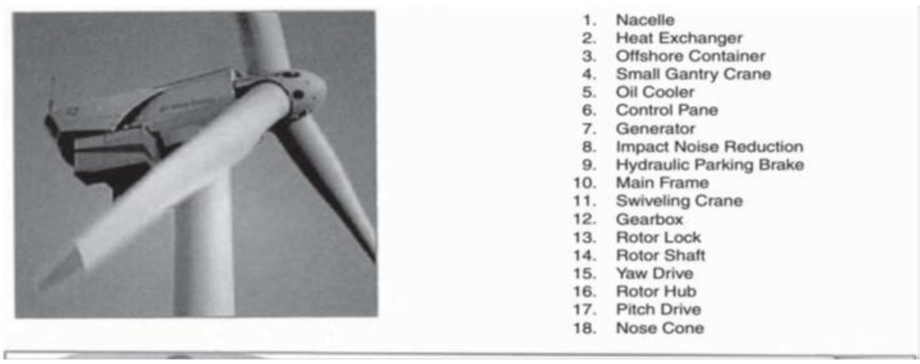
The upwind turbine operates facing into the wind in front of the tower, whereas the downwind runs facing away from the wind after the tower.

Vane:

It measures the wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

Yaw drive:

It keeps the upwind turbine facing into the wind as the wind direction changes. A yaw motor powers the yaw drive. Downwind turbines do not require a yaw drive, as the wind blows the rotor downwind. The design and operating features of various system components are described in the following subsections.



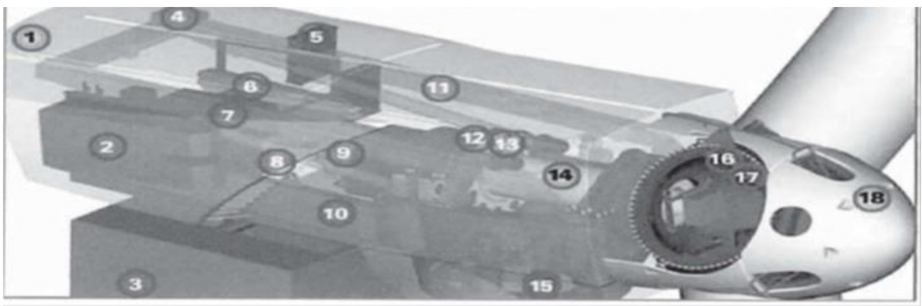


Figure: Horizontal-axis wind turbine showing major components.

The design and operating features of various system components are described in the following subsections:

A. Tower:

The wind tower supports the rotor and the nacelle containing the mechanical gear, the electrical generator, the yaw mechanism, and the stall control. Figure depicts the component details and layout in a large nacelle, and Figure shows the installation on the tower. The height of the tower in the past has been in the 20 to 50 m range. For medium and large-sized turbines, the tower height is approximately equal to the rotor diameter, as seen in the dimension drawing of a 600-kW wind turbine Small turbines are generally mounted on the tower a few rotor diameters high. Otherwise, they would suffer fatigue due to the poor wind speed found near the ground surface. Figure 4.5 shows tower heights of various-sized wind turbines relative to some known structures. Both steel and concrete towers are available and are being used. The construction can be tubular or lattice. Towers must be at least 25 to 30 m high to avoid turbulence caused by trees and buildings. Utility-scale towers are typically twice as high to take advantage of the swifter winds at those heights.

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B. Turbine:

Wind turbines are manufactured in sizes ranging from a few kW for stand-alone remote applications to a few MW each for utility-scale power generation. The turbine size has been steadily increasing. The average size of the turbine installed worldwide in 2002 was over 1 MW. By the end of 2003, about 1200 1.5-MW turbines made by GE Wind Energy alone were installed and in operation. Today, even larger machines are being routinely installed on a large commercial scale, such as GE's new 3.6-MW turbines for offshore wind farms both in Europe and in the U.S. It offers lighter variable-speed, pitchcontrolled blades on a softer support structure, resulting in a cost-effective foundation. Its rated wind speed is 14 m/sec with cut in speed at 3.5 m/sec and the cutout at 25 m/sec. The blade diameter is 104 m.

C. Blades:

Modern wind turbines have two or three blades, which are carefully constructed airfoils that utilize aerodynamic principles to capture as much power as possible. The airfoil design uses a longer upper-side surface whereas the bottom surface remains somewhat uniform. By the Bernoulli principle, a "lift" is created on the airfoil by the pressure difference in the wind flowing over the top and bottom surfaces of the foil. This aerodynamic lift force flies the plane high, but rotates the wind turbine blades about the hub. In addition to the lift force on the blades, a drag force is created, which acts Department of Electrical Engineering, Veer SurendraSai University of Technology Burla Page 90 perpendicular to the blades, impeding the lift effect and slowing the rotor down. The design objective is to get the highest lift-to-drag ratio that can be varied along the length of the blade to optimize the turbine's power output at various speeds. The rotor blades are the foremost visible part of the wind turbine, and represent the forefront of aerodynamic engineering. The steady mechanical stress due to centrifugal forces and fatigue under continuous vibrations make the blade design the weakest mechanical link in the system.

Extensive design effort is needed to avoid premature fatigue failure of the blades. A swift increase in turbine size has been recently made possible by the rapid progress in rotor blade technology, including emergence of the Carbon- and glass-fiber-based epoxy composites. The turbine blades are made of high-density wood or glass fiber and epoxy composites. The high pitch angle used for stall control also produces a high force. The resulting load on the blade can cause a high level of vibration and fatigue, possibly leading to a mechanical failure.

Regardless of the fixed- or variable-speed design, the engineer must deal with the stall forces. Researchers are moving from the 2-D to 3-D stress analyses to better understand and design for such forces. As a result, the blade design is continually changing, particularly at the blade root where the loading is maximum due to the cantilever effect. The aerodynamic design of the blade is important, as it determines the energy capture potential. The large and small machine blades have significantly different design philosophies. The small machine sitting on a tower relatively taller than the blade diameter, and generally unattended, requires a low-maintenance design. On the other hand, a large machine tends to optimize aerodynamic performance for the maximum possible energy capture. In either case, the blade cost is generally kept below 10% of the total installed cost.

D. Speed Control:

The wind turbine technology has changed significantly in the last 25 yr.1 Large wind turbines being installed today tend to be of variable-speed design, incorporating pitch control and power electronics. Small machines, on the other hand, must have simple, low cost power and speed control.

The speed control methods fall into the following categories:

No speed control whatsoever:

In this method, the turbine, the electrical generator, and the entire system are designed to withstand the extreme speed under gusty winds.

Yaw and tilt control:

The yaw control continuously orients the rotor in the direction of the wind. It can be as simple as the tail vane or more complex on modern towers. Theoretical considerations dictate free yaw as much as possible. However, rotating blades with large moments of inertia produce high gyroscopic torque during yaw, often resulting in loud noise. A rapid yaw may generate noise exceeding the local ordinance limit. Hence, a controlled yaw is often required and used, in which the rotor axis is shifted out of the wind direction when the wind speed exceeds the design limit.

Pitch control:
This changes the pitch of the blade with changing wind speed to regulate the rotor speed. Large-scale power generation is moving towards variable-speed rotors with power electronics incorporating a pitch control.

Stall control:
Yaw and tilt control gradually shifts the rotor axis in and out of the wind direction. But, in gusty winds above a certain speed, blades are shifted (profiled) into a position such that they stall and do not produce a lift force. At stall, the wind flow ceases to be smooth around the blade contour, but separates before reaching the trailing edge. This always happens at a high pitch angle. The blades experience a high drag, thus lowering the rotor power output. This way, the blades are kept under the allowable speed limit in gusty winds. This not only protects the blades from mechanical overstress, but also protects the electrical generator from overloading and overheating. Once stalled, the turbine has to be restarted after the gust has subsided.

Turbine Rating:

The method of assessing the nominal rating of a wind turbine has no globally accepted standard. The difficulty arises because the power output of the turbine depends on the square of the rotor diameter and the cube of the wind speed. The rotor of a given diameter, therefore, would generate different power at different wind speeds. A turbine that can generate 300 kW at 7 m/sec would produce 450 kW at 8 m/sec wind speed. What rating should then be assigned to this turbine? Should we also specify the rated speed? Early wind turbine designers created a rating system that specified the power output at some arbitrary wind speed. This method did not work well because everyone could not agree on one speed for specifying the power rating. The "rated" wind speeds varied from 10 to 15 m/sec under this practice. Manufacturers quoted on the higher side to claim a greater output from the same design. Such confusion in quoting the rating was avoided by some European manufacturers who quoted only the rotor diameter. But the confusion continued as to the maximum power the machine can generate under the highest wind speed in which the turbine can continuously and safely operate. Many manufacturers have, therefore, adopted the combined rating designations x/y, the generator's peak electrical capacity followed by the wind turbine diameter. For example, a 300/30-kW/m wind system means a 300-kW electrical generator
and a 30-m diameter turbine.

Classification of WEC system:

Several types of wind wheels have been used but the advantage of propeller rotating about a horizontal shaft, in a plane perpendicular to the direction of the wind make it the most likely type to realise economic generation on a large scale. A propeller consisting of two or three blades (with an aerofoil section) and capable of running at the high speeds is likely to be the most efficient. Present technology has been able to build systems with 60 m long blades, on towers as high as 305 m. A large tower system, to support many small rotor-generator units, can also be built.

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

Vertical-axis wind turbines (VAWTs) are a type of wind turbine where the main rotor shaft is set traverse, not necessarily vertical, to the wind and the main components are located at the base of the turbine. This arrangement allows the generator and gearbox to be located close to the ground, facilitating service and repair. Wind pressure rotates the wind vanes or propellers attached to a shaft.

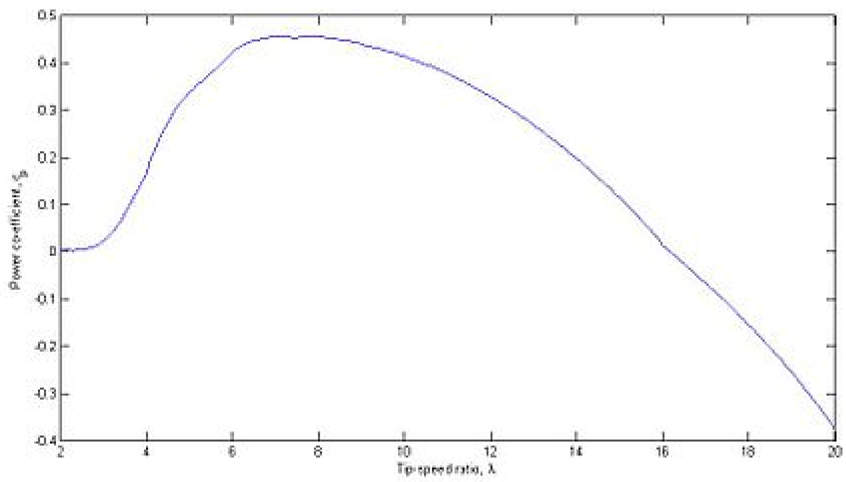
The revolving shaft rotates the rotor of a generator, through a mechanism of gears couplings etc. Thus, electricity is generated. The wind power plants can be operated in combination with steam or hydro power station, which will lead to saving in fuel and increase in firm capacity, respectively of these plants. Wind energy can prove to be a potential source of energy for solving the energy problem. It can certainly go a long way to supply pollution-free energy to millions of people, living in the villages all over the world. The economic viability of wind mills is better in situations where conventional transmission costs are extremely high (because of in accessibility and small load) or where continuous availability of supply is not essential so that only a limited amount of storage on standby power need be provided.

Power capacity of wind turbines:
General Electric (GE) makes a once widely used 1.5-megawatt model. 1.5 MW is its rated, or maximum, capacity, at which rate it will produce power when the wind is in the ideal range for that model, between 27 and 56 mph. Turbines are now generally in the range of 2-3 MW.
The power is generated from the energy in the wind, so a turbine’s power is determined by its ability to capture that energy and convert it to rotational torque that can turn the generator and push electrons into the grid. A taller tower provides access to steadier winds, and larger blades capture more wind energy. A larger generator requires larger blades and/or stronger winds.

Grid affected by commercial wind power:
The electrical grid must continuously balance supply and demand to keep the “pressure” (i.e., voltage) in the system constant. As demand draws off more power, supply must be increased. As demand slows, the supply must be decreased. Because wind turbines respond to the wind rather than the grid dispatchers, they must be treated like variable demand rather than reliable supply. The grid has to adjust supply in response to the fluctuations of wind power as well as those of demand.

Variable speed Operation of wind turbine:

A variable speed wind turbine is one which is specifically designed to operate over a wide range of rotor speeds. It is in direct contrast to fixed speed wind turbine where the rotor speed is approximately constant. The reason to vary the rotor speed is to capture the maximum aerodynamic power in the wind, as the wind speed varies. The aerodynamic efficiency, or coefficient of power, Cp for a fixed blade pitch angle is obtained by operating the wind turbine at the optimal tip-speed ratio as shown in the following graph.



Tip-speed ratio is given by the following expression,

$$\lambda = wR/v$$

whereomega is the rotor speed (in radians per second), R is the radius of the rotor, and v is the wind speed. As the wind speed varies, the rotor speed must be varied to maintain peak efficiency.

Before the need to connect wind turbines to the grid, turbines were fixed-speed. This was not a problem because turbines did not have to be synchronized with the frequency of the grid.

All grid-connected wind turbines, from the first one in 1939 until the development of variable-speed grid-connected wind turbines in the 1970s, were fixed-speed wind turbines. As of 2003, nearly all grid-connected wind turbines operate at an exactly constant speed (synchronous generators) or within a few percent of constant speed (induction generators).

Torque Rotor-speed diagrams

For a wind turbine, the power harvested is given by the following formula:

$$\mathrm{P} = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda)$$

whereP is the aerodynamic power and rho is the density of the air. The power coefficient is a representation of how much of the available power in the wind is captured by the wind turbine and can be looked up in the graph above.

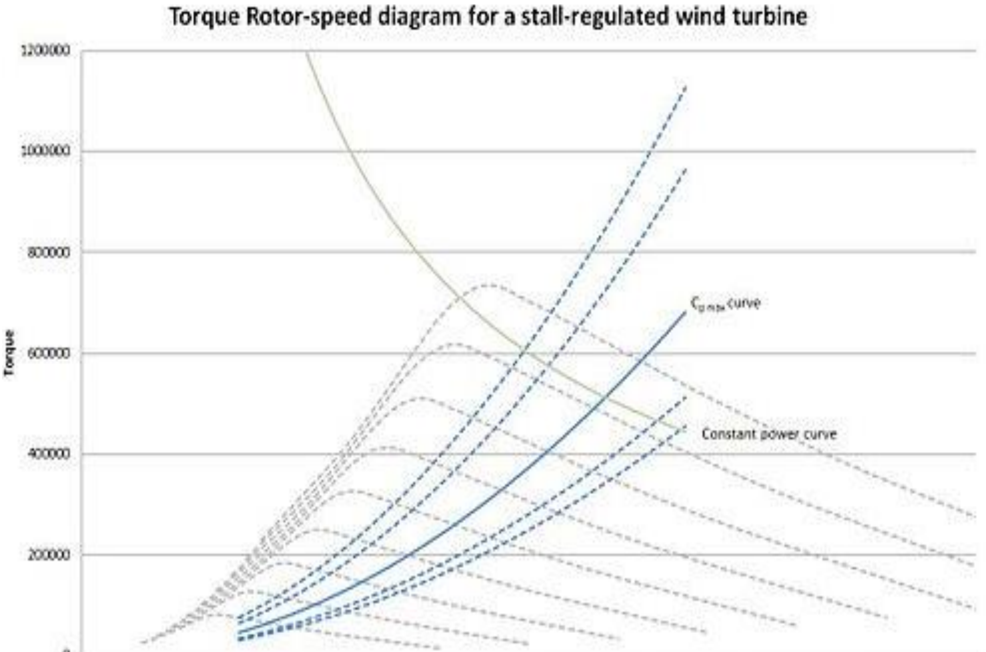
The torque Q, on the rotor shaft is given by the ratio of the power extracted to the rotor speed:

$\mathrm{Q} = \frac{P}{w}$

Thus we can get the following expressions for torque and power

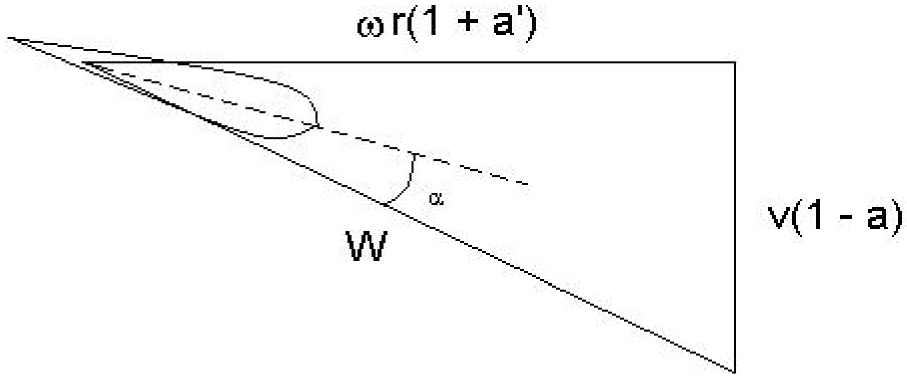
$$\mathrm{P} = \frac{1}{2\lambda^3}\rho\pi R^2 v^3 C_p(\lambda)$$

From the above equation, we can construct a torque-speed diagram for a wind turbine. This consists of multiple curves: a constant power curve which plots the relationship between torque and rotor speed for constant power (green curve); constant wind speed curves, which plot the relationship between torque and rotor speed for constant wind speeds (dashed grey curves); and constant efficiency curves, which plot the relationship between torque and rotor speed for constant efficiencies, Cp. This diagram is presented below:



Blade forces

Consider the following figure:



This is the depiction of the apparent wind speed, as seen by a blade (left of figure). The apparent wind speed is influenced by both the free-stream velocity of the air, and the rotor speed. From this figure, we can see that both the angle theta and the apparent wind speed W are functions of the rotor speed, omega . By extension, the lift and drag forces will also be functions of omega . This means that the axial and tangential forces that act on the blade vary with rotor speed. The force in the axial direction is given by the following formula:

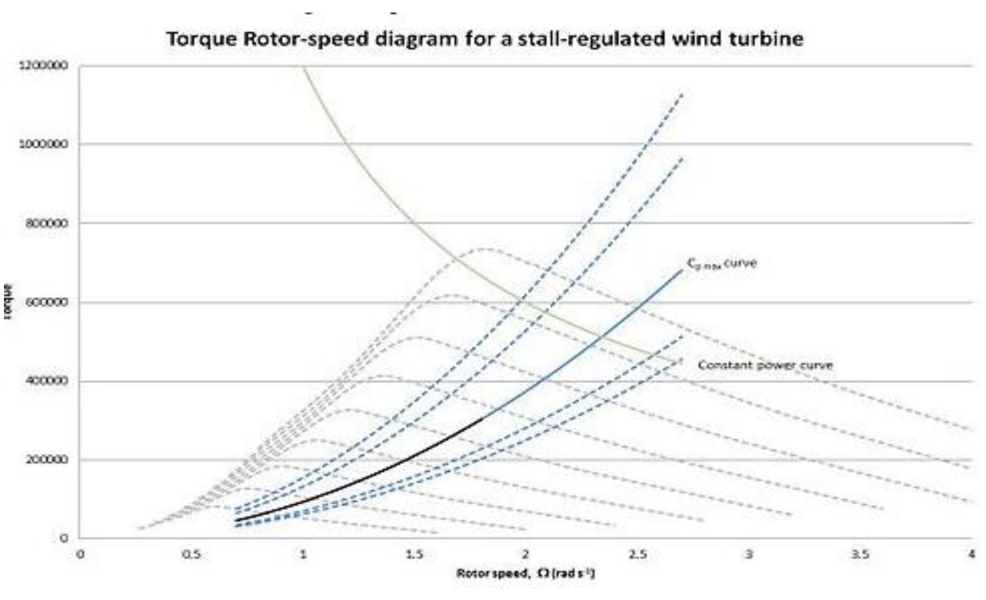
Operating strategies for variable speed

Stall regulated

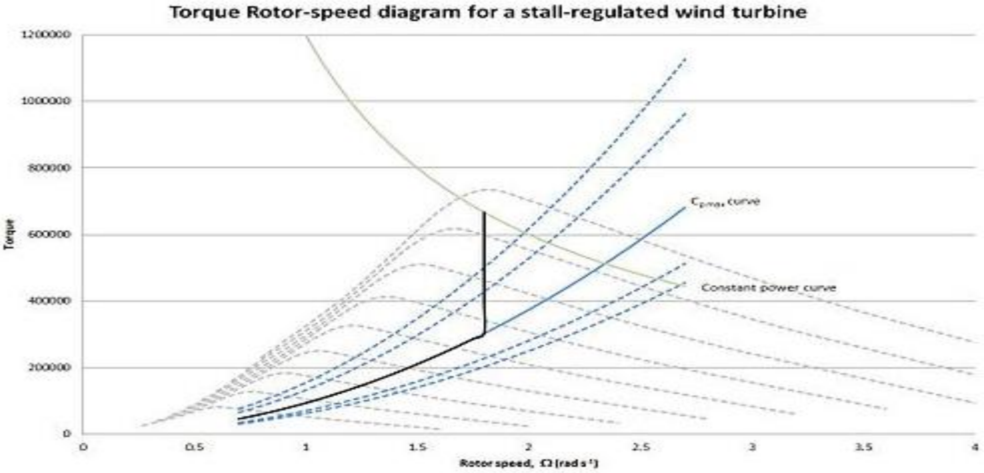
As discussed earlier, a wind turbine would ideally operate at its maximum efficiency for below rated power. Once rated power has been hit, the power is limited. This is for two reasons: ratings on the drivetrain equipment, such as the generator; and second to reduce the loads on the blades. An operating strategy for a wind turbine can thus be divided into a sub-rated-power component, and a rated-power component**.**

Below rated power

Below rated power, the wind turbine will ideally operate in such a way that Cp=C pmax. On a Torque-rotor speed diagram, this looks asfollows:



where the black line represents the initial section of the operating strategy for a variable speed stall-regulated wind turbine. Ideally, we would want to stay on the maximum efficiency curve until rated power is hit. However, as the rotor speed increases, the noise levels increase. To counter this, the rotor speed is not allowed to increase above a certain value. This is illustrated in the figure below:

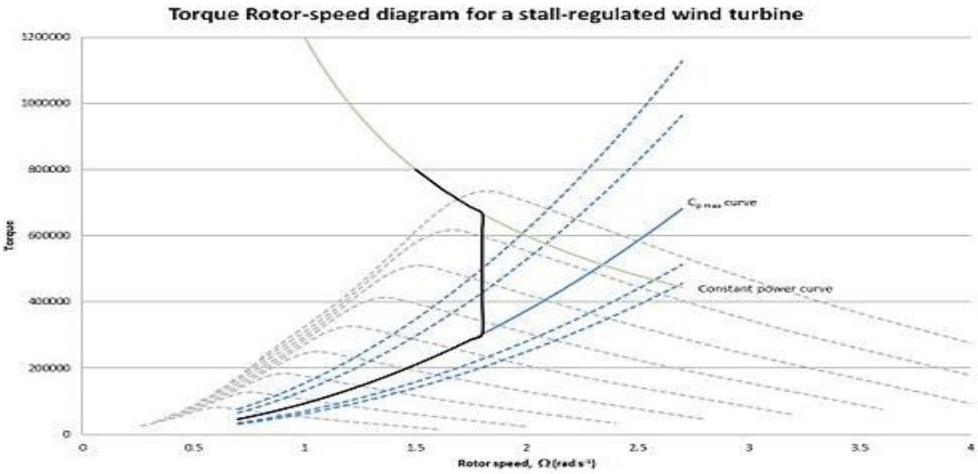


Rated power and above

Once the wind speed has reached a certain level, called rated wind speed, the turbine should not be able to produce any greater levels of power for higher wind speeds. A stall-regulated variable speed wind turbine has no pitching mechanism. However, the rotor speed is variable. The rotor speed can either be increased or decreased by an appropriately designed controller. In reference to the figure illustrated in the blade forces section, it is evident that the angle between the apparent wind speed and the plane of rotation is dependent upon the rotor speed. This angle is termed the angle of attack.

The lift and drag co-efficients for an airfoil are related to the angle of attack. Specifically, for high angles of attack, an airfoil stalls. That is, the drag substantially increases. The lift and drag forces influence the power production of a wind turbine. This can be seen from an analysis of the forces acting on a blade as air interacts with the blade (see the following link). Thus, forcing the airfoil to stall can result in power limiting.

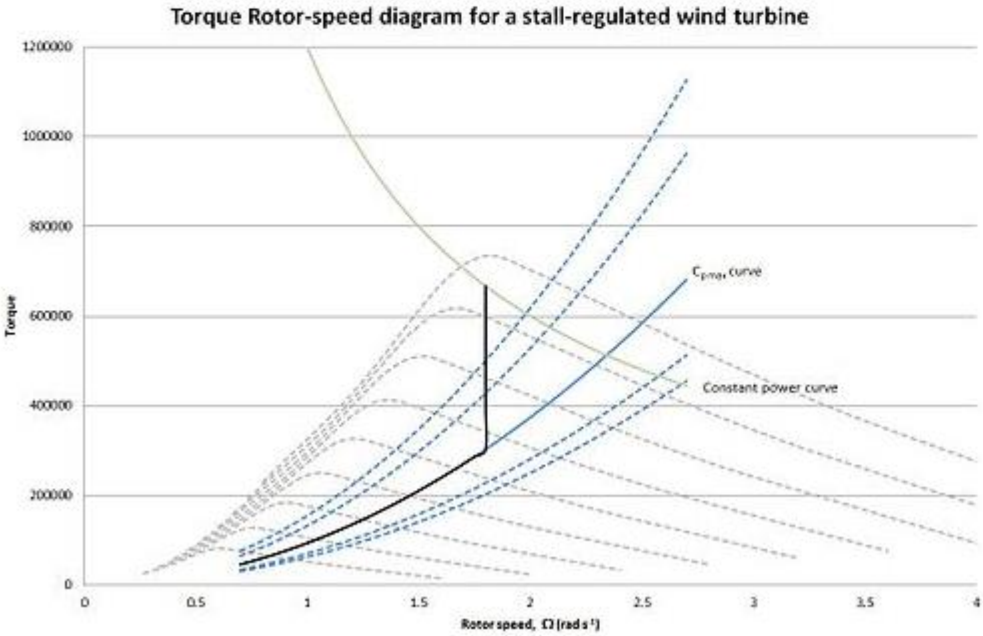
So it can be established that if the angle of attack needs to be increased to limit the power production of the wind turbine, the rotor speed must be reduced. Again, this can be seen from the figure in the blade forces section. It can also be seen from considering the torque-rotor speed diagram. In reference to the above torque-rotor speed diagram, by reducing the rotor speed at high wind speeds, the turbine enters the stall region, thus bringing some limiting to the power output.



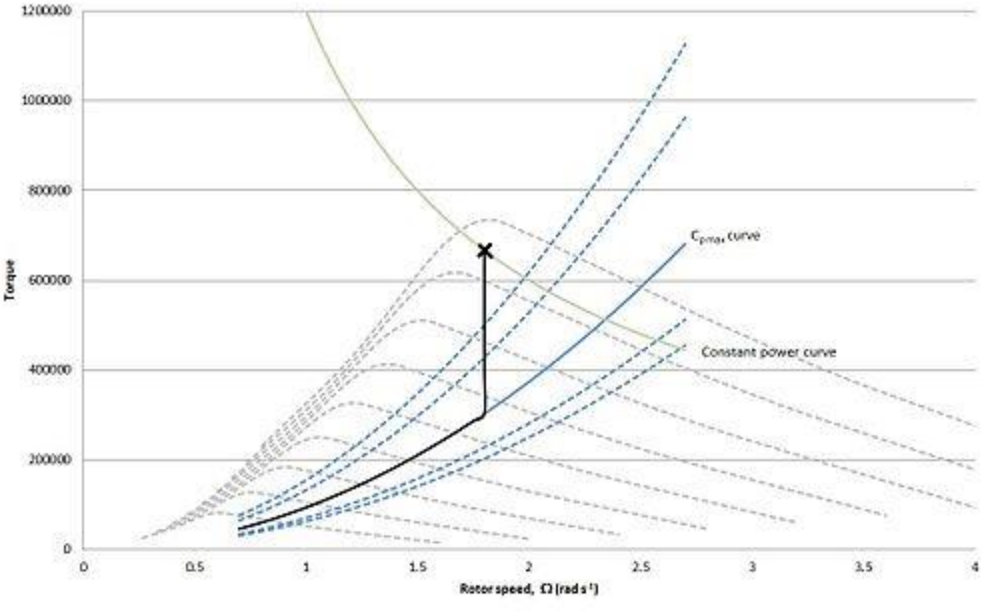
Pitchregulated
Pitch regulation thus allows the wind turbine to actively change the angle of attack of the air on the blades. This is preferred over a stall-regulated wind turbine as it enables far greater control of the power output.

Below rated power

Identical to the stall-regulated variable-speed wind turbine, the initial operating strategy is to operate on the Cpmax curve. However, due to constraints such as noise levels, this is not possible for the full range of sub-rated wind speeds. Below the rated wind speed, the following operating strategy is employed:



Above rated power
Above the rated wind speed, the pitching mechanism is employed. This allows a good level of control over the angle of attack, thus control over the torque. The previous torque rotor-speed diagrams are all plots when the pitch angle beta , is zero. A three dimensional plot can be produced which includes variations in pitch angle.Ultimately, in the 2D plot, above rated wind speed, the turbine will operate at the point marked 'x' on the diagram below.



Gearboxes
A variable speed may or may not have a gearbox, depending on the manufacturer's desires. Wind turbines without gearboxes are called direct-drive wind turbines. An advantage of a gearbox is that generators are typically designed to have the rotor rotating at a high speed within the stator. Direct drive wind turbines do not exhibit this feature. A disadvantage of a gearbox is reliability and failure rates.

Generators
Consider a variable speed wind turbine with a permanent magnet synchronous generator. The generator produces AC electricity. The frequency of the AC voltage generated by the wind turbine is a function of the speed of the rotor within the generator:

$$N = \frac{120f}{P}$$

whereN is the rotor speed, P is the number of poles in the generator, and f is the frequency of the output Voltage. That is, as the wind speed varies, the rotor speed varies, and so the frequency of the Voltage varies. This form of electricity cannot be directly connected to a transmission system. Instead, it must be corrected such that its frequency is constant. For this, power converters are employed, which results in the de-coupling of the wind turbine from the transmission system. As more wind turbines are included in a national power system, the inertia is decreased. This means that the frequency of the transmission system is more strongly affected by the loss of a single generating unit.

Power converters
As already mentioned, the voltage generated by a variable speed wind turbine is non-grid compliant. In order to supply the transmission network with power from these turbines, the signal must be passed through a power converter, which ensures that the frequency of the voltage of the electricity being generated by the wind turbine is the frequency of the transmission system when it is transferred onto the transmission system. Power converters first convert the signal to DC, and then convert the DC signal to an AC signal. Techniques used include pulse width modulation.

Environmental Impacts of Wind Power
Harnessing power from the wind is one of the cleanest and most sustainable ways to generate electricity as it produces no toxic pollution or global warming emissions. Wind is also abundant, inexhaustible, and affordable, which makes it a viable and large-scale alternative to fossil fuels. Despite its vast potential, there are a variety of environmental impacts associated with wind power generation that should be recognized and mitigated.

Land use
The land use impact of wind power facilities varies substantially depending on the site: wind turbines placed in flat areas typically use more land than those located in hilly areas. However, wind turbines do not occupy all of this land; they must be spaced approximately 5 to 10 rotor diameters apart (a rotor diameter is the diameter of the wind turbine blades). Thus, the turbines themselves and the surrounding infrastructure (including roads and transmission lines) occupy a small portion of the total area of a wind facility.

A survey by the National Renewable Energy Laboratory of large wind facilities in the United States found that they use between 30 and 141 acres per megawatt of power output capacity (a typical new utility-scale wind turbine is about 2 megawatts). However, less than 1 acre per megawatt is disturbed permanently and less than 3.5 acres per megawatt are disturbed temporarily during construction. The remainder of the land can be used for a variety of other productive purposes, including livestock grazing, agriculture, highways, and hiking trails. Alternatively, wind facilities can be sited on brownfields (abandoned or underused industrial land) or other commercial and industrial locations, which significantly reduces concerns about land use.

Offshore wind facilities require larger amounts of space because the turbines and blades are bigger than their land-based counterparts. Depending on their location, such offshore installations may compete with a variety of other ocean activities, such as fishing, recreational activities, sand and gravel extraction, oil and gas extraction, navigation, and aquaculture. Employing best practices in planning and siting can help minimize potential land use impacts of offshore and land-based wind projects.

Wildlife and habitat

The impact of wind turbines on wildlife, most notably on birds and bats, has been widely document and studied. A recent National Wind Coordinating Committee (NWCC) review of peer-reviewed research found evidence of bird and bat deaths from collisions with wind turbines and due to changes in air pressure caused by the spinning turbines, as well as from habitat disruption. The NWCC concluded that these impacts are relatively low and do not pose a threat to species populations.

Additionally, research into wildlife behavior and advances in wind turbine technology have helped to reduce bird and bat deaths. For example, wildlife biologists have found that bats are most active when wind speeds are low. Using this information, the Bats and Wind Energy Cooperative concluded that keeping wind turbines motionless during times of low wind speeds could reduce bat deaths by more than half without significantly affecting power production. Other wildlife impacts can be mitigated through better siting of wind turbines. The U.S. Fish and Wildlife Services has played a leadership role in this effort by convening an advisory group including representatives from industry, state and tribal governments, and nonprofit organizations that made comprehensive recommendations on appropriate wind farm siting and best management practices.

Offshore wind turbines can have similar impacts on marine birds, but as with onshore wind turbines, the bird deaths associated with offshore wind are minimal. Wind farms located offshore will also impact fish and other marine wildlife. Some studies suggest that turbines may actually increase fish populations by acting as artificial reefs. The impact will vary from site to site, and therefore proper research and monitoring systems are needed for each offshore wind facility

Public health and community

Sound and visual impact are the two main public health and community concerns associated with operating wind turbines. Most of the sound generated by wind turbines is aerodynamic, caused by the movement of turbine blades through the air. There is also mechanical sound generated by the turbine itself. Overall sound levels depend on turbine design and wind speed.

Some people living close to wind facilities have complained about sound and vibration issues, but industry and government-sponsored studies in Canada and Australia have found that these issues do not adversely impact public health. However, it is important for wind turbine developers to take these community concerns seriously by following “good neighbor” best practices for siting turbines and initiating open dialogue with affected community members. Additionally, technological advances, such as minimizing blade surface imperfections and using sound-absorbent materials can reduce wind turbine noise.Under certain lighting conditions, wind turbines can create an effect known as shadow flicker. This annoyance can be minimized with careful siting, planting trees or installing window awnings, or curtailing wind turbine operations when certain lighting conditions exist.

The Federal Aviation Administration (FAA) requires that large wind turbines, like all structures over 200 feet high, have white or red lights for aviation safety. However, the FAA recently determined that as long as there are no gaps in lighting greater than a half-mile, it is not necessary to light each tower in a multi-turbine wind project. Daytime lighting is unnecessary as long as the turbines are painted white. When it comes to aesthetics, wind turbines can elicit strong reactions. To some people, they are graceful sculptures; to others, they are eyesores that compromise the natural landscape. Whether a community is willing to accept an altered skyline in return for cleaner power should be decided in an open public dialogue.

Water use

There is no water impact associated with the operation of wind turbines. As in all manufacturing processes, some water is used to manufacture steel and cement for wind turbines.

Life-cycle global warming emissions

While there are no global warming emissions associated with operating wind turbines, there are emissions associated with other stages of a wind turbine's life-cycle, including materials production, materials transportation, on-site construction and assembly, operation and maintenance, and decommissioning and dismantlement.Estimates of total global warming emissions depend on a number of factors, including wind speed, percent of time the wind is blowing, and the material composition of the wind turbine. Most estimates of wind turbine life-cycle global warming emissions are between 0.02 and 0.04 pounds of carbon dioxide equivalent per kilowatt-hour. To put this into context, estimates of life-cycle global warming emissions for natural gas generated electricity are between 0.6 and 2 pounds of carbon dioxide equivalent per kilowatt-hour and estimates for coal-generated electricity are 1.4 and 3.6 pounds of carbon dioxide equivalent per kilowatt-hour

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MODULE - II
DESIGN AND OPERATION OF PV SYSTEM

Course Outcomes Mapped To Module II :

Students will be able to:

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

Program Outcomes Mapped To Module II :

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

Mapping Of CO(s) With PO(s) For Module II:

Course Outcomes (COs)	Program Outcomes (POs)											
	1	2	3	4	5	6	7	8	9	10	11	12
CO 4	√	√	√									
CO 5	√	√										
CO 6	√	√										

Introduction:

Renewable energy is generally defined as energy that comes from resources which are naturally replenished on a human timescale such as sunlight, wind, rain, tides, waves and geothermal heat. Renewable energy replaces conventional fuels in four distinct areas: electricity generation, hot water/space heating, motor fuels, and rural(off-grid) energy services. Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and bio fuels and hydrogen derived from renewable resources

How Solar Power Plant works?

Figure: Solar Power Plant

The sun is the source of energy that drives the cycle of life and death on earth. It is also the energy source that gives us warmth and evaporates water and melts snow. The sun is about 150,000,000 km away from the Earth. Due to its immense, but finite size, it has an angular diameter of 0.5 degree (32 minutes), as viewed from Earth.

Sun burns continuously via thermonuclear reactions (fusion). Inside the sun, radioactive processes releases energy and convection transfers solar energy to its exterior surface. Despite the extremely high temperatures needed at the core of the sun, to sustain its thermonuclear reactions, the sun has a black body temperature of 5770 K. Consequently, we receive a relatively constant flux density of energy, defined as the Solar Constant. Its mean value is 1366 W m-2.

The earth receives 1.6 × 1018 units of energy from the Sun annually, which is 20,000 times the requirement of mankind on the earth. Some of the solar energy causes evaporation of water, leading to rains and creation of rivers etc. Some of itis utilized in photosynthesis which is essential for sustenance of life on earth. Man has tried, from time immemorial, to harness this infinite source of energy, but has been able to tap only a negligibly small fraction of this energy.

When light travels from outer space to earth, solar energy is lost because of following reasons:

- Scattering: The rays collide with particles present in atmosphere
- Absorption: Because of water vapor there is absorption
- Cloud cover: The light rays are diffused because of clouds.
- Reflection: When the light rays hit the mountains present on the earth surface there is reflection.
- Climate: Latitude of the location, day (time in the year) also affects the amount of solar energy received by the place

Solar Radiation geometry:

In Solar Radiation geometry the following terms are important:

Horizon is the horizontal plane that extends from the point where the observer is standing, to infinity,straight through space. Since we're only working with relatively short distances (compared to theUniverse), a line extending N-S will be quite sufficient.Altitude (A) is the angle of the sun over the horizon. In this problem, we will be working with the sun at noon, so it will either be over the N or S horizon.

- Zenith (Z) is the angle that the sun is from directly overhead, and it is equal to 90-A. It, too, can be over the S or N horizon, but there is little need to state it.
- Declination (D) is the latitude at which the sun is directly overhead. It is always between 23.5 N and 23.5 S latitude, those occurring on the Solstices.
- Latitude (L) is the location N or S of the equator at which the observer is located. (It is determined by radii from the center of Earth at different angles to the equator. If such an angle is swept along the surface of the planet, it draws a circle.)

Solar radiation data is necessary for calculating cooling load for buildings, prediction of local air temperature and for the estimating power that can be generated from photovoltaic cells. Solar radiation falling on the surface of the earth is measured by instruments called pyranometers. The weather service in most countries has many stations to measure solar radiation using pyranometers. In India pyranometers have been used for a long time.

Generally flat plate collectors are mounted on roofs or sloping walls. In most of these collectors, the absorber element is made of a metal such as galvanised iron, aluminium, copper etc. and the cover is usually of glass of 4 mm thickness. The back of the absorber is insulated with glass wool, asbestos wool or some other insulating material. The casing, enclosing all the components of the collector is either made of wood or some light metal like aluminium. The cost, with such meterials, is rather too high to be acceptable for common use. As the temperatures needed for space heating are rather low, plastics are being considered as potential material for fabrication of various components of the flat, plate collector. This would make solar energy systems comparable with other energy systems.

Solar Concentrators:

Solar concentrators are the collection devices which increase the flux on the absorber surface as compared to the flux impinging on the concentrator surface. Optical concentration is achieved by the use of reflecting refracting elements, positioned to concentrate the incident flux onto a suitable absorber. Due to the apparent motion of the Sun.

The concentrating surface, whether reflecting or refracting will not be in a position to redirect the sun rays onto the absorber, throughout the day if both the concentrator surface, and absorber are stationary. Ideally, the total system consisting of mirrors or lenses and the absorber should follow the Sun’s apparent motion so that the Sun rays are always captured by the absorber. In general, a solar concentrator consists of the following a focusing device. A blackened metallic absorber provided with a transparent cover; and a tracking device for continuously following the Sun. Temperatures as high as 3000°C can be achieved with such devices and they find applications in both photo-thermal and photo-voltaic conversion of solar energy.

The use of solar concentrators has the following advantages:

- Increased energy delivery temperature, facilitating their dynamic match between temperature level and the task. Improved thermal efficiency due to reduced heat loss area.
- Reduced cost due to replacement of large quantities of expensive hardware material for constructing flat plate solar collector systems, by less expensive reflecting and/or refracting element and a smaller absorber tube.
- Increased number of thermal storage options at elevated temperatures, thereby reducing the storage cost. Parameters Characterizing Solar Concentrators
- The aperture area is that plane area through which the incident solar flux is accepted. It is defined by the physical extremities of the concentrator.
- The acceptance angle defines the limit to which the incident ray path may deviate, from the normal drawn to the aperture plane, and still reach the absorber.

The absorber area is the total area that receives the concentrated radiation. It is the area from which useful energy can be removed.Geometrical concentration ratio or the radiation balance concentration ratio is defined as the ratio of the aperture area to the absorber area.The optical efficiency is defined as the ratio of the energy, absorbed by the absorber, to the energy, incident on the aperture.The thermal efficiency is defined as the ratio of the useful energy delivered to the energy incident on the aperture.

Solar concentrators may be classified as point focus or line focus system. Point focus systems have circular symmetry and are generally used when high concentration is required as in the case of solar furnaces and central tower receiver systems. Line focus systems have cylindrical symmetry and generally used when medium concentration is sufficient to provide the desired operating temperature.

Solar Energy Storage and Applications:

Storage of Solar energy in a solar system may:

- Permit solar energy to be captured when insolation is high to be used when the need arises.
- Deliver electric load power demand during times when insolation is below normal or non-existent. Also caters to delivering short power-peaks
- Be located closed to the load
- Improve the reliability of solar thermal and solar PV systems
- Permit a better match between energy input and load demand output

Some of the important storage methods are:

- Mechanical Energy Storage – pumped storage, compressed air storage, flywheel storage
- Chemical Energy Storage – Batteries storage, Hydrogen storage and reversible chemical reactions storage
- Electromagnetic energy storage
- Electrostatic energy storage
- Thermal (heat) energy storage – Sensible heat storage and Latent heat storage
- Biological Storage
- Thermal (heat) energy storage

Energy storage may be in the form of sensible heat of solids or liquid medium, as heat of fusion in chemical systems or as chemical energy of products in the reversible chemical reaction. Mechanical energy could be converted to P.E. and stored in elevated fluidsEnergy can be stored by virtue of latent heat of change of phase of the storage medium. Phase-change materials like Glaubers salt have considerably higher thermal energy storage densities

Applications of Solar Energy:
Three broad categories of possible large scale applications of solar power are:

- The heating and cooling of residential and commercial buildings;
- The chemical and biological conversion of organic material to liquid, solid and gaseous fuels
- Conversion of solar energy to electricity.
- Solar distillation, pumping, solar cooking etc

The use of solar energy for generation of electricity is costly as compared to conventional methods. However, due to scarcity of fuel, solar energy will certainly find a place in planning the national energy resources.

Residential cooling and heating

- A flat plate collector is located on the roof of a house, which collects the solar energy. The cooling water is pumped through the tubes of the solar collector.
- The heat is transferred from the collector to the water and the hot water is stored in a storage tank which may be located at ground level or in the basement of the house. Hot water is then utilized to heat or cool the house by adjusting the automatic valve.
- A separate circuit is there to supply hot water. Thus all the three requirements i.e., space cooling, heating and water heating

Solar PV Cells:

The solar cells operate on the principle of photo electricity i.e., electrons are liberated from the surface of a body when light is incident on it. Backed by semi-conductor technology, it is now possible to utilize the phenomenon of photo-electricity.It is known that if an n-type semi-conductor is brought in contact with a p-type material, a contact potential difference is set-up at the junction (Schottky effect), due to diffusion of electrons. When the p-type material is exposed to light, its electrons get excited, by the photons of light, and pass into the n-type semi-conductor. Thus, an electric current is generated in a closed circuit. The pn junction silicon solar cells have emerged as the most important source of long duration power supply necessary for space vehicles. These cells are actuated by both, direct Sun rays and diffuse light.

The efficiency of silicon solar cells increases with decreasing temperature. In cold weather the decreased luminous flux is compensated for, by higher efficiency. The efficiency of these solar cells varies from 15 to 20%.Although the energy from the Sun is available free of cost, the cost of fabrication and installation of systems, for utilization of solar energy, is often too high to be economically viable. In order to make solar installations economically attractive, plastic materials are being increasingly used for the fabrication of various components of the system.

The efficiency of solar heating/cooling installation depends on the efficiency of collection of solar energy and its transfer to the working fluid (e.g. water, air etc.). There are two main classes of collectors. The flat plate collector is best suited for low and intermediate temperature applications (40°–60°, 80°–120°C) which include water heating for buildings, air heating and small industrial applications like agricultural drying etc. The concentrating collectors are usually employed for power generation and industrial process heating.

Working of Photovoltaic Plant :

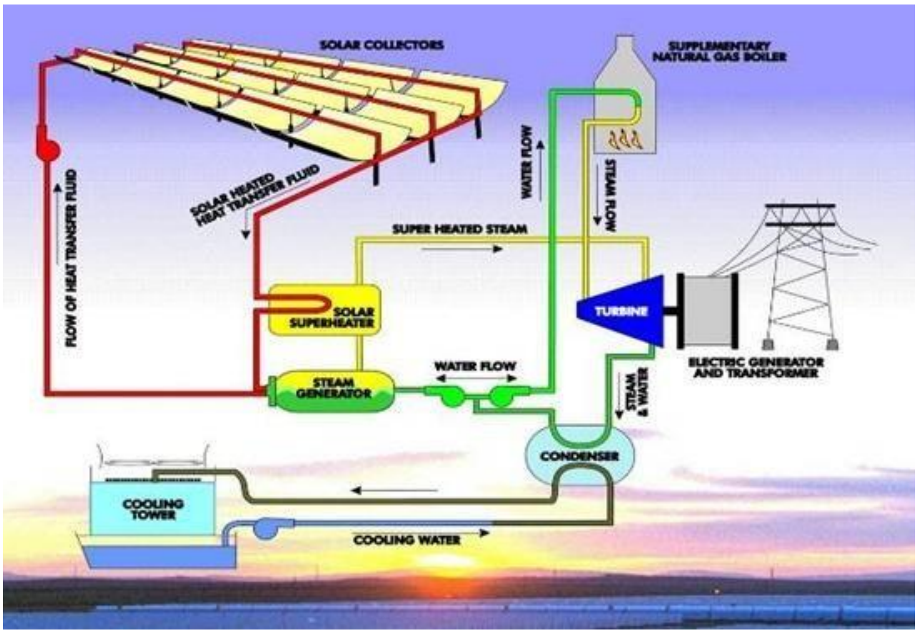


Figure: Photovoltaic Plant

Solar thermal power plant

Solar thermal power plants are electricity generation plants that utilize energy from the Sun to heat a fluid to a high temperature. This fluid then transfers its heat to water, which then becomes superheated steam. This steam is then used to turn turbines in a power plant, and this mechanical energy is converted into electricity by a generator. This type of generation is essentially the same as electricity generation that uses fossil fuels, but instead heats steam using sunlight instead of combustion of fossil fuels. These systems use solar collectors to concentrate the Sun's rays on one point to achieve appropriately high temperatures.
There are two types of systems to collect solar radiation and store it: passive systems and active systems. Solar thermal power plants are considered active systems. These plants are designed to operate using only solar energy, but most plants can use fossil fuel combustion to supplement output when needed.

Types of Plants
Despite the fact that there are several different types of solar thermal power plants, they are all the same in that they utilize mirrors to reflect and concentrate sunlight on a point. At this point the solar energy is collected and converted to heat energy, which creates steam and runs a generator. This creates electricity.

Parabolic Troughs

These troughs, also known as line focus collectors, are composed of a long, parabolic shaped reflector that concentrates incident sunlight on a pipe that runs down the trough. The collectors sometimes utilize a single-axis Solar tracking system to track the Sun across the sky as it moves from east to west to ensure that there is always maximum solar energy incident on the mirrors. The receiver pipe in the center can reach temperatures upward of 400°C as the trough focuses Sun at 30-100 times its normal intensity.

These troughs are lined up in rows on a solar field. A heat transfer fluid is heated as it is run through the pipes in the parabolic trough. This fluid then returns to heat exchangers at a central location where the heat is transferred to water, generating high-pressure superheated steam. This steam then moves a turbine to power a generator and produce electricity. The heat transfer fluid is then cooled and run back through the solar field.

Parabolic Dishes

These are large parabolic dishes that use motors to track the Sun. This ensures that they always receive the highest possible amount of incoming solar radiation that they then concentrate at the focal point of the dish. These dishes can concentrate sunlight much better than parabolic troughs and the fluid run through them can reach temperatures upwards of 750°C.In these systems, a Stirling engine coverts heat to mechanical energy by compressing working fluid when cold and allowing the heated fluid to expand outward in a piston or move through a turbine. A generator then converts this mechanical energy to electricity.

Solar Towers

Solar power towers are large towers that act as a central receiver for solar energy. They stand in the middle of a large array of mirrors that all concentrate sunlight on a point in the tower. These large number of flat, sun tracking mirrors are known as heliostats. In the tower, there is a mounted heat exchanger where the heat exchange fluid is warmed. The heat concentrated to this point can be 1500 times as intense as incident sunlight. The hot fluid is then used to create steam to run a turbine and generator, producing electricity. One drawback with these towers is they must be very large to be economical.

Benefits and Drawbacks

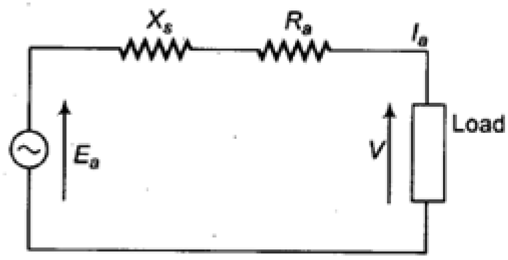
Because these systems can generate steam of such high temperatures, the conversion of heat energy to electricity is more efficient. As well, these plants get around the issue of being unable to efficiently store electricity by being able to store heat instead. The storage of heat is more efficient and cost-effective than storing electricity.

Additionally, these plants can produce dispatch ablebase load energy, which is important as it means these plants produce a reliable amount of energy and can be turned on or up at will, meeting the energy demands of society. In addition to this, solar thermal power plants represent a type of electricity generation technology that is cleaner than generating electricity by using fossil fuels. Thus, these are some of the cleanest options for generating electricity. Despite this, there are still associated environmental effects of these plants as a full life cycle analysis can show all associated carbon dioxide emissions involved in the building of these plants. However, emissions are still much lower than those associated with fossil fuel plants.

Some of the drawbacks include the large amount of land necessary for these plants to operate efficiently. As well, the water demand of these plants can also be seen as an issue, as the production of enough steam requires large volumes of water.A final potential impact of the use of large focusing mirrors is the harmful effect these plants have on birds. Birds that fly in the way of the focused rays of Sun can be incinerated. Some reports of bird deaths at power plants such as these amounts the deaths to about one bird every two minutes.

Synchronous Generators

- Synchronous machines are principally used as alternating current (AC)generators. They supply the electric power used by all sectors of modernsocieties: industrial, commercial, agricultural, and domestic.
- Synchronous generators usually operate together (or in parallel), forming alarge power system supplying electrical energy to the loads or consumers.
- Synchronous generators are built in large units, their rating ranging fromtens to hundreds of megawatts.
- Synchronous generator converts mechanical power to ac electric power. Thesource of mechanical power, the prime mover, may be a diesel engine, asteam turbine, a water turbine, or any similar device.
- For high-speed machines, the prime movers are usually steam turbinesemploying fossil or nuclear energy resources.
- Low-speed machines are often driven by hydro-turbines that employ waterpower for generation.
- Smaller synchronous machines are sometimes used for private generationand as standby units, with diesel engines or gas turbines as prime movers.



Equivalent circuit of a synchronous generator

Excitation System of a Synchronous Machine

The word Excitation means the production of flux by passing current in the field winding.The arrangement or the system used for the excitation of the synchronous machine is known as Excitation System. To excite the field winding of the rotor of the synchronous machine, direct current is required. Direct current is supplied to the rotor field of the small machine by a DC generator called Exciter. A small DC generator called Pilot Generator, supplies the current to the Exciter.The Exciter and the Pilot Exciter both are mounted on the main shaft of the Synchronous generator or motor. The DC output of the main Exciter is given to the field winding of the synchronous machine through brushes and slip rings. The pilot exciter is excluded in smaller machines.

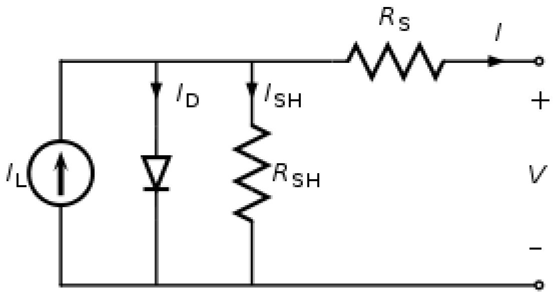
For medium size machines, AC Exciters are used in place of DC Exciter. AC Exciters are three phase AC generators. The output of an AC Exciter is rectified and supplied through the brushes, and the slip rings to the rotor winding of the synchronous machine.

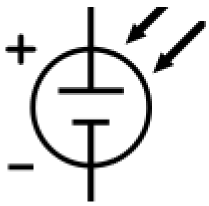
For large synchronous generators having few hundred megawatt ratings, the Excitation System requirement becomes very large. The problem of conveying such a large amount of power through the high-speed sliding contacts becomes formidable.

Presently, the large synchronous machines are using Brushless Excitation System. A Brushless Exciter is a small direct coupled AC generator with its field circuit on the stator and the armature circuit on the rotor. The three phase output of the AC exciter generator is rectified by solid state rectifiers. The rectified output is connected directly to the field winding, thus eliminating the use of brushes and slip rings.

A Brushless excitation system requires less maintenance due to the absence of brushes and slip rings. The power loss is also reduced. The DC required for the field of the exciter itself is sometimes provided by a small pilot exciter. A pilot exciter is a small AC generator with a permanent magnet mounted on the rotor shaft and the three phase winding on the stator. It provides the field current of the exciter. The exciter supplies the field current of the main machine. Thus, the use of a pilot exciter makes the excitation of the main generator completely independent of external supplies.

Equivalent circuit of a solar cell





To understand the electronic behavior of a solar cell, it is useful to create a model which is electrically equivalent, and is based on discrete electrical components whose behavior is well known. An ideal solar cell may be modelled by a
current source in parallel with a diode; in practice no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model. The resulting equivalent circuit of a solar cell is shown on the left. Also shown, on the right, is the schematic representation of a solar cell for use in circuit diagrams.
Characteristic equation
From the equivalent circuit it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor:
$I = I_L – I_D - I_{SH}$
I = output current
I_L = photo generated current
I_D= diode current
I_{SH} = shunt current

The current through these elements is governed by the voltage across them:
$V_j = V + IR_s$

Where

V_j = voltage across both diode and resistor R_{SH}

I = output current

R_S = series resistance

By the Shockley diode equation, the current diverted through the diode is:

$I_D = I_0\{\exp[\frac{qvj}{nKT}] - 1\}$

Where I_0 = reverse saturation current

n = diode ideality factor

q = elementary charge

k = Boltzmann's constant

T = Absolute temperature

By Ohm's law, the current diverted through the shunt resistor is:

$I_{SH} = Vj/R_{SH}$

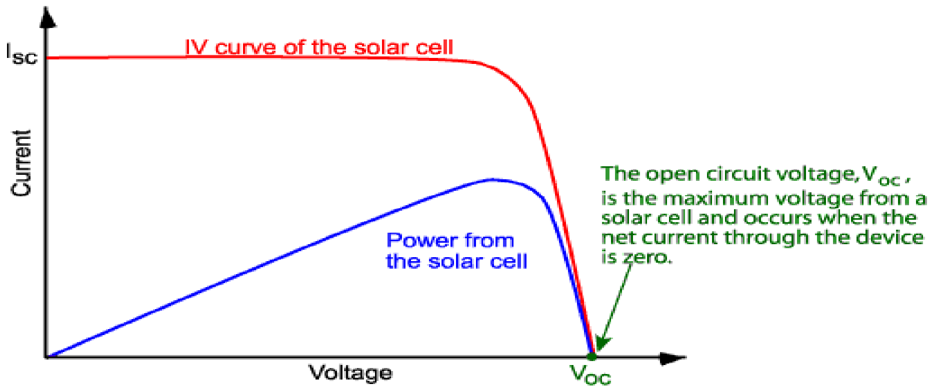
Where R_{SH} is a shunt resistance

Substituting these into the first equation produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

$I = I_L - I_0\{\exp[\frac{q(V+IRs)}{nKT}] - 1\} - \frac{V+IR_S}{R_{SH}}$

Open-Circuit Voltage

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



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

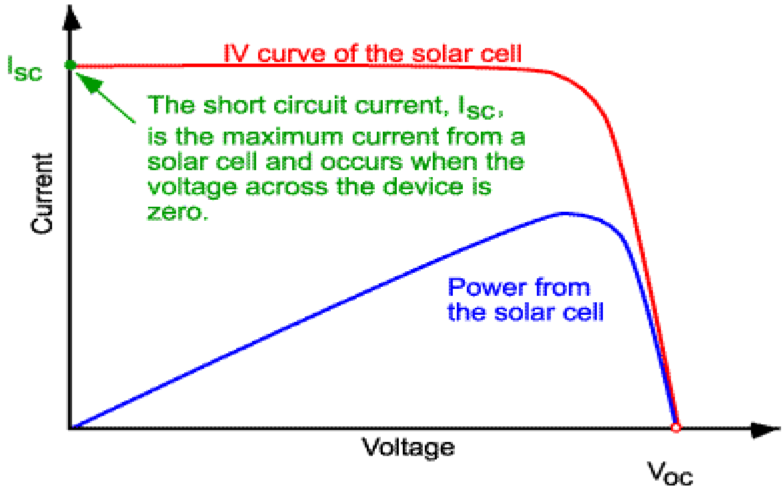
An equation for Voc is found by setting the net current equal to zero in the solar cell equation to give:

$$V_{OC} = \frac{nKT}{q}\ln\left(\frac{IL}{I0} + 1\right)$$

A casual inspection of the above equation might indicate that V_{OC} goes up linearly with temperature. However, this is not the case as I_0 increases rapidly with temperature primarily due to changes in the intrinsic carrier concentration n_i. The effect of temperature is complicated and varies with cell technology. V_{OC} decreases with temperature. If temperature changes, I_0 also changes.

Short-Circuit Current

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as I_{SC}, the short-circuit current is shown on the IV curve below.



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

The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

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

- the area of the solar cell. To remove the dependence of the solar cell area, it is more common to list the short-circuit current density (Jsc in mA/cm2) rather than the short-circuit current;
- the number of photons (i.e., the power of the incident light source). Isc from a solar cell is directly dependant on the light intensity as discussed in Effect of Light Intensity;
- the spectrum of the incident light. For most solar cell measurement, the spectrum is standardised to the AM1.5 spectrum;
- the optical properties (absorption and reflection) of the solar cell (discussed in Optical Losses); and
- the collection probability of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base.

When comparing solar cells of the same material type, the most critical material parameter is the diffusion length and surface passivation. In a cell with perfectly passivated surface and uniform generation, the equation for the short-circuit current can be approximated as:

$$I_{SC} = qG(L_n+L_p)$$

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

Silicon solar cells under an AM1.5 spectrum have a maximum possible current of 46 mA/cm2. Laboratory devices have measured short-circuit currents of over 42 mA/cm2, and commercial solar cell have short-circuit currents between about 28 mA/cm2 and 35 mA/cm2.

IV Curve

The IV curve of a solar cell is the superposition of the IV curve of the solar cell diode in the dark with the light-generated current.1 The light has the effect of shifting the IV curve down into the fourth quadrant where power can be extracted from the diode. Illuminating a cell adds to the normal "dark" currents in the diode so that the diode law becomes:

$$I = I_0\{\exp[\frac{qv}{nKT}] - 1\} - I_L$$

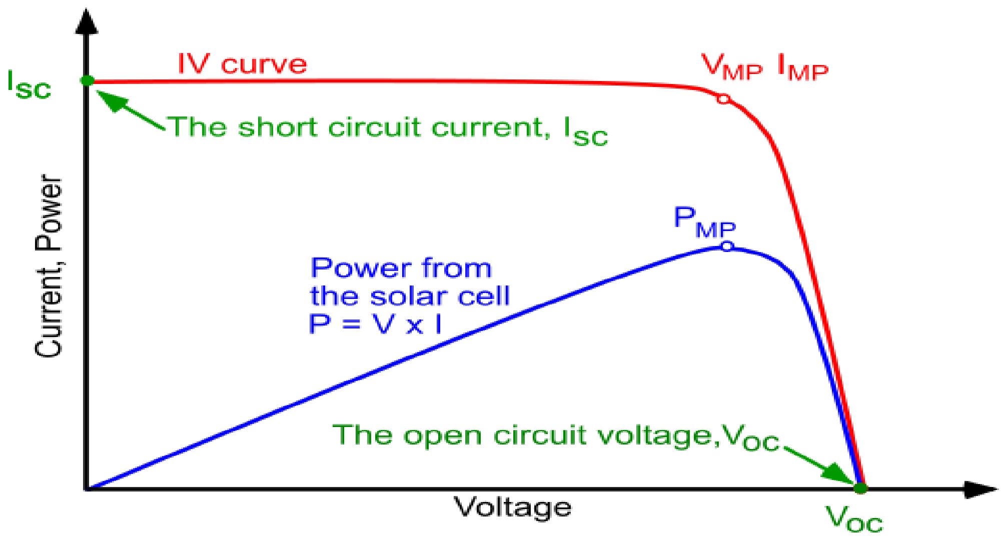
where I_L = light generated current.
The equation for the IV curve in the first quadrant is:

$$I = I_L - I_0\{\exp[\frac{qv}{nKT}] - 1\}$$

The -1 term in the above equation can usually be neglected. The exponential term is usually >> 1 except for voltages below 100 mV. Further, at low voltages, the light generated current I_L dominates the I_0 (...) term so the -1 term is not needed under illumination.

$$I = I_L - I_0\{\exp[\frac{qv}{nKT}]\}$$

Plotting the above equation gives the IV curve below with the relevant points on the curve labeled and discussed in more detail on the following pages. The power curve has aa maximum denoted as P_{MP} where the solar cell should be operated to give the maximum power output. It is also denoted as P_{MAX} or maximum power point (MPP) and occurs at a voltage of V_{MP} and a current of I_{MP}.



Current voltage (IV) cure of a solar cell. To get the maximum power output of a solar cell it needs to operate at the maximum power point, P_{MP}.

Solar power plant generate in a day

Depending on the region and its DNI (a measure of amount of sunlight available), a 1 MW solar power plant can generate between 3-4.5 MWh of electricity a day, or 1100-1600 MWh of electricity a year. This equates to 1.1-1.6 million units of electricity a year, per MW (recall that 1 MWh equals 1000 kWh, and a kWh is the unit of electricity). Why does a 1 MW solar power plant not generate 24 MWh of electricity a day? This is because 1 MW is the rated capacity that is applicable only for good sunshine hours. However, sun is available only between 7 AM and 7 PM, and even during this period, peak sunshine is available only for 2-3 hours. As a result, what a 1 MW if solar panels can produce during a day is much less than 24 MWh.

TRANSIENT STABILITY

Transient stability is the ability of the power system to maintainsynchronism whensubjected to a severe transient disturbance.It is primarily associated with parallel operation of the machines in the system, and in particularthe synchronous generators. A synchronous generator loses stability when itfalls out of step ,or slips, with respect to the rest of the ac network; what happens in such a case is that therotor of the synchronous generator advances beyond a certaincritical angle at which themagnetic coupling between the rotor (and hence the turbine / prime mover) and the statorfails. The rotor, no longer held in synchronism with the rotating field created by the statorcurrents, rotates relative to this field and pole slipping occurs. Each time the poles traversethe angular region where stability obtains, synchronizing forces attempt to pull the rotor backinto step.Large synchronous machines falling out of step in this manner cause violent fluctuations in the neighboring system voltages as well as violent groaning in the boilers feeding their turbines. Amachine or group of machines that has fallen out of step must quickly be brought back intostep or disconnected from the system.From the theory of the synchronous machine we have already seen that under steady stateconditions the synchronizing power between the rotor and stator reaches zero when the rotorangle reaches 90 degrees (ie. Thesteady-state stability limit). However, as we shall see,under transient conditions this angle may temporarily exceed 90 degrees without loss ofstability (synchronism). This is an important difference between steady state stability andtransient stability of synchronous machines (and power systems).Thetransient stability limit refers to the maximum possible flow of power past a point thatwill allow stability to be maintained following a sudden (generally large) disturbance. As weshall see, the transient stability limit is lower than the steady state stability limit and is thereforemore important. Another extremely important aspect of transient stability is that it involves large excursions inthe system variables and hence the non-linarites of the system have a considerable influence.The characteristics of a non-linear system are different at each different operating point and foreach different disturbance and so transient stability by its very nature is analyzed on acontingency basis . For example, even for a given steady state operating point, the transient stability limit varies with thetype, durationand location of disturbances occurring in thetransmission system. Since it is impossible to examine (and make a stability judgment on)every possible contingency, a good knowledge of the system is vital to ensure stability isassessed for allcredible contingencies.

MODULE-III
POWER CONDITIONING SCHEMES FOR SOLAR ENERGY SYSTEMS

Course Outcomes Mapped To Module III :

Students will be able to:

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

Program Outcomes Mapped To Module III :

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

Mapping Of CO(s) With PO(s) For Module III:

Course Outcomes (COs)	Program Outcomes (POs)											
	1	2	3	4	5	6	7	8	9	10	11	12
CO 5	√	√										
CO 6	√	√										
CO 7	√	√	√									

Switching devices for solar energy conversion:

A typical output voltage of PV panels can be on the order of 30 V, and it is too low for being converted to AC and fed to the grid. Therefore DC/DC conversion is often a necessary step before the DC current from the PV system is supplied to the inverter. Most of power conditioning units includes some type of DC/DC converter. Direct current converter transforms the DC voltage V1 to DC voltage V2 via adjusting the current (I):

$$V_1I_1 = V_2I_2$$

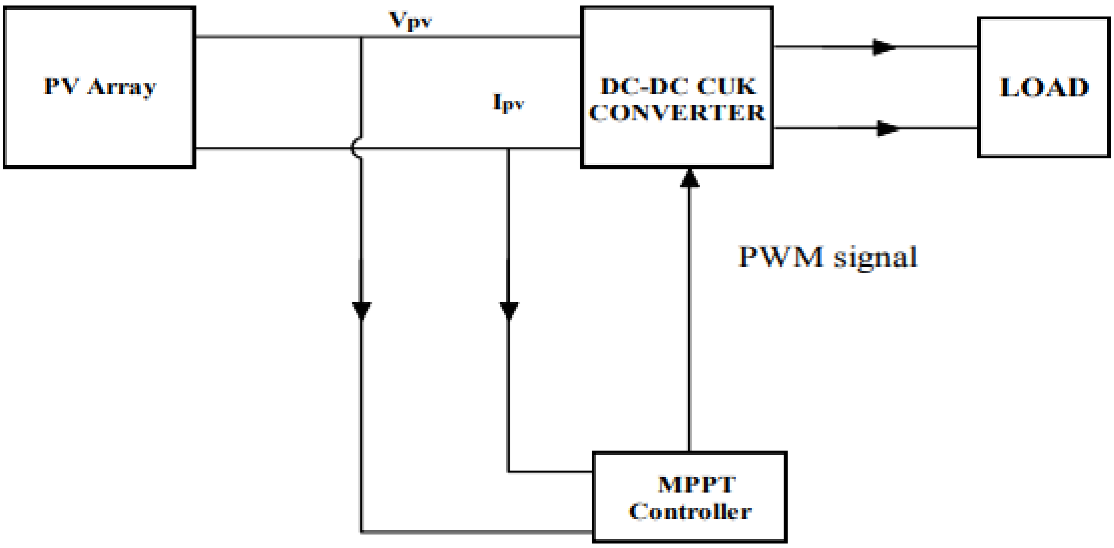
This is an ideal case, when input power is equal to the output power. In reality, there are always conversion losses, which lead to typical efficiencies in the range 90-95%.

DC/DC conversion allows keeping the voltage on the PV and voltage on the load separately controlled. There two main types of DC/DC converters depending on the direction of voltage change: (1) boost converters transform smaller voltage to higher voltage and (2) buck converters transform higher voltage to lower voltage.

OPERATION AND DESIGN ANALYSIS OF DC- DC CONVERTERS

In a PV module directly coupled to a load, the MPP changes as the module temperature and the solar irradiation change. This leads to mismatching of maximum power tracking and hence results in oversizing of the PV array and thus increases the overall system cost. MPPT controller can be solution to the problem. The MPPT maintains the PV module operating point at the MPP. The three basic components in MPPT design as shown in Figure are: a switchmode DC-DC converter, a control circuit, and tracking algorithm. The heart ofthe MPPT hardware is a DC-DC converter. MPPT uses the converter for regulating the input voltage at the MPP and to provide load matching for themaximum power transfer.

During load variations there is only one point at which the PV module provides its MPP. This point is when RL equal to load resistance at MPP (Ropt) RL=Ropt. But it is very difficult to select a fixed load which matches this value, and even if this is done, this point itself changes under changed climatic conditions. On the other hand, when a DC-DC converter is connected between the PV module and the load, the operating point depends on the impedance seen by the module (Ri), which depends on two parameters: RL and duty cycle D.



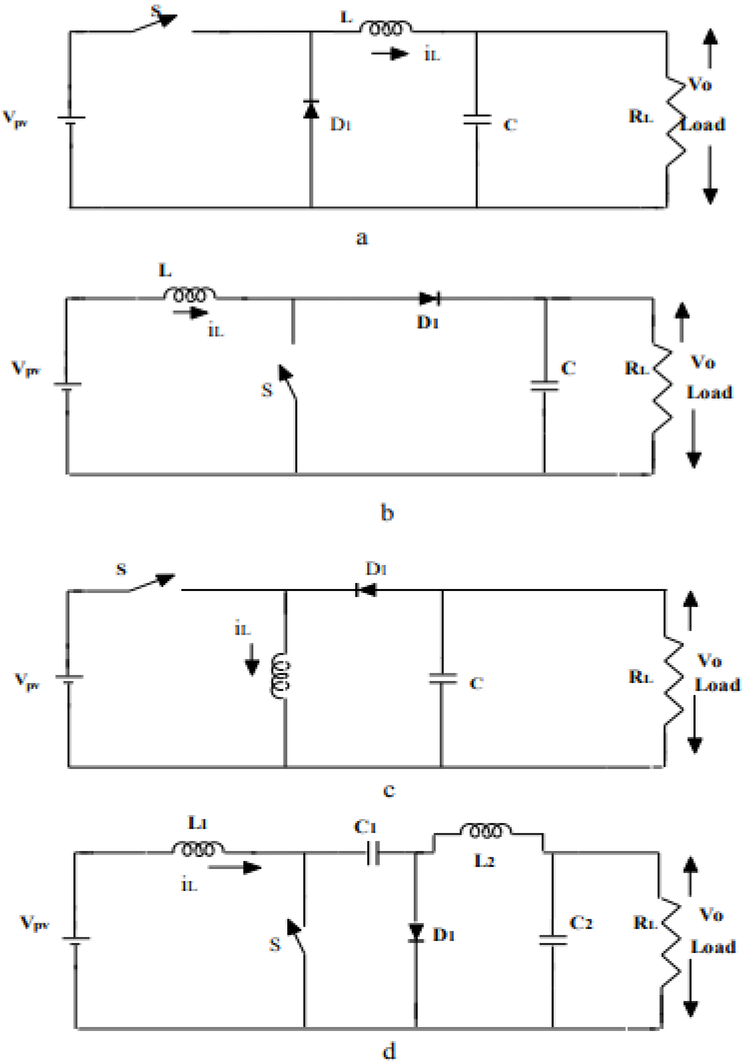
Thus under different loads, the duty cycle can be adjusted to change Ri to match Ropt at any atmospheric conditions. By changing the duty cycle of the PWM control signal, the load impedance as seen by the source varies and matches the point of the peak power of the source so as to transfer the maximum power to load. In this section, theoretical and practical proof for selecting the optimal DC-DC converter as interface between PV array and load is discussed.

Basic DC-DC Converter Topologies
Three basic DC- DC converter topologies are used in PV systems:
Step down (buck), step up (boost) and step down and up (buck boost and Cuk)converters. The performance of a DC-DC converter topology can be described the following parameters:
(a) Voltage gain (AV),
(b) Current gain (Ai),
(c) Input impedance (Ri),
(d) Boundary filter inductance (Lb), and
(e) Minimum filter capacitance (Cmin).

The converter may operate in two distinct modes of operation namely the continuous conduction mode (CCM) or the discontinuous conduction mode (DCM). CCM is the operational mode, where the current intensity that circulates through the inductance of the converter is not cancelled out at any interval of the commutation period T. DCM is the operational mode where the current intensity that circulates through the inductance of the converter is cancelled out during an interval of the commutation period T.
CCM is preferred for high efficiency and good utilization of semiconductor switches and passive components. The DCM may be used in applications with special control requirements. The inductance value (Lb) is the minimum inductance value to guarantee that the converter is working in the CCM. The capacitance Cmin is the minimum capacitance value required to reduce the ripple voltage to a given specified value. The above parameters can be calculated using the relationships in Table

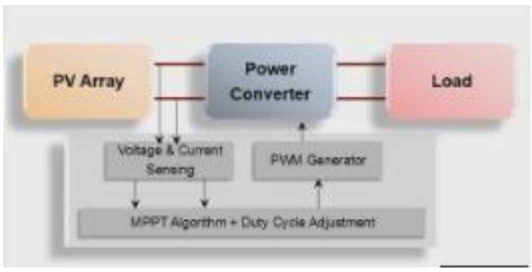
Performance Parameters	Buck	Boost	Buck Boost	Cuk
A_v	D	$\frac{1}{(1-D)}$	$-\frac{1}{(1-D)}$	$-\frac{D}{(1-D)}$
A_i	$\frac{1}{D}$	$(1-D)$	$-\frac{(1-D)}{D}$	$-\frac{(1-D)}{D}$
R_i	$\frac{R_L}{D^2}$	$(1-D)^2 R_L$	$\frac{(1-D)^2}{D^2} R_L$	$R_{i-CCM} = \frac{(1-D)^2}{D^2} R_L$ $R_{i-DCM} = \frac{kR_L}{D^2}$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

Now the effects of impedance, gain, climatic conditions and design analysis on working of various DC-DC converter topologies are discussed.



DC-DC converters a. Buck b.Boost c. Buck - Boost d.Cuk

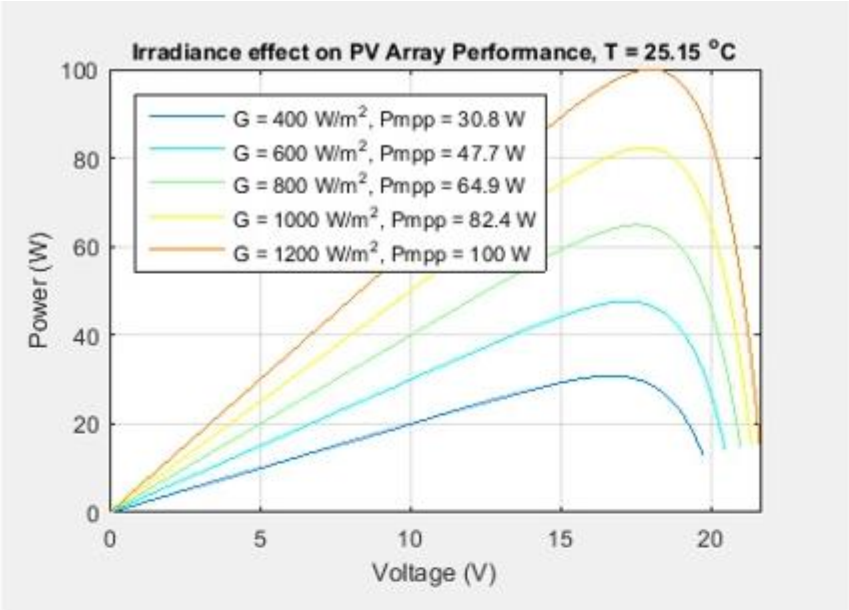
MPPT Algorithm



Maximum power point tracking (MPPT) is an algorithm implemented in photovoltaic (PV) inverters to continuously adjust the impedance seen by the solar array to keep the PV system operating at, or close to, the peak power point of the PV panel under varying conditions, like changing solar irradiance, temperature, and load.

Engineers developing solar inverters implement MPPT algorithms to maximize the power generated by PV systems. The algorithms control the voltage to ensure that the system operates at "maximum power point" (or peak voltage) on the power voltage curve, as shown below.

MPPT algorithms are typically used in the controller designs for PV systems. The algorithms account for factors such as variable irradiance (sunlight) and temperature to ensure that the PV system generates maximum power at all times.

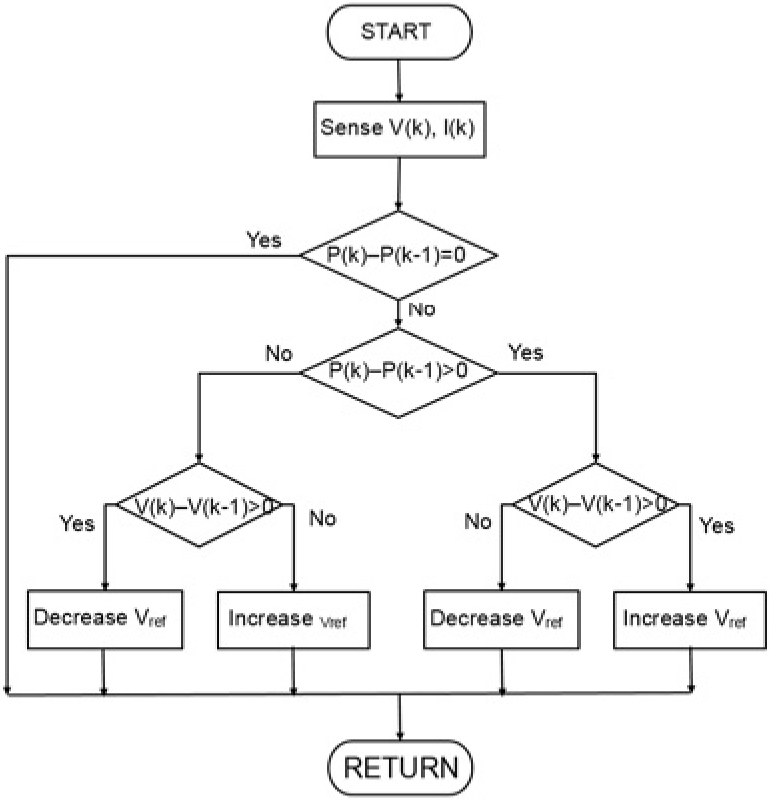


Power voltage curve with I-V and P-V characteristics of a photovoltaic system.

The three most common MPPT algorithms are:

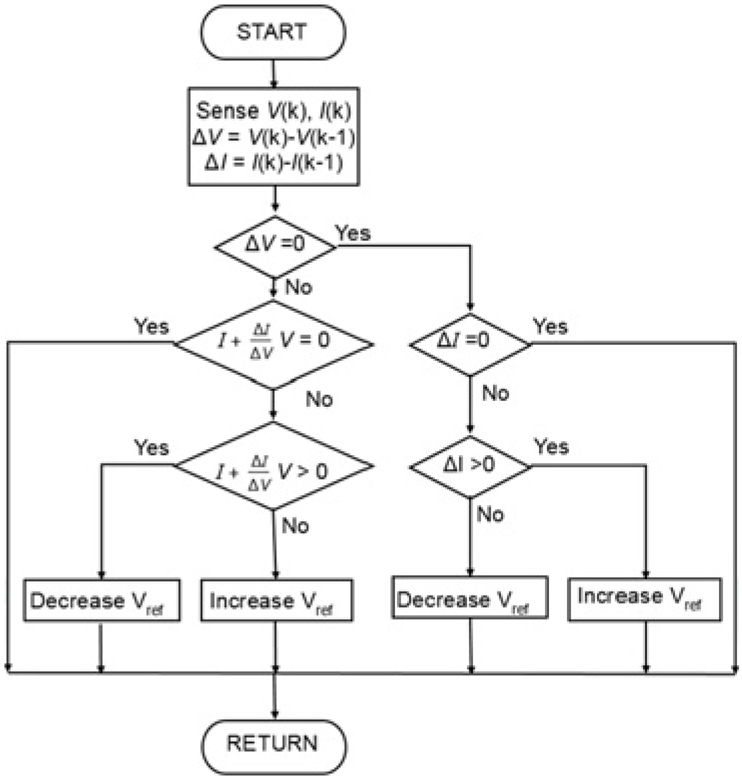
Perturbation and observation (P&O):

This algorithm perturbs the operating voltage to ensure maximum power. While there are several advanced and more optimized variants of this algorithm, a basic P&O MPPT algorithm is shown below.



Incremental conductance:

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



Incremental conductance algorithm.

Fractional open-circuit voltage:

This algorithm is based on the principle that the maximum power point voltage is always a constant fraction of the open circuit voltage. The open circuit voltage of the cells in the photovoltaic array is measured and used as in input to the controller.

MATLAB and Simulink can be used as platforms to implement these algorithms.

AC Power conditioner

A power conditioner (also known as a line conditioner or power line conditioner) is a device intended to improve the quality of the power that is delivered to electrical load equipment. The term most often refers to a device that acts in one or more ways to deliver a voltage of the proper level and characteristics to enable load equipment to function properly. In some uses, power conditioner refers to a voltage regulator with at least one other function to improve power quality (e.g. power factor correction, noise suppression, transient impulse protection, etc.)

The terms "power conditioning" and "power conditioner" can be misleading, as the word "power" here refers to the electricity generally rather than the more technical electric power.

Conditioners specifically work to smooth the sinusoidal A.C. wave form and maintain a constant voltage over varying loads.

An AC power conditioner is the typical power conditioner that provides "clean" AC power to sensitive electrical equipment. Usually this is used for home or office applications and has up to 10 or more receptacles or outlets and commonly provides surge protection as well as noise filtering.

Power line conditioners take in power and modify it based on the requirements of the machinery to which they are connected. Attributes to be conditioned are measured with various devices, such as, Phasor measurement units. Voltage spikes are most common during electrical storms or malfunctions in the main power lines. The surge protector stops the flow of electricity from reaching a machine by shutting off the power source.

The term "Power Conditioning" has been difficult to define historically. However, with the advances in power technology and recognition by IEEE, NEMA, and other standards organizations, a new actual engineering definition has now been developed and accepted to provide an accurate depiction of this definition.

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

A good quality power conditioner is designed with internal filter banks to isolate the individual power outlets or receptacles on the power conditioner.[citation needed] This eliminates interference or "cross-talk" between components. For example, if the application will be a home theater system, the noise suppression rating listed in the technical specifications of the power conditioner will be very important.[citation needed] This rating is expressed in decibels (db). The higher the db rating, the better the noise suppression.

Active power filters (APF) are filters which can perform the job of harmonic elimination. Active power filters can be used to filter out harmonics in the power system which are significantly below the switching frequency of the filter. The active power filters are used to filter out both higher and lower order harmonics in the power system.

The main difference between active power filters and passive power filters is that APFs mitigate harmonics by injecting active power with the same frequency but with reverse phase to cancel that harmonic, where passive power filters use combinations of resistors (R), inductors (L) and capacitors (C) and does not require an external power source or active components such as transistors. This difference makes it possible for APFs to mitigate a wide range of harmonics.

The power conditioner will also have a "joule" rating. A joule is a measurement of energy or heat required to sustain one watt for one second, known as a watt second. Since electrical surges are momentary spikes, the joule rating indicates how much electrical energy the suppressor can absorb at once before becoming damaged itself. The higher the joule rating, the greater the protection.
Power conditioners vary in function and size, generally according to their use. Some power conditioners provide minimal voltage regulation while others protect against six or more power quality problems. Units may be small enough to mount on a printed circuit board or large enough to protect an entire factory.

Small power conditioners are rated in volt-amperes (V·A) while larger units are rated in kilovolt-amperes (kV·A).

Ideally electric power would be supplied as a sine wave with the amplitude and frequency given by national standards (in the case of mains) or system specifications (in the case of a power feed not directly attached to the mains) with an impedance of zero ohms at all frequencies.

No real life power feed will ever meet this ideal. Deviations may include:

Variations in the peak or RMS voltage are both important to different types of equipment.
When the RMS voltage exceeds the nominal voltage by 10 to 80% for 0.5 cycle to 1 minute, the event is called a "swell".
A "dip" (in British English) or a "sag" (in American English – the two terms are equivalent) is the opposite situation: the RMS voltage is below the nominal voltage by 10 to 90% for 0.5 cycle to 1 minute.
Random or repetitive variations in the RMS voltage between 90 and 110% of nominal can produce a flicker in lighting equipment. A precise definition of such voltage fluctuations that produce flicker has been subject to ongoing debate in more than one scientific community for many years.
Abrupt, very brief increases in voltage, called "spikes", "impulses", or "surges", generally caused by large inductive loads being turned off, or more severely by lightning.

"Undervoltage" occurs when the nominal voltage drops below 90% for more than 1 minute. The term "brownout" in common usage has no formal definition but is commonly used to describe a reduction in system voltage by the utility or system operator to decrease demand or to increase system operating margins.
"Overvoltage" occurs when the nominal voltage rises above 110% for more than 1 minute.
Variations in the frequency
Variations in the wave shape – usually described as harmonics
Nonzero low-frequency impedance (when a load draws more power, the voltage drops)
Nonzero high-frequency impedance (when a load demands a large amount of current, then stops demanding it suddenly, there will be a dip or spike in the voltage due to the inductances in the power supply line)

Synchronization Between Solar Panel & AC Grid

SOFTWARE AND EQUIPMENTS USED
A solar panel (also solar module, photovoltaic module or photovoltaic panel) is a packaged, connected assembly of photovoltaic cells. The solar panel can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications. Each panel is rated by its DC output power under standard test conditions, and typically ranges from 100 to 320 watts.
Solar panels use light energy (photons) from the sun to generate electricity through the photovoltaic effect. The majority of modules use wafer-based crystalline silicon cells or thin-film cells based on cadmium telluride or silicon. The structural (load carrying) member of a module can either be the top layer or the back layer. Cells must also be protected from mechanical damage and moisture. Most solar panels are rigid, but semi-flexible ones are available, based on thin-film cells.

Labview is a highly productive development environment for creating custom applications that interact with real-world data or signals in fields such as science and engineering. Here, we are using 9.0 version of Labview. Labview itself is a software development environment that contains numerous components, several of which are required for any type of test, measurement, or control application. Each component is designed in some way to save you time or otherwise make you more productive by eliminating unnecessary details or making difficult operations easier. Labview programs are called virtual instruments, or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes and multimeters. In Labview, we build a user interface, or front panel, with controls and indicators. Controls are knobs, push buttons, dials, and other input mechanisms. Indicators are graphs, LEDs, and other output displays. After you build the user interface, you add code using VIs and structures to control the front panel objects. The block diagram contains this code. Labview is designed to help us solve technical challenges that we face daily. Regardless of what industry we are in, Labview has built in functions for common tasks such as data acquisition and analysis, to more specialized functions for applications such as control design,simulation, or RF design. Regardless of our programming experience Labview has thousands of built-in analysis functions, and a wide array of toolkits and modules that offer specific functionality in areas such as real-time control, RF design, SCADA application development, motion control and machine vision, to name just a few. We can use Labview to quickly configure and use almost any measurement device, from stand-alone instruments to USB data acquisition devices, motion controllers, image acquisition systems, and programmable logic controllers (PLCs). Larger applications are made by adding lower level VIs to a main VI. VIs that are part of another application are referred to as "sub VIs. For example, we might create several VIs that perform different signal analysis and then use them as function blocks in your overall application.

Data acquisition is the process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer. Data acquisition systems (abbreviated with the acronym DAS or DAQ) typically convert analog waveforms into digital values for processing. DAQ hardware is what usually interfaces between the signal and a PC. A DAQ card, or a data acquisitions card, is used to transfer data into a computer. This method allows for seamless transfer of input and output data through either digital or analog signals or channels. DAQ cards operate by utilizing both DAQ hardware and software.

Harmonic EliminationTechniques

In the smart grid system, lots of electronics devices including a variety of converters such as the thyristor and static power converters, which acts also as nonlinear load, thereby introduces current harmonics that eventually affect the quality of the power delivered to the consumer. To mitigate this and provide the end user and connected appliances high quality generated energy some harmonic elimination or reduction techniques are applied, such as the following;

Filters

The conventional method of reducing harmonics in power systems is the use ofpassive filters, active filters, filters in shunt orientation and even hybrid filter. Severalresearchefficient method for reducing harmonic content in both the current and voltage. This harmonic reduction technique according to the researchers, is cheaper ers have reported the use of a filter as the best means of harmonic mitigationin power systems. An efficient method for reducing harmonic content in both the current and voltage. This harmonic reduction technique according to the researchers, is cheaper compared to the use of active filter and easy to implement. The most used passive filter in harmonic mitigation is that which consist of tuned series inductive-capacitive (LC) circuit.Also, the use of passive filter, causes a situation which results in resonance and the very large passive filters have to be use to mitigate harmonic effectively. The researcher proposed the utilization of three passive filters, a high pass filter to mitigate higher order harmonic contents and two single-tuned filters that are tuned at the frequencies of the 11th and 13th order Harmonic technique that applies the six pulse multiplication converter in single-tuned shunt configuration passive filters to reduce power losses, increase power systems general efficiency.

The authors eliminated the 3rd order harmonic which is quite a dominant harmonic resulting in significant power quality loss as well as the 5th and 7th order current harmonics. Again as in most cases, when an applied voltage in pure sine wave or sinusoidal, the nonlinear loads will continuously draw a non-sinusoidal current, due to the nonlinear load varying impedance, thus polluting the system with harmonics and distorting the voltage. The researchers proposed an experimentallyvalidated active power filter that can be utilized not just for eliminating harmonics inpower systems but also to improve power factor issues as well as balance loads inboth the linear and non-linear systems. Similar, presented aprototype of three-phase active filter for harmonic mitigation

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

Pulse width modulation

The usage of Passive filters, Active filter and Pulse Width Modulation (PWM), for reducing harmonics in grid systems. Stating the challenges of passive filters has being bulky as well as the introduction of resonances into the system while active filters provide a solution to these problems and gives improved efficiency. The researchers state that the most common methods for recent times have been the PWM method, which employs a voltage source inverter. The improvement in the decoupling techniques, led to the instantaneous real and reactive current technique (id-iq) that is used mostly and gives wonderful outcome when used with a proportional integral controller, which was used for several grid situations integrating, with hybrid renewable energy sources (HRES) as well as without HRES. We employ a technique called disturbance compensation control. They classified controlling methods for harmonics reduction into two categories: feedback-based current control and disturbance compensation control. Examples of feedback-based current control techniques include hysteresis control, deadbeat control, and the specific frequency components current control method. Each of the foregoing, have the challenges that is overcomed by the disturbance compensation control method. The authors stated that shut active filter reduces harmonics resulting from hysteresis but not in systems using L-C-L filters where special consideration is required, as the L-C-L output current is associated with quite a massive ripple current. While the deadbeat requirement of the instantaneous state variable values makes systems having analog filters, that need long time constants for circuits sensing, unsuitable. Also there is reducing of harmonics by resonant current compensators and current controllers in addition to outer compensators (usually a voltage loop), which are examples of specific frequency controlled technique, creates strong interference that will result in overall poor efficiency of the system.

Selective elimination pulse width modulation

The recent improvement in power system, with fast switching IGBTs, make semiconductor device less attractive in inverter configurations such as inverters connected in series, inverters connected in parallel, multilevel reactive power compensator, multiple rectifiers, neutral point clamp and optimization inverters. First, is the Selective Harmonics Elimination Pulse Width Modulation (SHEPWM) technique that implements phase-shift harmonic suppression, while the second method utilizes mirror harmonic reduction techniques. Both methods are series connected voltage source. Other control techniques such as space vector PWM, sinusoidal PWM, nonsinusoidal carrier PWM, mixed PWM, and SHEPWM. PWM inverters. The SHEPWM will provide the hihest quality among all the PWM methods. Other techniques are single and three-phase half-bridge voltages source inverter type and its corresponding fullbridge version. There also are square wave modulation techniques, unipolar and bipolar PWM techniques.

MODULE - IV
WIND ENERGY CONVERSION SYSTEMS

Course Outcomes Mapped To Module IV :

Students will be able to:

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

Program Outcomes Mapped To Module IV :

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

Mapping Of CO(s) With PO(s) For Module IV:

Course Outcomes (COs)	Program Outcomes (POs)											
	1	2	3	4	5	6	7	8	9	10	11	12
CO 1	√											
CO 3	√	√										
CO 8	√		√									

Induction Generator as a Wind Power Generator

Rotating electrical machines are commonly used in wind energy systems and most of these electrical machines can function as either a motor or a generator, depending upon its particular application. But as well as the Synchronous Generator we looked at in the previous tutorial, there is also another more popular type of 3-phase rotational machine that we can use as a wind turbine generator called an Induction Generator.

Single Phase Induction Generator

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

However, the rotors of the two machines are quite different with the rotor of an induction generator typically consisting of one of two types of arrangement: a “squirrel cage”, or a “wound rotor”.
Induction Generator construction is based on the very common squirrel-cage induction motor type machine as they are cheap, reliable, and readily available in a wide range of electrical sizes from fractional horse power machines to multi-megawatt capacities making them ideal for use in both domestic and commercial renewable energy wind power applications.

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

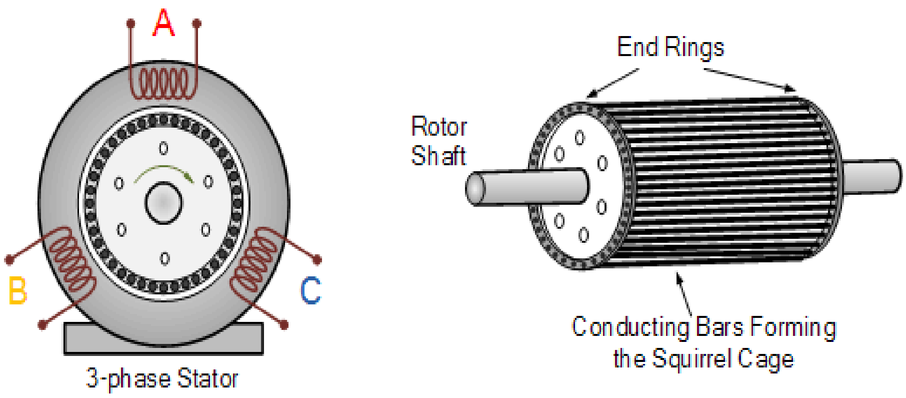
For economy and reliability many wind power turbines use induction motors as generator which are driven through a mechanical gearbox to increase their speed of rotation, performance and efficiency. However, induction generators require reactive power usually provided by shunt capacitors in the individual wind turbines.

Induction machines are also known as Asynchronous Machines, that is they rotate below synchronous speed when used as a motor, and above synchronous speed when used as a generator. So when rotated faster than its normal operating or no-load speed, induction generator produces AC electricity. Because an induction generator synchronizes directly with the main utility grid – that is, produces electricity at the same frequency and voltage – no rectifiers or inverters are required.

However, the induction generator may provide the necessary power directly to the mains utility grid, but it also needs reactive power to its supply which is provided by the utility grid. Stand alone (off-grid) operation of the induction generator is also possible but the disadvantage here is that the generator requires additional capacitors connected to its windings for self-excitation.

Three-phase induction machines are very well suited for wind power and even hydroelectric generation. Induction machines, when functioning as generators, have a fixed stator and a rotational rotor the same as for the synchronous generator. However, excitation (creation of a magnetic field) of the rotor is performed differently and a typical design of the rotor is the squirrel-cage structure, where conducting bars are embedded within the rotors body and connected together at their ends by shorting rings as shown.

Induction Generator Construction



As already mentioned at the beginning one of the many advantages of the asynchronous machine is that it can be used as generator without any additional circuitry, such as an exciter or voltage controller, when it is connected to a three-phase mains supply. When an idle asynchronous generator is connected to an alternating current grid, voltage is induced into the rotor winding, similar to a transformer with the frequency of this induced voltage being equal to the frequency of the applied voltage.

As the squirrel cage rotors conducting bars are short-circuited together, a large current flows around them and a magnetic field is created inside the rotor causing the machine to rotate.

Since the rotor cage magnetic field follows the stators magnetic field, the rotor accelerates up to synchronous speed set by the frequency of the grid supply. The faster the rotor rotates, the lower is the resulting relative speed difference between the rotor cage and the rotating stator field and thus the voltage induced into its winding.

As the rotor nears synchronous speed it slows down as the weakening rotor magnetic field is insufficient to overcome the friction losses of the rotor in idle mode. The result is that the rotor is now rotating slower than synchronous speed. This means then that an induction machine can never reach its synchronous speed as to reach it there would be no current induced into the rotors squirrel cage, no magnetic field and thus no torque.

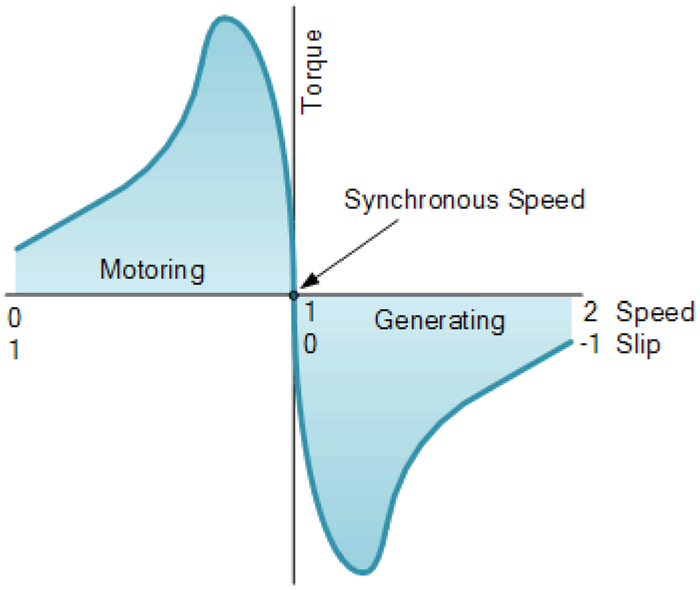
The difference in rotational speed between the stators rotating magnetic field and the rotor speed is referred to in induction machines as “slip”. Slip must exist for there to be torque at the rotor shaft. In other words, “slip”, which is a descriptive way of explain how the rotor is continually “slipping-back” from synchronization, is the difference in speed between the stators synchronous speed, given as: $ns = f/P$ in rpm, and the rotors actual speed nR also in rpm, and which is expressed as a percentage, (%-slip).

Then the fractional slip s, of an induction machine is given as: fractional slip

This slip means that an induction generators operation is thus “asynchronous” (not-synchronised) and the heavier the load attached to an asynchronous generator, the higher is the resulting slip, as higher loads require stronger magnetic fields. More slip is associated with more induced voltage, more current and a stronger magnetic field.

Thus for an induction machine to operate as a motor its operating speed will always less than the rotational speed of the stator field, namely, the synchronous speed. For an induction machine to work as a generator its operating speed must be above the rated synchronous speed as shown.

Torque/Speed Characteristics of an Induction Machine



At standstill, the stators rotating magnetic field has the same rotational speed with respect to both the stator and the rotor as the frequency of the rotor and stator currents are the same, therefore at standstill slip is positive and equal to one (s = +1).

At synchronous speed the difference between the speed and frequency of the rotor and stator is zero, therefore at synchronous speed no electricity is consumed or produced and slip is equal to zero (s = 0).

If the speed of the generator is driven above this synchronous speed by external means the resultant effect will be that the rotor will rotate faster than the rotating magnetic field of the stator and the polarity of the induced rotor voltage and current is reversed.

The result is that the slip now becomes negative (s = -1), and the induction machine generates current at a leading power factor back into the mains utility grid. The power transferred as an electromagnetic force from the rotor to the stator can be increased by simply rotating the rotor faster which will then result in an increase in the amount of electricity generated. The torque characteristics of an induction generator (s = 0 to -1) is a reflection of the induction motor characteristics (s = +1 to 0) as shown.

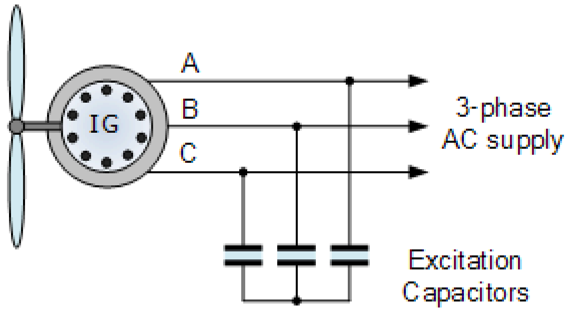
The speed of the induction generator will vary with the rotational force (moment, or torque) applied to it by the winds energy but it will continue to generate electricity until its rotational speed falls below idle. In practice, the difference between the rotational speed at peak generating power and at idle, (synchronous speed) is very small, only a few percent of the maximum synchronous speed. For example, a 4-pole generator with a synchronous idle speed of 1500 rpm attached to the utility grid with a 50 Hz current, may produce its maximum generated power rotating at only 1-to-5% higher, (1515 to 1575 rpm), easily achieved using a gearbox.

This is a very useful mechanical property that the generator will increase or decrease its speed slightly if the torque varies. This means that there will be less wear and tear on the gearbox resulting in low maintenance and long service life and this is one of the most important reasons for using an Induction Generator rather than a synchronous generator on a wind turbine which is directly connected to the electrical utility grid.

Off-grid Induction Generator
We have seen above that an induction generator requires the stator to be magnetised from the utility grid before it can generate electricity. But you can also run an induction generator in a stand alone, off-grid system by supplying the necessary out-of-phase exciting or magnetising current from excitation capacitors connected across the stator terminals of the machine. This also requires that there is some

residual magnetism in the rotors iron laminations when you start the turbine. A typical circuit for a three-phase squirrel-cage induction machine for use off-grid is shown below. The excitation capacitors are shown in a star (wye) connection but can also be connected a delta (triangular) arrangement.

Capacitor Start Induction Generator

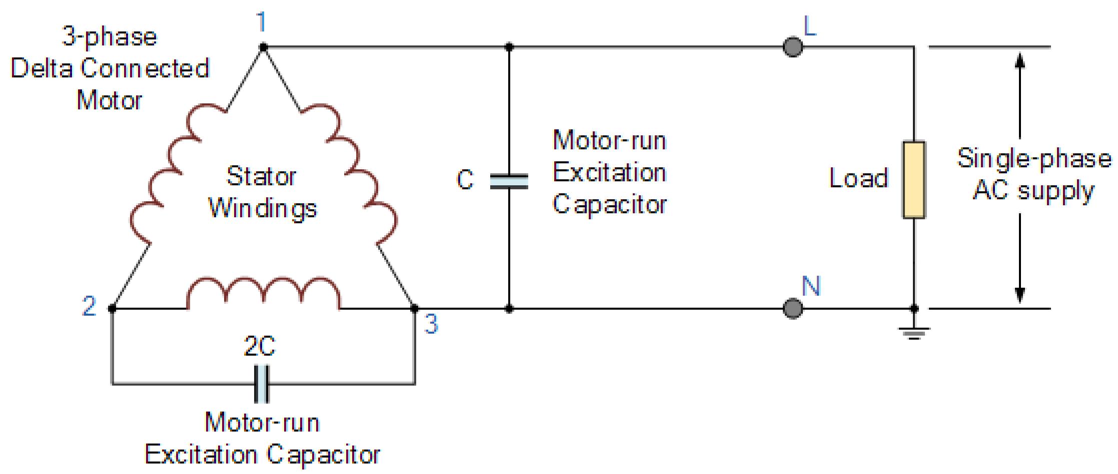


The excitation capacitors are standard motor-starting capacitors that are used to provide the required reactive power for excitation which would otherwise be supplied by the utility grid. The induction generator will self-excite using these external capacitors only if the rotor has sufficient residual magnetism.

In the self-excited mode, the generator output frequency and voltage are affected by the rotational speed, the turbine load, and the capacitance value in farads of the capacitors. Then in order for self-excitation of the generator to occur, there needs to be a minimum rotational speed for the value of capacitance used across the stator windings.

The "Self-excited induction generator", (SEIG) is a good candidate for wind powered electric generation applications especially in variable wind speed and remote areas, because they do not need external power supply to produce the magnetic field. A three-phase induction generator can be converted into a variable speed single-phase induction generator by connecting two excitation capacitors across the three-phase windings. One of value C amount of capacitance on one phase and the other of value 2C amount of capacitance across the other phase as shown**.**

Single-phase Output from a 3-phase Induction Generator



By doing this the generator will run more smoothly operating nearer to unity (100%) power factor (PF). In the single-phase operation, it is possible to obtain near three phase efficiency producing approximately 80% of the machines maximum rating. However, care must be taken when converting a 3-phase supply into a single-phase supply as the single phase line-to-line voltage output will be twice that of the rated winding.

Induction generators work well with single-phase or three-phase systems that are interconnected to the utility or as a self-excited stand alone generator for small scale wind power applications allowing for variable speed operation. However, induction generators require reactive excitation to operate at full power thus they are ideally suited for interconnection to the utility grid as part of an grid-tied wind power system.

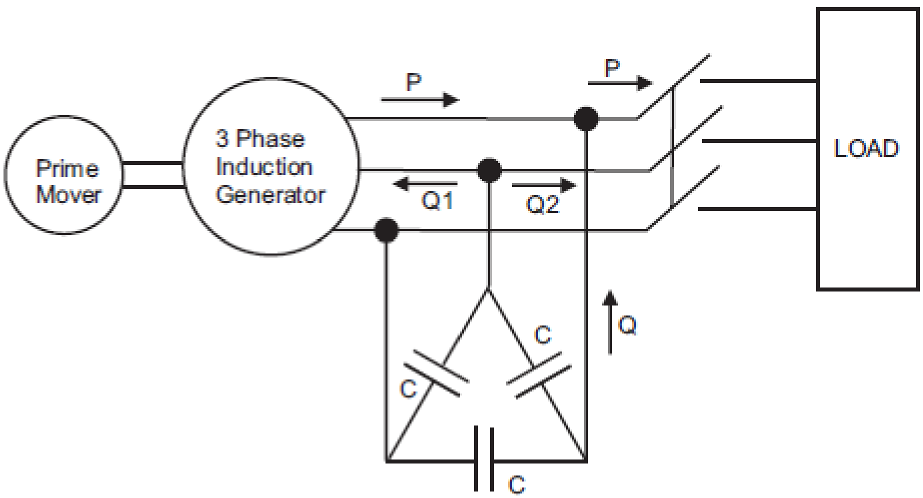
Self-excited induction generator (SEIG) for isolated power generators

Induction machines are sometimes used as a generator. These are known as induction generators or asynchronous generators. So under what conditions will an induction machine will behave as an induction generator?
An induction machine will behave as an induction generator when:
Slip becomes negative due to this the rotor current and rotor emf attains negative value.The prime mover torque becomes opposite to electric torque**.**Now let us discuss how we can achieve these conditions. Suppose that an induction machine is coupled with the prime mover whose speed can be controlled. If the speed of the prime mover is increased such that the slip becomes negative (i.e. speed of the prime mover becomes greater than the synchronous speed).

Due to this, all the conditions that we have mentioned above will become fulfilled and the machine will behave like an induction generator. Now if the speed of the prime mover is further increased such that it exceeds the negative maximum value of the torque produced then the generating efficiency of the generator vanishes. Clearly, the speed of the induction generator during the whole operation is not synchronous, therefore the induction generator is also called a synchronous generator.

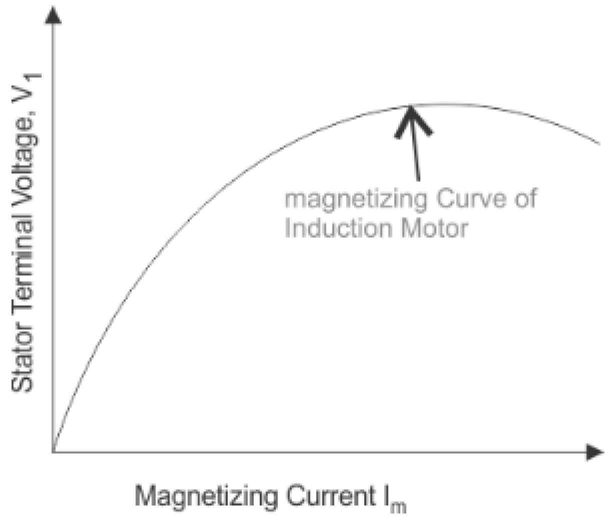
An induction generator is not a self-excited machine. Therefore in order to develop the rotating magnetic field, it requires magnetizing current and reactive power. The induction generator obtains its magnetizing current and reactive power from the various sources like the supply mains or it may be another synchronous generator.An induction generator can't work in isolation because it continuously requires reactive power from the supply system. However, we can have a self-excited or isolated induction generation if we use a capacitor bank for reactive power supply instead of an AC supply system. We'll now discuss isolated induction generators in detail.

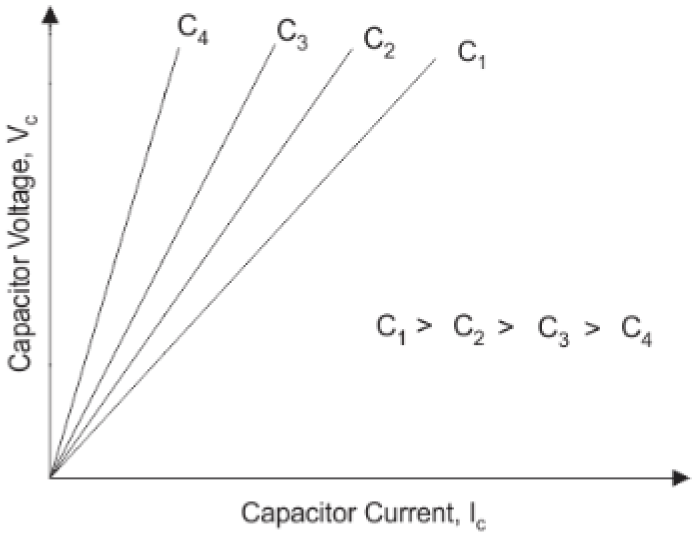
Isolated Induction Generator
This type of generator is also known as a self excited generator. Now why it is called self-excited? It is because it uses a capacitor bank which is connected across its stator terminals as shown in the diagram given below.



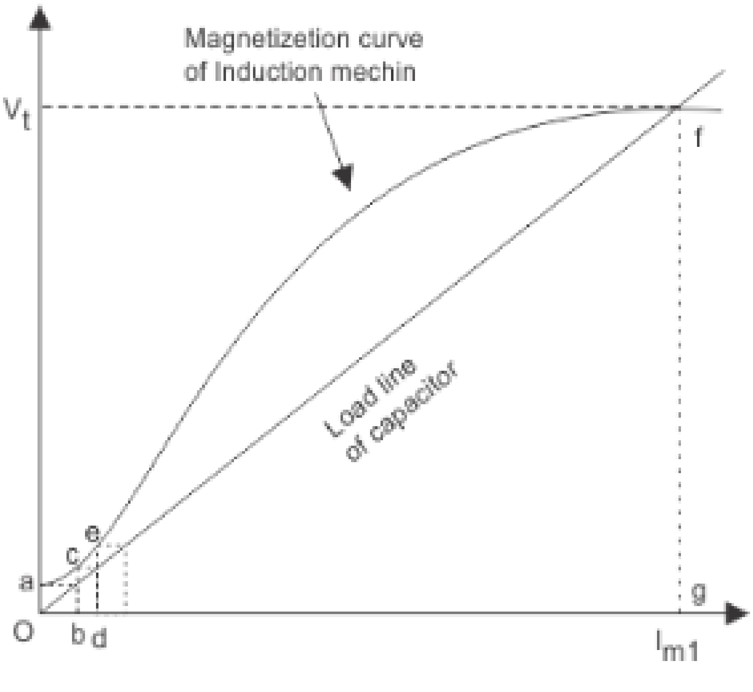
The function of the capacitor bank is to provide the lagging reactive power to the induction generator as well as load. So mathematically we can write total reactive power provided by the capacitor bank is equals to the summation of the reactive power consumed by the induction generator as well as the load.

There is generation of small terminal voltage oa (as in figure given below) across the stator terminal due the residual magnetism when the rotor of the induction machine runs at the required speed. Due to this voltage oa the capacitor current ob is produced. The current bc sends current od which generates the voltage de.





The cumulative process of voltage generation continues till the saturation curve of the induction generator cuts the capacitor load line at some point. This point is marked as f in the given curve.



Application of Induction Generator

Let us discuss application of induction generator: We have two types of induction generator let us discuss the application of each type of generator separately: Externally excited generators are widely used for regenerative breaking of hoists driven by the three phase induction motors.

Self-excited generators are used in the wind mills. Thus this type of generator helps in converting the unconventional sources of energy into electrical energy.
Now let us discuss some disadvantages of externally excited generator:

The efficiency of the externally excited generator is not so good.
We cannot use externally excited generator at lagging power factor which major drawback of this type of generator.
The amount of reactive power used to run these types of generator required is quite large.

Advantages of Induction Generators

- It has robust construction requiring less maintenance
- Relatively cheaper
- Small size per kW output power (i.e. high energy density)
- It runs in parallel without hunting
- No synchronization to the supply line is required like a synchronous generator

Disadvantages of Induction Generators
It cannot generate reactive voltamperes. It requires reactive voltamperes from the supply line to furnish its excitation.

DC power for SEIGs
An induction machine requires an externally-supplied armature current. Because the rotor field always lags behind the stator field, the induction machine always consumes reactive power, regardless of whether it is operating as a generator or a motor.

A source of excitation current for magnetizing flux (reactive power) for the stator is still required, to induce rotor current. This can be supplied from the electrical grid or, once it starts producing power, from the generator itself. The generating mode for induction motors is complicated by the need to excite the rotor, which begins with only residual magnetization. In some cases, that residual magnetization is enough to self-excite the motor under load. Therefore, it is necessary to either snap the motor and connect it momentarily to a live grid or to add capacitors charged initially by residual magnetism and providing the required reactive power during operation. Similar is the operation of the induction motor in parallel with a synchronous motor serving as a power factor compensator. A feature in the generator mode in parallel to the grid is that the rotor speed is higher than in the driving mode. Then active energy is being given to the grid.[1]Another disadvantage of induction motor generator is that it consumes a significant magnetizing current $I0 = (20\text{-}35)\%$.

An induction machine can be started by charging the capacitors, with a DC source, while the generator is turning typically at or above generating speeds. Once the DC source is removed the capacitors will provide the magnetization current required to begin producing voltage.

An induction machine that has recently been operating may also spontaneously produce voltage and current due to residual magnetism left in the core.

Wind Energy System Performance
Clean & Environment friendly Fuel source:– It doesn’t pollute air like power plant relying on combustion of fossil fuel. It does not produce atmospheric emissions that cause acid rain or green house gases (carbon dioxide (CO_2) or methane (CH_4)). Noise and visual pollution are both environmental factors, but they don’t have a negative effect on the earth, water table or the quality of the air we breathe.

Renewable & Sustainable:– Winds are caused by heating of atmosphere by the sun, earth surface irregularities and the rotation of the earth. For as long as the sun shines the wind blows, the energy produced can be harnessed and It will never run out, unlike the Earth's fossil fuel reserves.

Cost Effective:– Wind energy is completely free. There's no market for the demand and supply of wind energy's, It can be used by anyone and is one of the lowest price renewable technologies available today, depending upon the wind resource and the particular project's financing.

Industrial and Domestic Installation:– Wind turbines can be built on existing farms or ranches where most of the best wind sites are found. Wind turbines uses only a fraction of the land which causes no trouble in work for the farmers and rancher, providing landowners with additional income paid by the owners of the wind power plants. Many landowners opt to install smaller, less powerful wind turbines in order to provide part of a domestic electricity supply.

Fluctuation of Wind and Good wind sites:– Wind energy has a drawback that it is not a constant energy source. Although wind energy is sustainable and will never run out, the wind isn't always blowing. This can cause serious problems for wind turbine developers who will often spend significant time and money investigating whether or not a particular site is suitable for the generation of wind power. For a wind turbine to be efficient, the location where it is built needs to have an adequate supply of wind energy.

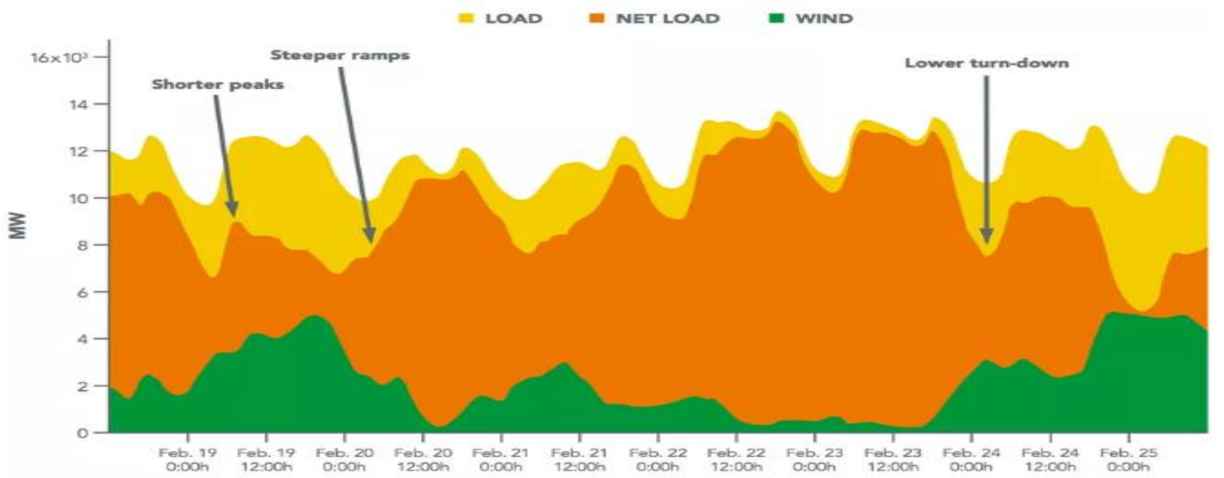
Noise and aesthetic pollution:– Wind turbines generate noise and visual pollution. A single wind turbine can be heard from hundreds of meters away. Although steps are often taken to site wind turbines away from dwellings. Many people like the look of wind turbines, others do not and see them as a blot on the landscape.

Not a profitable use of land:– Alternative uses for the land might be more highly valued than electricity generation.

Threat to wildlife:– Birds have been killed by flying into spinning turbine blades. However it is believed that wind turbines pose less of a threat to wildlife than other man made structures such as cell phone masts and radio towers. Most of the problems have been resolved or greatly reduced through technological development or by properly siting wind plants.

Why wind is such a challenge for energy grids
Variability: This is the biggest and most vexing.

Power plants that run on fuel (along with some hydro and geothermal plants) can be ramped up and down on command. They are, in the jargon, "dispatchable." But VRE plants produce power only when the wind is blowing or the sun is shining. Grid operators don't control VRE, they accommodate it, which requires some agility.
This figure shows why, using wind power as an illustration:



This shows one week of electricity supply and demand (details and location not particularly important). The green at the bottom is power coming in from wind. The yellow at the top is total demand. The orange in the middle is the gap between the two, the amount that has to be supplied by conventional power plants.

Another way of looking at it: from the perspective of the grid operator, who has control over a set amount of dispatchable power, VRE energy supply is functionally equivalent to reduction in demand — large, rapidly rising and falling fluctuations in demand for dispatchable power.

On the chart above, "shorter peaks" refers to times when conventional plants are supplying the day's "peak load," which is when power is most valuable. VRE reduces or "shaves" the peak, thus screwing with the economics of conventional plants. "Steeper ramps" refers to times when conventional plants have to increase or decrease their output quickly in response to fluctuations in VRE — often more quickly than they are designed or regulated for. And "lower turn-down" means that in times of high VRE supply, conventional plants will have to run at the lowest output they are capable of, i.e., "minimum load."

All these effects of variability pose challenges to the rules and economics that govern existing power infrastructure.

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

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

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

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

Solutions

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

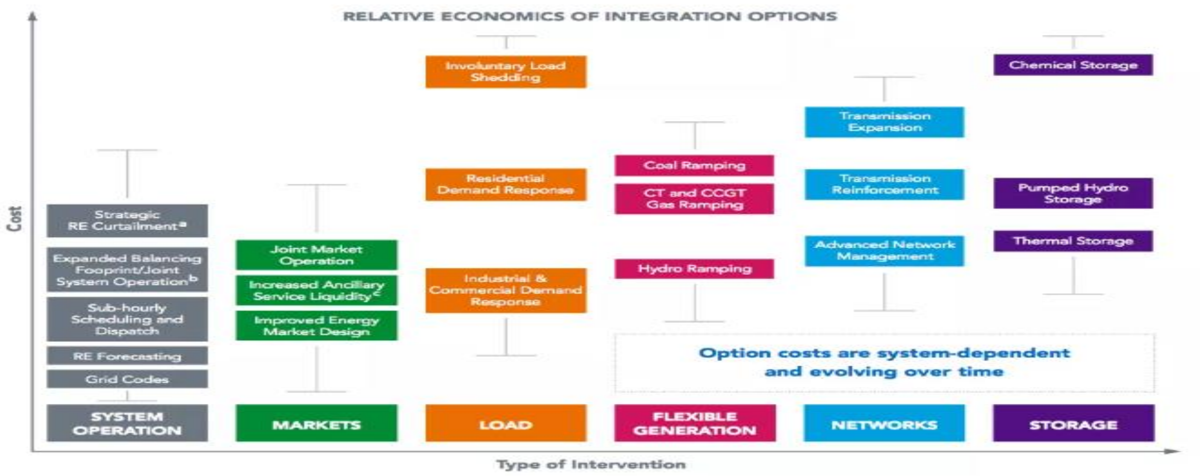
Flexible rules and markets: Most grids are physically capable of more flexibility than they exhibit. Changes to the rules and markets that govern how plants are scheduled and dispatched, how reliability is assured, and how customers are billed, says NREL, "can allow access to significant existing flexibility,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

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

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

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

Interconnected transmission networks: This one's pretty simple. Wind and solar resources become less variable if aggregated across a broader region. The bigger the geographical area linked up by power lines, the more likely it is that the sun is shining or the wind is blowing somewhere within that area.



Methods are used to control the fluctuation of power in wind turbine

Wind turbines are designed to yield Maximum output at a wind speed of 15M/S if the wind speed is more the excess energy is wasted. But the rotor is to be protected from damage .This done by power control mechanism.

The important method use in power control is as follows:

Pitch Control :-

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

Passive Stall control :

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

Yaw Control :-

- This is another method in which the turbine is rotated about a vertical axis facing or away from the wind.
- This method is used only in small wind turbines power plant 1 KW or less.

Harmonics in a Wind Power Plant

The number of wind power plants (WPP) increases world widely and the nominalpower of an average wind power plant increases. In many countries wind power hasalready taken an important part in the electrical energy production mix. Due to theimportance of wind power, manufacturers and transmission system operators (TSO)cannot ignore the effects of wind power plants on the power quality and power systemstability.

Wind power plants introduce a great number of non-linear power electronic devices like full scale frequency converters into the grid. A large number of non-linear power electronic devices can have significant effect on the harmonic emissions. These harmonics can form a serious threat for power quality . That is why harmonic analysis has to be developed and taken as an integrated part of wind power plant design. Because every power network is unique and has different characteristics, the effect of the harmonics on every power system varies. Nevertheless, some common features can be found. Even if the percentage of the harmonics seemed small, the harmonic emission becomes a significant issue when the capacity of a wind power plant is hundreds of megawatts.

Emission of harmonics is not the only problem. Another problem occurs when the frequency of a harmonic current coincides with a resonance frequency. Optimal circumstances for a devastating resonance occur if some of the harmonics (or inter harmonics) coincides with the network resonance frequency.

Harmonics have many kinds of adverse effects in a power network. The major part of the components used in power networks is mainly designed for the fundamental frequency. Many times, the components operate in conditions that do not form an optimal operating environment, which can have adverse effects on the components. Harmonic emissions are a commonly recognised problem in wind power plants.

Probably the most significant problem is that harmonic currents cause overheating and extra losses in many components, like cables, capacitor banks, generators, transformers, reactors and any kinds of electronic equipment. Overheating shortens their useful lifetime, and in an extreme case, can lead to the destruction of some component, especially in the case of capacitor banks

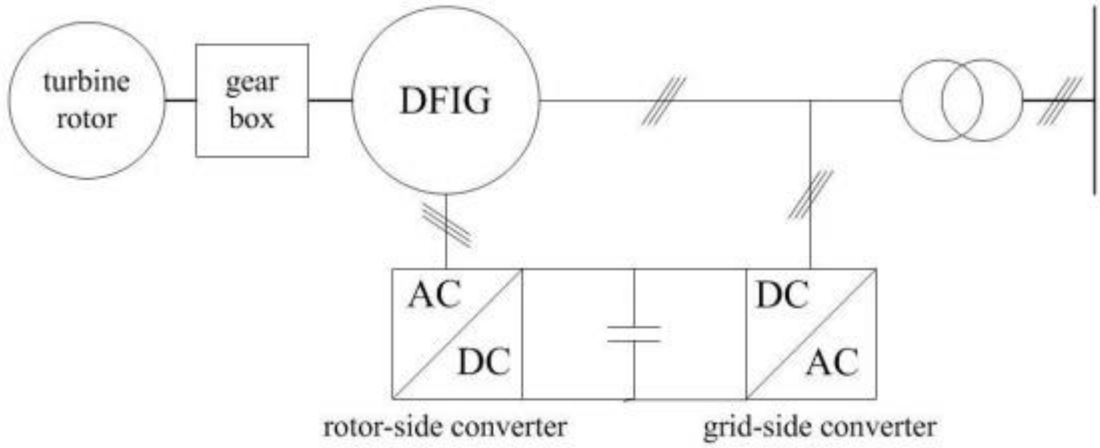
When a power system has components with large a capacitance or inductance, the probability of the existence of resonances increases, as explained before. If harmonic currents or voltages are high enough, they can provoke an unnecessary tripping of protective relays. They can also degrade the interruption capability of circuit breakers. If the filtering is not well designed, harmonics may cause adverse effects on the measuring devices that are not made for taking into account the existence of distorted waveforms. These malfunctions can have an effect on measured results although devices might be equipped with filters.The functioning of many electronic devices is based on the determination of the shape of voltage waveform, for example detecting the zero-crossing point. As harmonic distortion can shift this point, the risk of system malfunction is evident. Especially important is to mention the drawback of harmonics on impedance measurement that is used in distance relays.

The power transferred in power networks and communication networks is in a totally different scale (megawatt versus milliwatt), so even a relatively small amount of current distortion in the power network can easily provoke significant noise in a metallic communication circuit at harmonic frequencies.In modern wind power plants a huge number of different power electronic apparatus is installed, which is the main reason for harmonics in the wind power plants.

The switching operations of the pulse width modulation (PWM) controlled converters are the main sources of harmonic and inter harmonic currents, but not the only ones. Generally speaking, converters create harmonics in the range of a few kilohertz. Measuring and controlling these harmonics is one of the greatest challenges of the power quality in wind power plants. The next sections present the most significant types of harmonic sources.

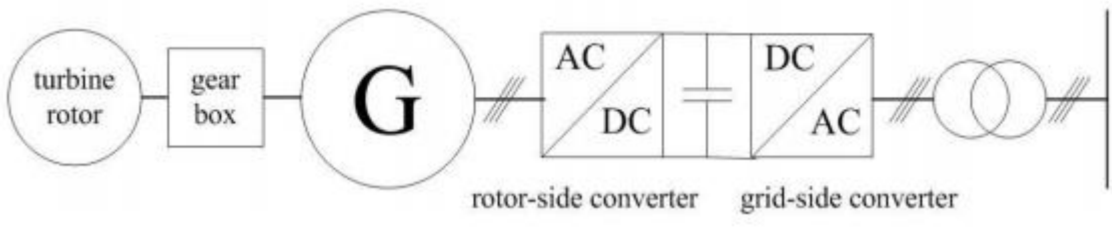
Power Converters in Wind Turbines

Nowadays new wind turbines are variable speed wind turbines that are connected either partly or totally to the internal medium voltage network of a wind power plant through a power electronic converter. In the both types, the power converter actually has two parts, the rotor side converter and the grid side converter that are jointed together by parallel capacitance. This kind of converter is called back-to-back Converter. Now, two most common types of wind turbines are presented. The first one is called doubly fed induction generator (DFIG). It offers the flexibility to operate at the maximum power output over a wide range of wind speed without the necessity of having a full rated converter. The main idea of a doubly fed induction generator turbine is shown in. The rotor side converter handles the active and reactive power control of the generator and the grid side converter keeps the voltage of the DC link constant. Three stripes in the figures are a mark of a three phase voltage and current.



Double fed induction generator (DFIG) with a rotor, a gear box and a converter. The generator is connected to three phase AC grid. Three stripes signify a three phase current and voltage.

Another type of wind turbines is the full scale converter, where all the power from the generator and flows through the converter. The generator can be either an induction generator or a synchronous generator. In the latter case the generator is usually a permanent magnet synchronous generator that is the most widely used type of synchronous generators. Permanent magnet synchronous generator becomes more and more feasible option along the development of the technology. The arrangement of using a synchronous generator with a full scale converter provides a lot of flexibility in the operation as it can support the network offering reactive power even if there was not wind at all. An arrangement of a synchronous generator with a full scale converter is shown in Figure



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A full scale converter configuration with a turbine rotor, a gear box, a generator (G) and a back-to-back converter . The generator is connected to three phase AC grid. Three stripes signify a three phase current and voltage.

The harmonic emissions of wind turbines can be classified as characteristic and noncharacteristic harmonics. The characteristic harmonics depend on the converter topology and switching strategy used during an ideal operation (with no disturbances). For a six-pulse converter, the characteristic harmonics are the harmonics of the harmonic order 6□ ± 1, where □ is a positive integer. Similarly for a twelve-pulse converter the characteristic harmonics are of the order 12 ± 1. Apparently, the non-characteristic harmonics are the harmonics that are not counted as characteristic harmonics. They are not depending on the converter topology, but the operating point of the converter. This type of harmonics can be as large and as significant as the characteristic harmonics.

Power Factor: Improvement, Formula & Definition

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

Hence the entire circuit behaves as resistive circuit and the entire electrical power is dissipated in the form of heat. Here the voltage and current are in same phase and the total electrical power is given by:

Electrical power = Voltage across element x Current through the element its unit is Watt = Joule/sec.

Now coming to AC circuit, here both inductor and capacitor offer a certain amount of impedance given by:

$$X_L = 2\pi fL = \frac{1}{2\pi fC}$$

The inductor stores electrical energy in the form of magnetic energy and capacitor stores electrical energy in the form of electrostatic energy. Neither of them dissipates it. Further, there is a phase shift between voltage and current.

Hence when we consider the entire circuit consisting of a resistor, inductor, and capacitor, there exists some phase difference between the source voltage and current.

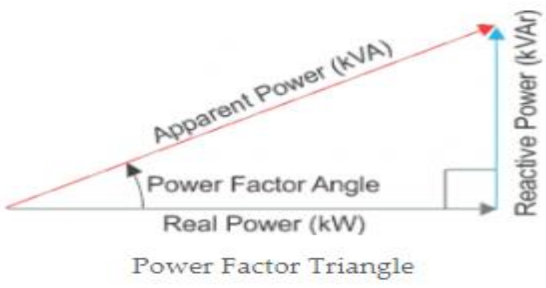
The cosine of this phase difference is called electrical power factor. This factor ($-1 < \cos\varphi < 1$) represents the fraction of the total power that is used to do the useful work. The other fraction of electrical power is stored in the form of magnetic energy or electrostatic energy in the inductor and capacitor respectively.

The total power in this case is:
Total Electrical power = Voltage across element x Current through the element

This is called apparent power and its unit is VA (Volt Amp) and denoted by 'S'. A fraction of this total electrical power which does our useful work is called active power. We denote it as 'P'.

P = Active power = Total electrical power.cosφ and its unit is watt.
The other fraction of power is called reactive power. Reactive power does no useful work, but it is required for the active work to be done. We denote it with 'Q' and mathematically is given by:

Q = Reactive power = Total electrical power.sinφ and its unit is VAR (Volt Amp Reactive). This reactive power oscillates between source and load. To help understand this better all these power are represented in the form of a triangle.



Power Factor Triangle

Mathematically, $S^2 = P^2 + Q^2$ and electrical power factor is active power / apparent power.

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

Cosφ = Active power / Apparent power

Need for Power Factor Improvement

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

KVA = KW/cosφ

Hence, the size and cost of the machine is also reduced.

This is why electrical power factor should be maintained close to unity – it is significantly cheaper.
Methods of Power Factor Improvement

There are three main ways to improve power factor:

- Capacitor Banks
- Synchronous Condensers
- Phase Advancers

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

Synchronous Condensers
Synchronous condensers are 3 phase synchronous motor with no load attached to its shaft.The synchronous motor has the characteristics of operating under any power factor leading, lagging or unity depending upon the excitation. For inductive loads, a synchronous condenser is connected towards load side and is overexcited.Synchronous condensers make it behave like a capacitor. It draws the lagging current from the supply or supplies the reactive power.

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

Power Factor Calculation

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

Now, we know P = VIcosφ

From this cosφ = P/VI = $\frac{wattmeter\ reading}{voltmeter\ reading \times Ammeter\ reading}$

Hence, we can get the electrical power factor.

Now we can calculate the reactive power Q = VIsinφ

This reactive power can now be supplied from the capacitor installed in parallel with the load in local. The reactive power of a capacitor can be calculated using the following formula:

Q = $\frac{V^2}{X_c} \rightarrow C = \frac{Q}{2\pi f V^2}$

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

Course Outcomes Mapped To Module V :

Students will be able to:

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

Program Outcomes Mapped To Module V :

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

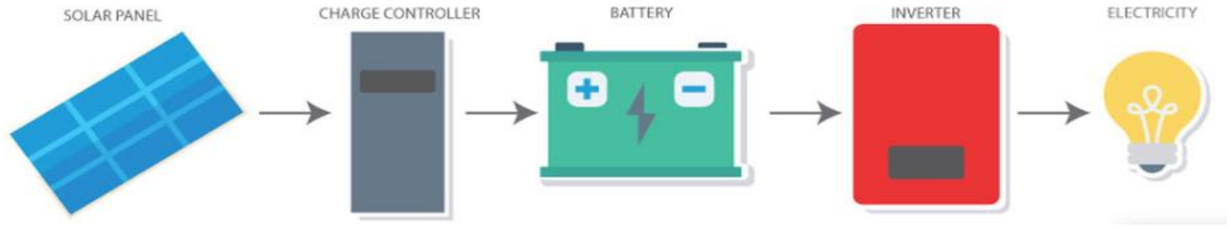
Mapping Of CO(s) With PO(s) For Module V:

Course Outcomes (COs)	Program Outcomes (POs)											
	1	2	3	4	5	6	7	8	9	10	11	12
CO 9	√	√										
CO 10	√	√										

Grid Connect vs Stand Alone Solar Power Systems

Grid connect solar power

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



Stand alone solar power

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

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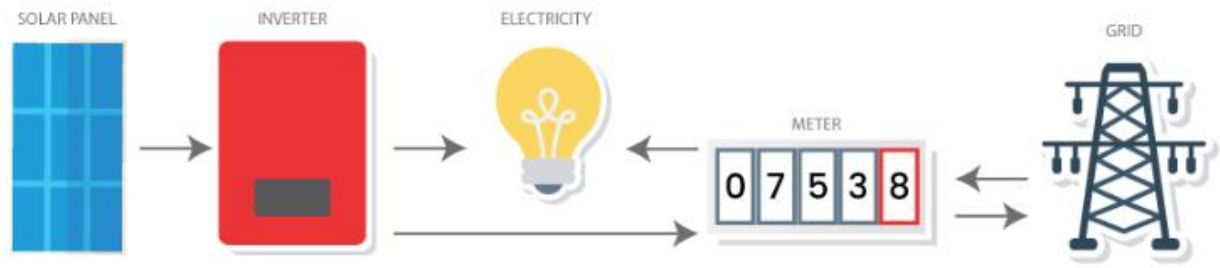

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Power Quality issues

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

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

Nowadays, the renewable sources generation is rapidly developing in Europe. In the last 17th years, the average growth rate is of wind generation is 15.6% annually. As these renewable sources are increasingly penetrating the power systems, the impact of the RES on network operation and power quality is becoming important. The intermittent character of the wind and solar irradiation constrains the power system to have an available power reserve. Due to the output power variations of the wind turbines, voltage fluctuations are produced. In weak networks or in power systems with a high wind generation penetration, the integration of these sources can be limited by the flicker level that must not exceed the standardized limits.

The photovoltaic (PV) installations, interconnected to the mains supply, can be single-phase connected (photovoltaic installations with capacity less than 5 kW) or three-phase connected (photovoltaic installations with capacity greater than 5 kW). The direct-coupled PV systems, without electrical energy storage, inject in the power system a generated power that follows the intermittency of the primary energy source. In this case, important voltage variations can occur at the PCC. The connection of PV systems to the low voltage grid can determine voltage variations and harmonic currents.

Voltage fluctuations

Determination of voltage fluctuations (flicker effect) due to output power variations of renewable sources is difficult, because depend of the source's type, of generator's characteristics and network impedance. For the case of wind turbines, the long term flicker coefficient P_{lt} due to commutations, computed over a 120 min interval and for step variations, becomes:

$$P_{lt} = \frac{8}{S_{SC}}.N_{120}^{0.31}.K_f(\varphi_{SC}).S_r$$

where N_{120} is the number of possible commutations in a 120 min interval, $k_f(\psi sc)$ is the flicker factor defined for angle $\psi_{sc} = \arctan(X_{sc}/R_{sc})$, S_r − rated power of the installation, and S_{sc} − fault level at point of common coupling (PCC).

For a 10 minutes interval, the short-term flicker P_{st} is defined:

$$P_{lt} = \frac{18}{S_{SC}}.N_{10}^{0.31}.K_f(\varphi_{SC}).S_r$$

where N_{10} is the number of possible commutations in a 10 min interval.

The values of flicker indicator for wind turbines, due to normal operation, can be evaluated using flicker coefficient $c(\psi_{sc}, \upsilon_a)$, dependent on average annual wind speed, υ_a, in the point where the wind turbine is installed, and the phase angle of short circuit impedance, ψ_{sc}:

$$P_{st} = P_{lt} = C(\varphi_{SC,} Va).\frac{Sr}{S_{SC}}$$

The flicker coefficient $c(\psi_{sc}, \upsilon_a)$ for a specified value of the angle ψ_{sc}, for a specified value of the wind speed υ_a and for a certain installation is given by the installation manufacturer, or can be experimentally determined based on standard procedures. Depending on the voltage level where the wind generator (wind farms) is connected, the angle ψ_{sc} can take values between 30° (for the medium voltage network) and 85° (for the high voltage network).

Power Quality Issues Affected by Distributed Generation | Electricity

Voltage Regulation:

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

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

Sustained Interruptions:

This is the traditional reliability area. Many generators are designed to provide backup power to the load in case of power interruption. However, Distributed Generation has the potential to increase the number of interruptions in some cases.

Much of the Distributed Generation that is already in place was installed as backup generation. The most common technology used for backup generation is diesel gensets. The bulk of the capacity of this form of DG can be realized simply by transferring the load to the backup system. However, there will be additional power that can be extracted by paralleling with the power system. Many Distributed Generation installations will operate with better power quality while paralleled with the utility system because of its large capacity.

However, not all backup Distributed Generation can be paralleled without great expense. Not all Distributed Generation technologies are capable of significant improvements in reliability. To achieve improvement, the Distributed Generation must be capable of serving the load when the utility system cannot.

Harmonics:

There are harmonics concerns with both rotating machines and inverters, although concern with inverters is less with modern technologies.

There are many who still associate Distributed Generation with bad experiences with harmonics from electronic power converters. If thyristor-based, line-commutated inverters were still the norm, this would be a large problem.

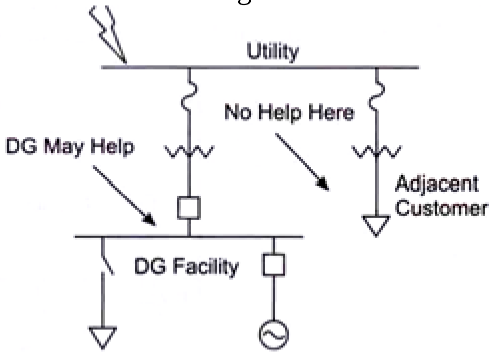
Fortunately, the technologies requiring inverters have adopted the switching inverters. This has eliminated the bulk of the harmonics problems from these technologies.

One problem that occurs infrequently arises when a switching inverter is installed in a system that is resonant at frequencies produced by the switching process. The symptom is usually high-frequency hash appearing on the voltage waveform. The usual power quality complaint, if any, is that clocks supplied by this voltage run fast at times. This problem is generally solved by adding a capacitor to the bus that is of sufficient size to shut off the high-frequency components without causing additional resonances.

Harmonics from rotating machines are not always negligible, particularly in grid parallel operation. The utility power system acts as a short circuit to zero-sequence triplen harmonics in the voltage, which can result in surprisingly high currents. For grounded wye-wye or delta-wye service transformers, only synchronous machines with 2/3 pitch can be paralleled without special provisions to limit neutral current.

For service transformer connections with a delta-connected winding on the Distributed Generation side, nearly any type of three-phase alternator can be paralleled without this harmonic problem.

Voltage Sags:
The most common power quality problem is a voltage sag, but the ability of Distributed Generation to help alleviate sags is very dependent on the type of generation technology and the interconnection location. Figure illustrates a case in which Distributed Generation is interconnected on the load side of the service transformer. During a voltage sag, DG might act to counter the sag. Large rotating machines can help support the voltage magnitudes and phase relationships. Although not a normal feature, it is conceivable to control an inverter to counteract voltage excursions.



The Distributed Generation influence on sags at its own load bus is aided by the impedance of the service transformer, which provides some isolation from the source of the sag on the utility system. However, this impedance hinders the ability of the Distributed Generation to provide any relief to other loads on the same feeder.

Distributed Generation larger than 1 M W will often be required to have its own service transformer. The point of common coupling with any load is the primary distribution system. Therefore, it is not likely that Distributed Generation connected in this manner will have any impact on the voltage sag characteristic seen by other loads served from the feeder.

Power Quality Issues and its MitigationTechniques
Electrical energy is the most efficient and popular form of energy and the modernsociety is heavily dependent on the electric supply. The life cannot be imagined withoutthe supply of electricity. At the same time the quality and continuity of the electric powersupplied is also very important for the efficient functioning of the end user equipment.Most of the commercial and industrial loads demand high quality uninterrupted power.Thus maintaining the qualitative power is of utmost important. The quality of the power is affected if there is any deviation in the voltage andfrequency values at which the power is being supplied. This affects the performance andlife time of the end user equipment. Whereas, the continuity of the power supplied isaffected by the faults which occur in the power system. So to maintain the continuity ofthe power being supplied, the faults should be cleared at a faster rate and for this the
power system switchgear should be designed to operate without any time lag. The power quality is affected many problems which occur in transmission systemand distribution system. Some of them are like- harmonics, transients, sudden switchingoperations, voltage fluctuations, frequency variations etc. These problems are alsoresponsible in deteriorating the consumer appliances. In order to enhance the behavior ofthe power system, these all problems should be eliminated. With the recent advancements in power electronic devices, there are manypossibilities to reduce these problems in the power system.

Short Interruption:

If the duration for which the interruption occurs is of few mille seconds then it is called as short interruption.

Causes:

The causes of these interruptions are-

Opening of an Automatic Re-closure

Lightening stroke or Insulation Flash overConsequences:

The data storage system gets affected

There may be malfunction of sensitive devices like- PLC's, ASD's

Long Interruptions:

If the duration for which the interruption occur is large ranging from few mille seconds to several seconds then it is noticed as long interruption.

Causes:

The causes of these interruptions are-

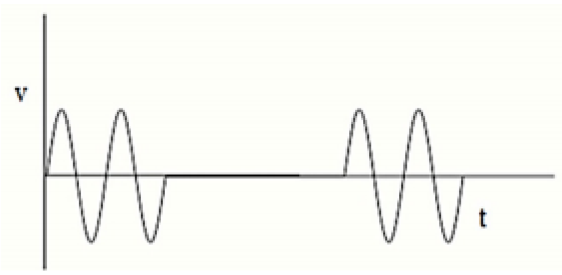
Faults in power system network

Human error

Improper functioning of protective equipment

Consequences:

This type of interruption leads to the stoppage of power completely for a period of time until the fault is cleared.



Voltage Signal with Long Interruption

Waveform Distortion:

The power system network tries to generate and transmit sinusoidal voltage andcurrent signals. But the sinusoidal nature is not maintained and distortions occur in thesignal. The cause of waveform distortions are:

DC Offset: The DC voltage which is present in the signal is known as DC offset.Due to the presence of DC offset, the signal shifts by certain level from its actualreference level.

Harmonics: These are voltage and current signals at frequencies which areintegral multiples of the fundamental frequency. These are caused due to thepresence of non-linear loads in the power system network. Inter Harmonics: These are the harmonics at frequencies which are not theintegral multiples of fundamental frequency.

Notching: This is a periodic disturbance caused by the transfer of current fromone phase to another during the commutation of a power electronic device.

Noise: This is caused by the presence of unwanted signals. Noise is caused due tointerference with communication networks.

Frequency Variations:

The electric power network is designed to operate at a specified value (50 Hz) offrequency. The frequency of the framework is identified with the rotational rate of thegenerators in the system. The frequency variations are caused if there is any imbalance inthe supply and demand. Large variations in the frequency are caused due to the failure ofa generator or sudden switching of loads.

Transients:

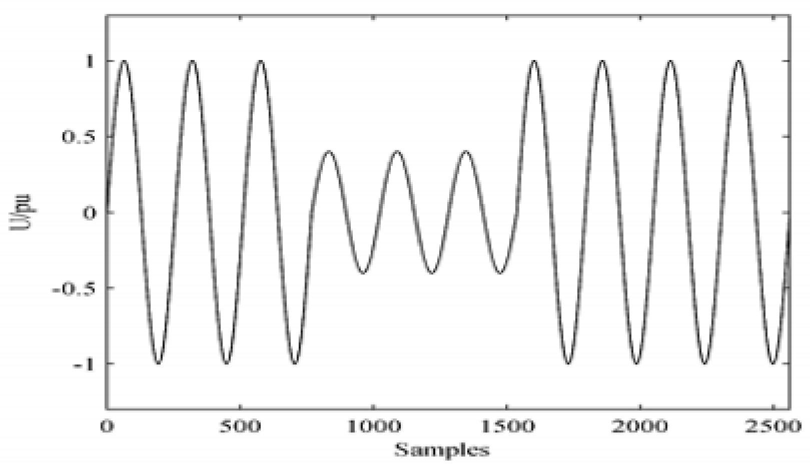
The transients are the momentary changes in voltage and current signals in the powersystem over a short period of time. These transients are categorized into two typesimpulsive, oscillatory. The impulsive transients are unidirectional whereas the oscillatorytransients have swings with rapid change of polarity.

Causes:

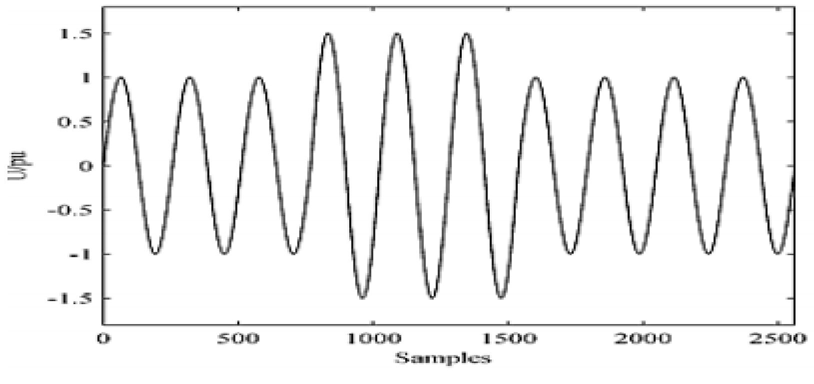
There are many causes due to which transients are produced in the power system. They

are-
 Arcing between the contacts of the switches
 Sudden switching of loads
 Poor or loose connections
 Lightening strokes
Consequences:
 Electronics devices are affected and show wrong results
 Motors run with higher temperature
 Failure of ballasts in the fluorescent lights
 Reduce the efficiency and lifetime of equipment

Voltage Sag:
The voltage sag is defined as the dip in the voltage level by 10% to 90% for a periodof half cycle or more. The voltage signal with sag in shown in Fig.
Causes:
The causes of voltage sag are-
 Starting of an electric motor, which draws more current
 Faults in the power system
 Sudden increase in the load connected to the system
Consequences:
 Failure of contactors and switchgear
 Malfunction of Adjustable Speed Drives (ASD's)



Voltage Swell:
Voltage swell is defined as the rise in the voltage beyond the normal value by 10%to 80% for a period of half cycle or more. The voltage signal with swell in shown in fig.

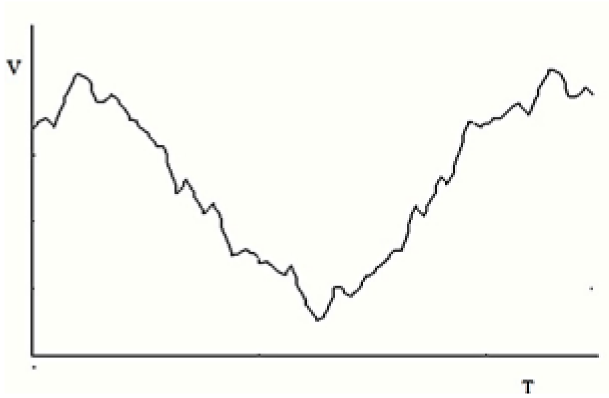


Causes:
 De-energization of large load
Energization of a capacitor bank
 Abrupt interruption of current
 Change in ground reference on ungrounded phases

Consequences:
 Electronic parts get damaged due to over voltage
 Insulation breakdown
 Overheating

Voltage Unbalance:
 The unbalance in the voltage is defined as the situation where the magnitudes andphase angles between the voltage signals of different phases are not equal.
Causes:
 Presence of large single-phase loads
 Faults arising in the system
Consequences:
 Presence of harmonics
 Reduced efficiency of the system
 Increased power losses
 Reduce the life time of the equipment

Voltage Fluctuation:
These are a series of a random voltage changes that exist within the specified voltage ranges. Fig shows the voltage fluctuations that occur in a power system.
Causes:
These are caused by the
Frequency start/ stop of electric ballasts
 Oscillating loads
 Electric arc furnaces
Consequences:
 Flickering of lights
 Unsteadiness in the visuals



Among the different power quality problems discussed, the under voltage or voltage sag is the prominent one as it occurs often and affects the power system network largely.

VOLTAGE SAG ANALYSIS
Definition: "A decrease in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min. Typical values are 0.1 to 0.9 pu."

Characteristics of Voltage Sag:
The voltage sag is characterized by its magnitude, duration and phase angle jump. Each of them is explained below in detail.

Magnitude of Sag:
A sag magnitude is defined as the minimum voltage remaining during the event.The magnitude can be defined in a number of ways. The most common approach is touse the rms voltage. The other alternatives are to use fundamental rms voltage or peakvoltage. Thus, sag is considered as the residual or remaining voltage during the event. In case of three-phase system where the dip in voltage is not same in all phases, the phase with lowest dip is used to characterize sag.

The magnitude of voltage sag at a certain point depend on-
 Type of fault
 Fault impedance
 System Configuration
 Distance of the fault from the point of consideration

Duration of Sag:

Classification of Sag

Type of sag	Duration	Magnitude
Instantaneous	0.5 to 30 cycles	0.1 – 0.9 p.u.
Momentary	30 cycles to 3 sec	0.1 – 0.9 p.u.
Temporary	3 sec to 1 min	0.1 – 0.9 p.u.

The duration of sag is the time for which the voltage is below a threshold value. It isdetermined by the fault clearing time. In a three phase system all the three rms voltagesshould be considered to calculate the duration of the sag. A sag starts when one of thephase rms voltage is less than the threshold and continues until all the three phasevoltages are recovered above the threshold value. Based on the duration of sag, thevoltage sags are classified as shown in Table-I.

Phase-Angle Jump:
The short circuits in power system not only cause a dip in voltage, but also changethe phase angle of the system. The change of phase angle is called as "Phase-AngleJump". It causes the shift in zero crossing of the instantaneous voltage. This phenomenonaffects the power electronic converters which use phase angle information for theirfiring.

Point-on-Wave:
To perfectly characterize sag, the point-on-wave where the sag starts and where itends should be found with high precession. The point-on-wave is nothing but the phaseangle at which the sag occurs. These values are generally expressed in radians ordegrees.

Voltage Sag Mitigation Analysis:
To prevent the occurrence of voltage sag preventive measures can be taken at different stages. They are

During the Production of Equipment:
The basic and economical solution is to strengthen the sensitive devices to the powerquality problems. This prevents the damage of these devices to the abnormalities in thepower system. The device manufacturers use a specific curve like ITIC (InformationTechnology Industry Council) curve during manufacturing. This curve specifies thewithstanding capability of sensitive devices like computers, PLC's, ASD's duringvoltage imbalance occurring in the system. Based on this curve the design is improved sothat the damage of these devices is prevented.

Analysis of the Causes:
The second basic way to prevent the occurrence of voltage sag is to analyze thecauses that lead to voltage imbalance. Improving the poor wiring and weak groundingsystems can prevent the damage of the sensitive equipment. The medium which causespower quality problems should be avoided to the extent possible.

Power Conditioning Equipment:
The use of power conditioning equipment is the most common solution to protect thepower system network from these problems. Most of the power conditioning equipmentis voltage monitoring devices as most of the faults that occur in power system are voltageimbalance faults. These devices may be connected at the source side or in thetransmission network, or at the load end. In general, these devices are connected at thepoint of common coupling (PCC) where the load is connected to the supply. This is done as the cost of the power conditioning device increases from load end to source side. There are different power conditioning devices like

Line-voltage regulators:
These are special transformers connected in series with the transmission line designed to regulate the voltage in accordance with thechanges in the system. Examples of line voltage regulators are- tap changingtransformers, CVT’s, buck-boost regulators etc.

M-G Sets (Motor-generator Sets):
These M-G sets are installed at the load sidein order to supply power to critical loads during the interruptions from the powersupply company. In this maintenance and safety are main concern.

Magnetic Synthesizers:
These employ resonant circuits made of inductors and capacitors. They are used to filter the harmonics from affecting the loads. But these are bulky and noisy.

SVC (Static VAR Compensators):
These also use passive elements like inductorsand capacitors. But the use of solid state switches to control the voltage injectionincreases their efficiency. The switches are controlled such that correct
magnitude of voltage is injected at correct point of time so that voltagefluctuations are reduced. But these are expensive.

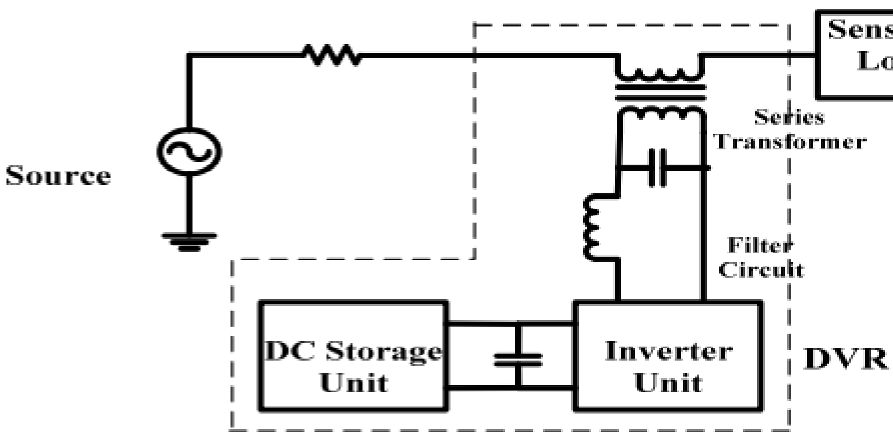
UPS (Uninterruptible Power Supplies):
It provides a constant voltage duringboth voltage sags and outages from a battery or super conducting material. Themain parts of an UPS are battery, rectifier and an inverter.

S**MES (Superconducting magnetic energy storage):**
SMES stores electrical energy within a superconducting magnet. It provides a large amount of power
(750 KVA to 500 MVA) within a short time.

Custom Power Devices:
All the above mentioned conventional devices are notsuitable to mitigate voltage disturbances effectively. Therefore, there is a need touse new type of devices known as Custom Power Devices. These are powerelectronic equipment aimed to help in mitigating power quality problems. Theseare of many types like- Dynamic Voltage Regulator (DVR), D-STATCOM, autotransformer, UPQC etc

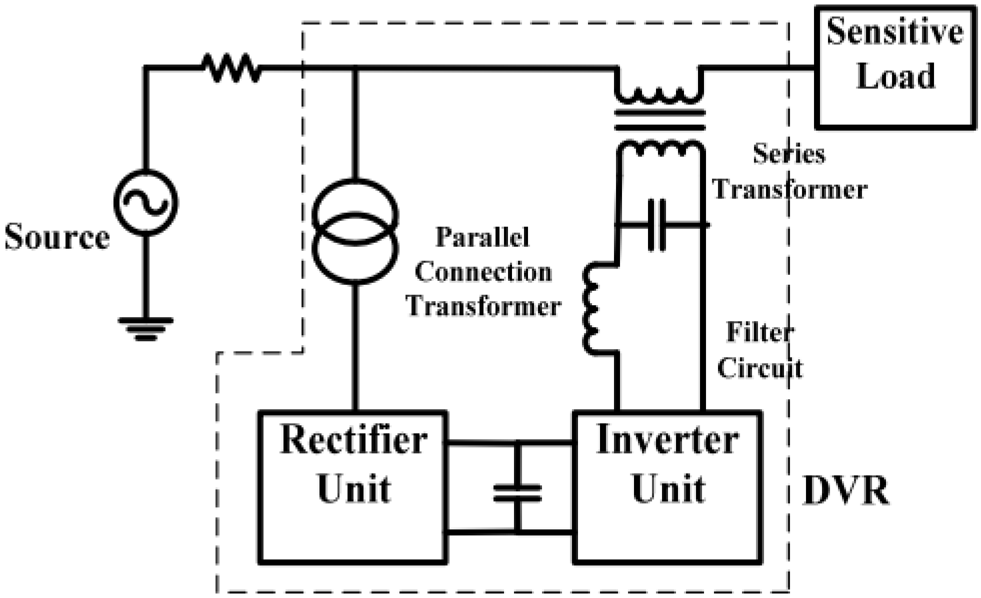
Dynamic Voltage Restorer (DVR)
A Dynamic Voltage Restorer is a power electronic converter based gadget intendedto ensure the discriminating burdens from all supply-side unsettling influences other thandeficiencies . It is connected in arrangement with the distribution feeder for the mostpart at the purpose of regular coupling.

Basic Structure:
The DVR is a series connected power electronic device used to inject voltage ofrequired magnitude and frequency. The basic structure of a DVR is shown in Fig. Itcontains the following components-
• Voltage Source Inverter (VSI)
• DC storage unit
• Filter circuit and Series Transformer



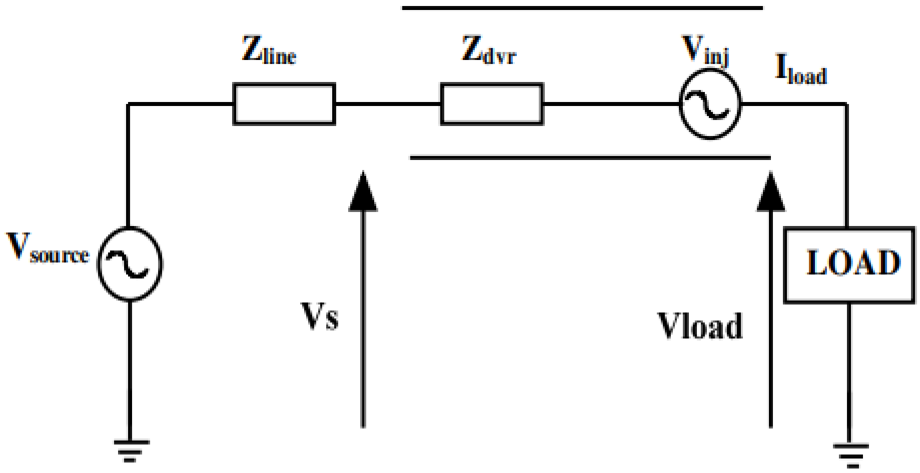
Voltage Source Inverter (VSI):
The VSI consists of solid state switches like IGBT's or GTO's used to convert the DC input to AC. It is used to inject the AC voltage to compensate the decrease in the supply voltage. The switches of the VSI are operated based on the pulse width modulation (PWM) technique to generate the voltage of required magnitude and frequency.

DC Storage Unit:
The storage unit may consist of batteries, capacitors, flywheel, orsuper magnetic energy storage (SMES). For DVR with internal storage capacity,energy is taken from the faulted grid supply during the sag. This configuration is shown in Fig. Here a rectifier is used to convert the AC voltage from the grid to DC voltage required by the VSI.



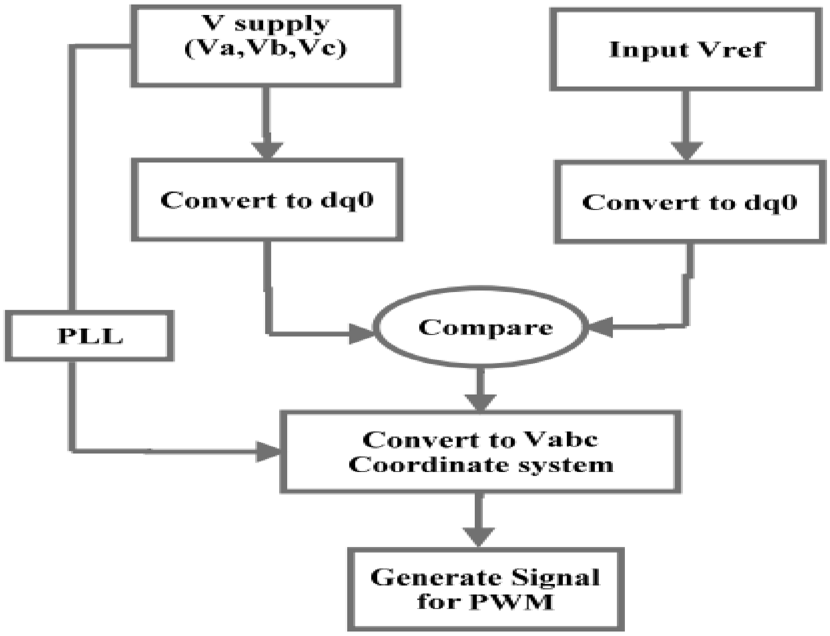
Filter Circuit:
An LC filter is connected at the output of the VSI to filter theharmonics that are present in the output voltage of VSI. It also reduces the dv/dteffect on the windings of the transformer.
Series Transformer:
A series transformer is used to connect the DVR with thedistribution feeder. In case of three phase system, three single phase transformersare used to connect the DVR with the power network.

Series Transformer:
A series transformer is used to connect the DVR with thedistribution feeder. In case of three phase system, three single phase transformersare used to connect the DVR with the power network.
Operating Principle:
The main operation of the DVR is to inject voltage of required magnitude andfrequency when desired by the power system network. During the normal operation, theDVR will be in stand-by mode. During the disturbances in the system, the nominal orrated voltage is compared with the voltage variation and the DVR injects the differencevoltage that is required by the load. The equivalent circuit of a DVR connected to thepower network is shown in Fig. Here Vs is the supply voltage, Vinj is the voltage injected by the DVR and VL is the load voltage



Control Strategy:

The principle contemplations for the control of a DVR are- identification of the beginand completion of the hang, voltage reference era, transient and unfaltering state controlof the infused voltage and security of the system.Any control technique implementedto control the DVR should fulfill all the above aspects.
The basic idea behind the control strategy is to find the amount by which the supply voltage is dropped. For this the three phase supply voltage is compared with the reference voltage Vref. If there is voltage sag (or any other voltage imbalance) then an error occurs. This error voltage is then sent to the PWM generator, which generates the firing pulses to the switches of the VSI such that required voltage is generated. The whole control strategy can be implemented in 2-ϕ rotating (d-q) coordinate system. The flow chart of the control technique based on dq0 transformation is shown in Fig.



Applications of DVR:
There are many applications of DVR in addition to mitigate voltage sag. They are DVR can be used to compensate the load voltage harmonics and improves the power quality of the system.
DVR can be used under system frequency variations to provide the real power required by the load. This is done by connecting a uncontrolled rectifier at the input of the VSI.
DVR can also protect the system against voltage swell or any other voltageimbalances that occur in the power system.

D-STATCOM

A Distribution Static Compensator is in short known as D-STATCOM. It is a powerelectronic converter based device used to protect the distribution bus from voltageunbalances. It is connected in shunt to the distribution bus generally at the PCC.

Basic Structure:

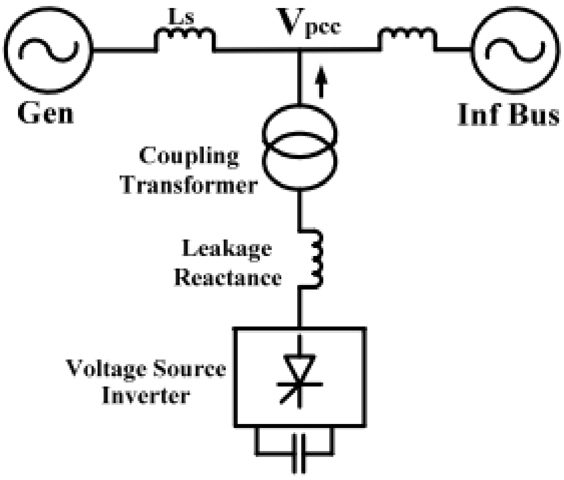
D-STATCOM is a shunt connected device designed to regulate the voltage either bygenerating or absorbing the reactive power. The schematic diagram of a D-STATCOM isas shown in Fig. It contains-

DC Capacitor

• Voltage Source Inverter (VSI)

• Coupling Transformer

• Reactor



As in the case of DVR, the VSI generates voltage by taking the input from the charged capacitor. It uses PWM switching technique for this purpose. This voltage is delivered to the system through the reactance of the coupling transformer. The voltage difference across the reactor is used to produce the active and reactive power exchange between the STATCOM and the transmission network. This exchange is done much more rapidly than a synchronous condenser and improves the performance of the system.

Operating Principle:

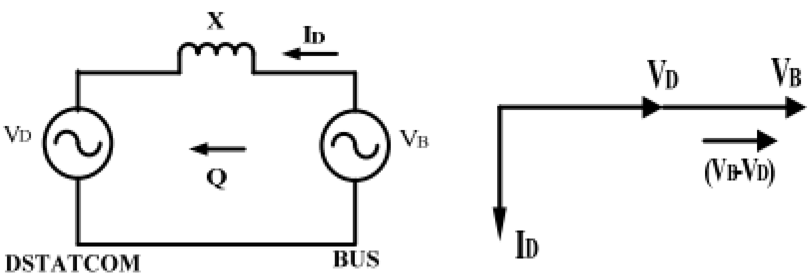
A D-STATCOM is capable of compensating either bus voltage or line current. It canoperate in two modes based on the parameter which it regulates . They are-

• Voltage Mode Operation: In this mode, it can make the bus voltage to which itis connected a sinusoid. This can be achieved irrespective of the unbalance ordistortion in the supply voltage.

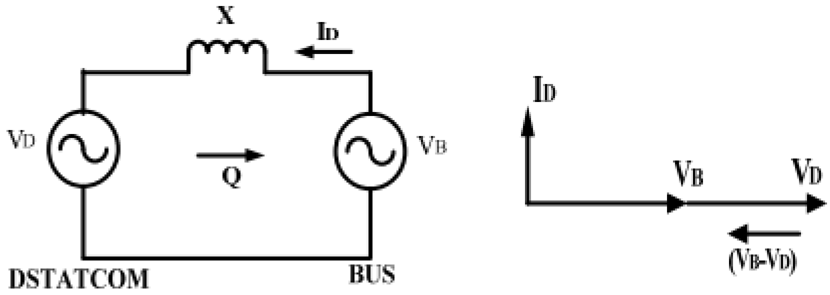
• Current Mode Operation: In this mode of operation, the D-STATCOM forcesthe source current to be a balanced sinusoid irrespective of the load currentharmonics.

The basic operating principle of a D-STATCOM in voltage sag mitigation is toregulate the bus voltage by generating or absorbing the reactive power. Therefore, the DSTATCOM operates either as an inductor or as a capacitor based on the magnitude of thebus voltage.

• Inductive Operation: If the bus voltage magnitude (VB) is more than the rated voltage then the D-STATCOM acts as an inductor absorbing the reactive power from the system. The circuit and phasor diagram are shown in Fig.



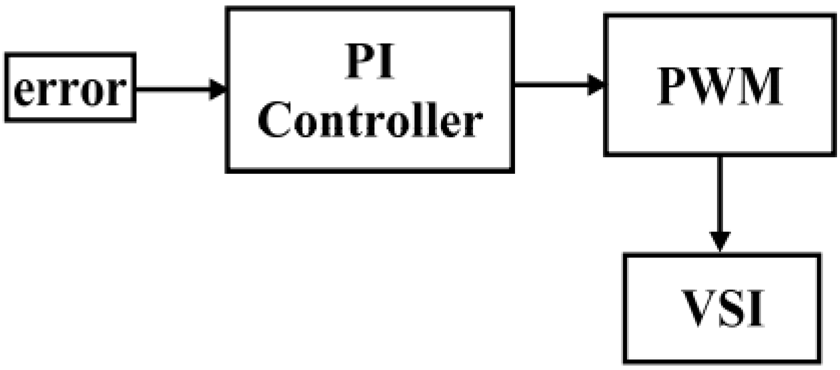
Capacitive Operation: If the bus voltage magnitude (VB) is less than the rated voltage then the D-STATCOM acts as a capacitor generating the reactive power to the system. The circuit and phasor diagram of this mode of operation are shown in Fig.



Control Strategy:

The main aim of the control strategy implemented to control a D-STATCOM usedfor voltage mitigation is to control the amount of reactive power exchanged between theSTATCOM and the supply bus. When the PCC voltage is less than the reference (rated)value then the D-ATACOM generates reactive power and when PCC voltage is morethan the reference (rated) value then the D-ATACOM absorbs reactive power.

To achieve the desired characteristics, the firing pulses to PWM VSI are controlled.The actual bus voltage is compared with the reference value and the error is passedthrough a PI controller. The controller generates a signal which is given as an input to thePWM generator. The generator finally generates triggering pulses such that the voltageimbalance is corrected. The block diagram of the control circuit is shown in Fig.



Applications of D-STATCOM:

The applications of the D-STATCOM are-

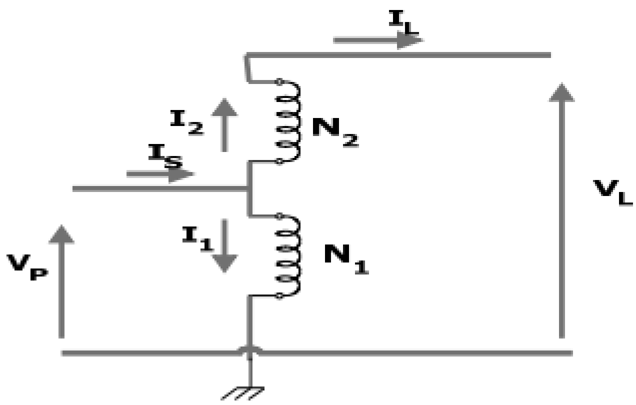
- Stabilize the voltage of the power grid
- Reduce the harmonics
- Increase the transmission capacity
- Reactive power compensation
- Power Factor correction

Auto-Transformer

An auto transformer is a single winding transformer where there is no isolationbetween the primary and secondary windings. This device requires less conductormaterial in its construction and is of less size and weight when compared to the normaltwo winding transformer. This device can be used in mitigating the voltage sag whencontrolled properly. The principle of operation and the control technique are explainedbelow**.**

Basic Structure:

The basic structure of an auto transformer is shown in Fig. In this circuitconfiguration the secondary voltage is more than the primary voltage and the transformeroperates as a step-up transformer. This configuration is used in voltage sag mitigation.

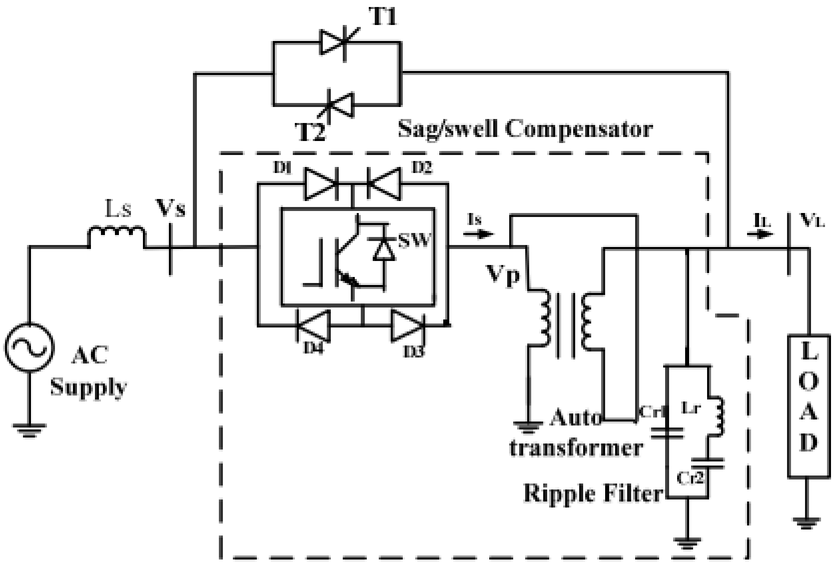


From the circuit diagram,
V_P is the primary voltage
V_L is the load voltage
$I_S$is the source current
I_L is the load current
The turns ratio N1:N2 is taken as unity and the relation between primary and secondary voltages and currents is given by the equation

$$\frac{V_L}{V_P} = \frac{I_S}{I_L} = \frac{N_1 + N_2}{N_1}$$

Operating Principle:

The auto transformer is controlled by a PWM operated power electronic switch. Thesingle-phase diagram of a power system network with a PWM switched auto transformerused for voltage sag mitigation is shown in Fig

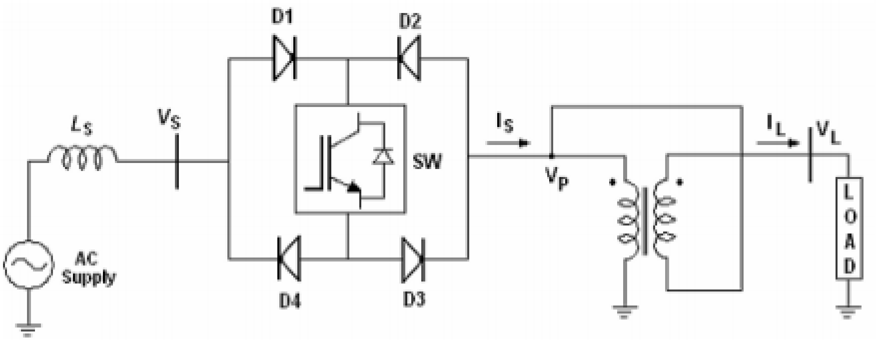


The circuit contains the following components-

- An IGBT Switch: This switch is operated based on the pulses generated by the PWM generator and controls the auto transformer operation.
- Auto-Transformer: It is used to boost the voltage so that the load voltage remains constant irrespective of the variations in the supply voltage. It is controlled by the IGBT switch.
- Ripple Filter: The output voltage given by the auto-transformer contains harmonics along with the fundamental component. Thus, these harmonics should be filtered out to maintain the THD for the given system voltage at the load should be within the IEEE standard norms. Therefore, a ripple filter is used at the output of the auto-transformer.

• Bypass Switch: There is a bypass switch made of SCR's connected in antiparallel. This switch is used to bypass the auto-transformer during the normal operation. During voltage sag condition, this switch remains off and autotransformer operates.

The single-phase circuit diagram during voltage sag condition is shown in Fig.
Here the bypass switch is off and the auto-transformer works based on the IGBT switch operation to generate required voltage on the load side



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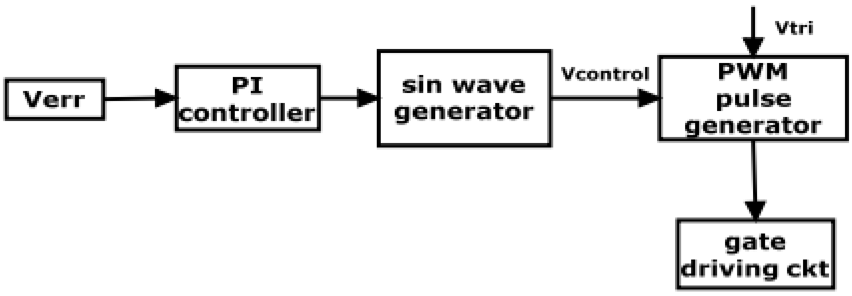
Control Strategy:

The main aim of the control strategy is to control the pulses generated to the IGBTswitch such that the auto-transformer generates desired voltage to mitigate the voltagesag. The RMS value of the load voltage is compared with a reference value (Vref). Undernormal operating conditions there is no error and no pulses are generated to the IGBTswitch and auto-transformer do not work. When there is voltage sag then an error occursand based on the error value PWM generator generates pulses to the IGBT switch.Accordingly, the auto-transformer operates and the load voltage is maintained constant. The block diagram of the control Strategy is shown in Fig.



The voltage error is passed through a PI controller and it generates a phase angle δ. With this phase angle a control voltage is generated using sine wave generator by using equation

$V_{control} = m_a \sin(wt+\delta)$

Where m_a is the modulation index

The magnitude of the control voltage is dependent on the phase angle δ. The phase angle is proportional to the degree of disturbance. Here the voltage which has been generated called control voltage is compared with the triangular voltage Vtri for the cause to generate the pulses which can be fed to the IGBT switch. In this way the auto transformer is controlled to mitigate the voltage sag.

Advantages:

The PWM switched auto-transformer is advantageous over the other devices in mitigating the voltage sag. The advantages are as follows-

• Less cost
• Less number of switches required
• Reduced gate driver circuit size
• No energy storage device

Among the different methods to mitigate the voltage sag, the use of FACTdevices is the best method The FACT devices like DVR, D-STATCOM are helpful in overcoming thevoltage unbalance problems in power system DVR is a series connected device and injects voltage to compensate the voltageimbalance. D-STATCOM is a shunt connected device and injects current into the system These devices are connected to the power network at the point of interest toprotect the critical loads . These devices also have other advantages like harmonic reduction, power factorcorrection . The amount of apparent power infusion required by D-STATCOM is higher thanthat of DVR for a given voltage sag . DVR acts slowly but is good in reducing the harmonic content .Both DVR and D-STATCOM require more number of power electronic switchesand storage devices for their operation .To overcome this problem, PWM switched auto-transformer is used formitigating the voltage sag. Here the numbers of switches required are less and hence the switching losses arealso reduced. The size and cost of the device are less and hence PWM switched autotransformer is an efficient and economical solution for voltage sag mitigation.